VISION AND COLOUR VISION.*

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When I first took up the subjects of vision and colour vision, it had been definitely proved that the rod and cone layer of the retina was the percipient layer of the eye and the point of origin of visual impulses. It was pointed out by Helmholtz that the evidence only proved that the cones were percipient elements and that there was no evidence that the rods were percipient elements. At a later date this view was re-affirmed by Nagel. The current view at the time which was specially advocated by von Kries, was that the cones were the percipient elements in daylight and that the rods were percipient elements in a dim light. This is the duplicity theory, or theory of the double retina. On the discovery of the visual purple by Boll, it was at first thought that the visual substance had been discovered but the further researches of Kühne showed that the visual purple was only present in the rods and that as the area of most distinct vision, the fovea, contained only cones it could not be essential to vision.

The eye resembles a photographic apparatus and actual photographs have been taken on the retina and fixed by Kühne. It will be noticed that on the duplicity theory there is a very unsatisfactory correspondence with the film of a photographic apparatus. Any photographer knows that the sensitiveness of this film must be under control and a different sensitiveness is required for different intensities of light but here on the duplicity hypothesis there is only a mechanical arrangement. On this hypothesis the sensitive percipient elements by day, the cones, are surrounded by much more sensitive percipient elements, the rods, which are supposed to function only in dim light. On this hypothesis, therefore, these delicate percipient elements—the rods—are subjected to a strong light which in a photographic apparatus would undoubtedly blur the photograph. In what way can the rods be in abeyance in the day time? But Bauer has shewn that the visual purple is regenerated more rapidly under the stimulus of light than it is in absolute darkness, so that it must have a function in the day time. If, however, we suppose that the function of the rods is to regulate the sensitiveness of the photographic film, that is to say they are the nerve elements which liberate the visual purple into the liquid surrounding the cones, making this film more or less sensitive in accordance with the requirements of vision, we have an explanation of every known fact of vision.

The decomposition of the visual purple surrounding the cones causes stimulation of the cones and a visual impulse is set up. It will be noticed that on this view the cones are stimulated externally and not internally. This is a much more reasonable theory than stimulation from within the cone. For it is difficult to see how from the stimulation within the cone hypothesis the waste products can escape and a cone return to a condition in which it is able to receive further stimulation. It is probable that even in the early forms of vision, stimulation of the nerve ends took place not through the direct stimulation of the nerve end by light but indirectly through some light-absorbing substance which when acted upon by light gave off products which stimulated the nerve end. This appears to be the case even with the vision of insects. The cones again are transparent and do not appear capable of absorbing light and, therefore, it is difficult to comprehend how they can be directly acted upon by light so as to set up a nervous impulse.

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It would seem likely that the photo-chemical processes necessary for vision must have an elaborate nervous mechanism which could only arise from the retina. The peculiar arrangements of the rods seems to indicate that these are the elements involved. Kühne writes:—"It must not be forgotten that the retinal epithelium of the choroid has been proved to be a very important physiological or chemical constituent of the retina, or, stated shortly, as a purpurogenous gland, the cells of which can scarcely fail to possess a very peculiar complicated innervation. Now I do not see that irritable fibres can arise from other source than from the nervous mass of the retina." It does not appear to have occurred to Kühne that the rods were the nervous elements for which he was seeking. He looked for some direct connection between the rods and the pigment cells. We know that in other parts of the nervous system it is sufficient to have contact between the cells without direct continuity.

It is curious that Kühne¹ actually did find the visual purple in a fluid form diffused into the retina. He writes: "In one of these eyes which had been laid open in the dark for an hour, I saw to my great surprise the whole of the retinal mass flooded by a clear purple solution, which, when poured upon a plate, exhibited the same behaviour to light as the mass itself." This refers to the retina of a shark. Kühne did not recognize the significance of the observation. Bayliss² states:—"When light falls on the peripheral parts of the retina in man, it is found that, when diminished so as to be just visible, it is only that part of the spectrum between wave-lengths 600 and 440 μ m (orange to blue) that is visible at all, and the sensation is one of light only, without colour, whatever the wave-length used. Now Victor Henri and Larguier des Bancelles (1911) have determined the amount of energy just sufficient to excite (threshold energy) the bleaching effect on the pigment and the amount of light absorbed by it, all at various wave-lengths between the values named. When put into curves, these three factors are found to follow the same course. This means that to produce the same sensation, by different wave-lengths, requires such an amount of radiant energy that the amount absorbed by the visual purple is the same in all cases. This is a powerful argument in favour of the participation of the pigment in vision, at all events in that particular form of the sensation investigated. The same investigators find that the absolute quantity of energy required varies with the duration of action according to a complex law, which seems to result from a combination of that of excitation of nerve with that of a photo-chemical reaction. If the energy quantum be worked out by the formula in Nernst (1913), it is 2×10^{-12} erg for the D line, practically the same as the limit of the sensibility of the retina. This sensibility is then the maximum possible.

In order to ascertain whether von Kries, the author of the duplicity theory, could find any objection to the theory advanced above, I visited him and his first remark was, "I must say at once that your theory of vision explains numerous facts for which mine is totally unable to account." Subsequently, I gave a paper on the theory of vision, by special request in two sections, the Physiological and the Ophthalmological, at the International Medical Congress at Budapest. In neither section was there any adverse comment and Prof. von Tschermak, Professor of Physiology at Vienna, subsequently wrote to the "Lancet" supporting the theory. No adverse criticism of any weight has been given of the above theory, but supporters of the duplicity theory have simply stated that it is opposed by the facts which support the duplicity theory. But the duplicity theory is supported almost

(1) *The Photochemistry of the Retina and on the Visual Purple*, by W. Kühne, translated by M. Foster, 1878, p. 34.

(2) *Principles of General Physiology*. Page 521. 1915.

entirely by misstatements. Even when the duplicity theory explains a fact, a better explanation can be given on the above theory. Then, again, there are facts which cannot be explained at all by the duplicity theory but which are a natural consequence of the above theory.

The following are the misstatements given as facts supporting the duplicity theory:—(1) that certain animals have only cones and others have only rods; (2) that the periphery of the retina is colour-blind; (3) that the eye is totally colour-blind in dark adaptation; (4) that the Purkinje phenomenon and the recurrent image are not found with the fovea; (5) that Porter-graphs consist of two branches, one the branch corresponding to light above .25 meter-candle, corresponding to the cones, and the branch for light below .25 corresponding to the rods. With regard to these I offer the following criticisms:—

Though I have examined numerous collections, I have never been able to find any animal with only rods or only cones, neither have I found anyone who has seen such a retina. The tortoise is the most quoted; it is stated to have only cones. The rods and cones in the retina of the tortoise are as clearly defined and distinct as in the human retina. The periphery of the retina is not colour-blind when colours of sufficient intensity are used. The reader can test this for himself with a doctor's red lamp. He will find he can see it as red to the extreme periphery. In dark adaptation the eye is not totally colour-blind. Those interested in the subject should read the masterly paper by Burch on "Colour Vision by Very Weak Light". Further, there is no scotoma or blind area corresponding to the rod free portion of the macula which is equal to a visual angle of about three degrees. The Purkinje phenomenon and recurrent image are found with the fovea.

Frank Allen states that in his experiments all branches of the Porter-graphs were obtained on the same central area of the retina where rods are fewest in number or are altogether absent, the flickering at the point of fixation being specially noted. The presence of B branches in the graphs obtained under these conditions is therefore, quite adverse to the duplicity theory. The larger number of branches of the Porter-graphs and their identification with enhancing and depressing reflex actions seem to remove the graphs completely from their support of the duplicity theory.

Secondly, facts which are explained in some measure by the duplicity theory can be explained in a far better manner by my theory. For instance, the Purkinje phenomenon is found with other photo-chemical substances so that it is only a photo-chemical phenomenon. The visual purple gives a curve which is very similar to that of many other photo-chemical substances. We know that with photo-chemical substances the chemical effect is not proportional to the intensity of the light, a different curve is obtained with weak light from that which is formed with light of greater intensity. It is reasonable, therefore, to suppose that the visual purple which is formed by the pigment cells under the influence of a bright light would be somewhat different in character from that which is formed in darkness. Again, from the chemical analogy just given, even if the visual purple were of the same character we should not expect similar curves with different intensities of light. It is probable that both factors are in operation.

The fact that a small star is seen more clearly on the para-foveal region than with the foveal region has been given as a strong fact supporting the duplicity theory, but the yellow pigment of the yellow spot has been entirely overlooked.

This absorbs light, particularly blue, and would account for the phenomenon. Pertz has shewn that the dark adapted fovea is more sensitive to red light than the periphery, and yet red light bleaches the visual purple. Again, the most sensitive portion of the dark adapted retina forms an oval with its long axis horizontal, the oval being 10 degrees in its vertical axis and 15 to 20 degrees in its horizontal axis. This is just at the edge of the yellow spot where there are few rods. If this were a rod phenomenon the light should appear much brighter further out where the rods are much more numerous.

Congenital night blindness has been supposed to be due to absence of rods, but a better explanation is that the cones are not so sensitive as normal to a feeble stimulation, especially as this condition can be produced by continuous exposure by day to a bright light—as for instance that reflected from snow. Congenital day blindness has been supposed to be due to absence of the cones, but a better explanation is that the mechanism of light adaptation is defective probably from defective development of the rod and cone apparatus. This is supported by the fact that many of these persons see red imperfectly, and the rods are not supposed to convey impulses leading to the perception of colour.

Dark and Light Adaptation.

In light adaptation, more visual purple is used up but more is formed. In dark adaptation, though less is formed much less is used up and so accumulates in the peripheral regions. The sensitization of the foveal region from the periphery appears to be directly under the control of the nervous system. On awaking in the night and looking at the ceiling and seeing the area corresponding as a black spot, it has often been several minutes before the purple circles have started which sensitize the foveal region and make it appear as a bright star.

We now come to facts which are inexplicable by the duplicity theory. The presence of visual purple in liquid form in the retina and surrounding but not in the cones. This will explain all the facts discovered by Hecht, who has concluded that there is dilute visual purple in the cones. The fact that vision is plainly under control of the nervous system is not explained.

The Varying Sensibility of the Fovea.

At one moment the fovea appears the least sensitive portion of the retina and at the next moment may be the most sensitive portion of the retina. Helmholtz, whilst recording the fact, confessed that he was quite unable to suggest an explanation. The following simple experiment shows this fact:—On opening an eye on awaking in the morning and looking at the ceiling the central portion is seen as an irregular, circular, rhomboidal or star-shaped black spot. On closing the eye again a bluish violet circle appears at the periphery or middle of the field of vision, contracts and then after breaking up into a star-shaped figure and becoming brighter disappears, to be followed by another contracting circle. If the eye be opened when the star figure has formed in the centre it will appear as a bright, rose-coloured star, much brighter than any other part of the field of vision. If, however, we wait till the star has broken up and disappeared before opening the eye, it will be found that only a black spot is seen in the centre. This is explained on the theory

that when there is visual-purple in the fovea this is the most sensitive portion of the retina ; when there is none there it is blind. It also shows conclusively that the fovea is sensitized from the periphery.

Currents seen in the field of vision not due to the circulation. There are numerous methods by which currents in the field of vision which are not due to the circulation can be seen. The following is one example: If one eye be partially covered with an opaque disc whilst both eyes are directed forwards in a not too brightly illuminated room and special attention be paid to the covered eye, an appearance of whirling currents will be seen with this eye. These currents appear to be directed towards the centre and have a very similar appearance to a whirlpool. On closing both eyes, all the portion in which the whirling currents are seen appears as dull purple. These currents cannot be due to vessels, because we know that the centre of the retina, corresponding to the point where the greatest movement is seen, is free from vessels. The appearance is also very different from that of the movement of blood in vessels. The experiment succeeds best if the eyes have been previously exposed to a fairly bright light. An opaque disc in a spectacle frame suffices admirably, a certain amount of light being allowed to enter the eye from the periphery.

The currents carry the visual quality, colour and brightness of the region from whence they come into an after-image. They also tend to move an after-image towards the centre; thus, if we have two similar after-images, one situated in the centre and the other a short distance from the centre, the one external to the centre may be carried into the centre and combine with the one already there. These currents are formed by the flow of sensitized liquid.

The following simple experiment shows in a very conclusive manner the influence of the para-foveal regions on the foveal region of the retina. Let a piece of black cardboard eight inches square be taken and place this on a wall-paper with a coloured pattern. The light in the room should not be too bright but the experiment can be done easily in an ordinary room with the daylight of the present time. The black cardboard should be viewed with one eye at a distance of six feet, the eye being kept as immovable as possible. It will then be noticed that portions of the colours of the wall-paper will appear to detach themselves from the wall-paper and move with a slow spiral motion into the black area. This will go on until the whole black area has completely disappeared, the surface being covered with a mixture of colours similar to those on the wall-paper. If a Persian carpet be used for the purpose of the experiment the area will be covered with a mixture of the colours of the carpet. If a uniform colour be used the black area will be covered by that colour. It may even make another colour disappear. For instance, if a piece of red paper an inch and a half square be placed on a piece of yellow-green cardboard the yellow-green will invade the red until only a yellow-green surface is seen. If any difficulty be experienced, the reader should try the experiment in a dimmer light, but I have not found anyone, until the present, who has not seen the phenomenon with ease.

There are numerous variations of the experiment. If a piece of yellow paper be placed on a blue ground and viewed as above it will be noticed that the blue will invade the yellow until the latter appears quite white and then gradually becomes blue.

The bending of the re-current image at the fovea discovered by Hess is not explained by the duplicity theory, neither is the function of the yellow pigment of the yellow spot.

This acts as a yellow screen preventing too great decomposition of the visual purple in the yellow spot region.

Sufficient attention has not been paid to subjective experiments. It is forgotten that all our sensations are subjective. The duplicity theory entirely fails to explain the change in position in the field of vision of after-images on movement of the eye. Two after-images may combine into one, or a red after-image may go right through a green one. This proves conclusively that the stimulus is liquid. (See the very able paper by Ferree on this point.) ("The American Journal of Psychol.," page 484, 1908).

The cones, therefore, are the sole percipient elements, and on being stimulated start impulses which are conveyed along the optic nerve to the brain and stimulate certain cells of the visual centre causing a sensation of light, and other cells causing a sensation of colour. (This has been proved by Henschen.) The impulses vary in character according to the wave-length of the light causing them.

Colour-blindness is due to defective development of the colour-perceiving cells. This theory has enabled me to predict numerous new facts opposed to the old theories.

The classification of mankind according to the number of colours seen in the spectrum, namely, heptachromic, hexachromic, pentachromic, tetrachromic, trichromic, dichromic, and absolutely colour-blind is a very real classification and does not involve any theory. In addition, we have those with a defect of light perception, namely, shortening of the red or violet end of the spectrum or defect in light perception of any portion of the spectrum. These defects are quite distinct from those in which the luminosity curve is normal. For practical purposes we are only concerned with the dichromic and trichromic, namely, those who see two or three colours in the spectrum respectively and those who have shortening of the red end of the spectrum preventing them from seeing a red light at the requisite distance. Houston has shown that the trichromatic theory is mathematically untenable for normal colour-vision, but it is even more mathematically untenable for abnormal colour-vision; for instance, no attempt has ever been made to show how it is that fifty per cent. of the dangerously colour-blind can pass the Holmgren wool test. If a hypothetical sensation were diminished it would alter the colour perception of the individual completely, as unequals being taken from equals could not leave an equal remainder. Ninety per cent. of the dangerously colour-blind agree with the normal white equation, they also agree with an abnormal white equation. Though a construction could be made mathematically to agree with either of these results it cannot be made to agree with both. In the same way matches may be made between spectral colours which agree so far as luminosity is concerned with those made by the normal.

The object of this lecture is to show why the colour-blind pass certain tests and fail in others. The dichromic are truly dichromic because they possess only two colour sensations, red and violet, but they are not dichromic in the

sense of light perception. There are innumerable varieties of dichromic vision, but they all agree on one point, namely, that with mixtures of red and violet every spectral colour can be matched. As the varieties of dichromic vision are innumerable, tests constructed for one case may entirely fail with another and much worse case. The ordinary dichromic with a small neutral division will confuse certain reds and greens because he regards green as a pale red, but when the neutral division is very large so that the whole of the green of the spectrum appears as white he will not confuse red and green because he regards all greens as whites. If the white division of the spectrum be larger still, so that the yellow and blue are included, he now regards yellow, blue, and green as white, and he will make a match between yellow and blue and green but will not confuse yellow and red or blue and violet. Those designated trichromic see three colours in the spectrum, red, green and violet, and have a diminished number of monochromatic divisions in the spectrum. They are very difficult to detect by any of the ordinary tests, and this is obvious when it is considered that they have three definite colour sensations. Their chief defect is that they have no yellow sensation, regarding yellow as red-green. The late Sir William Ramsay, who was a trichromic, stated that a green field in which poppies were very numerous gave him the same sensation as a yellow object. When examined with my lantern they have continual difficulty over white or yellow lights, which are really both yellow, calling yellow after red, green or green after red. The shortening of the red end of the spectrum varies very considerably and many with considerable shortening of the red end of the spectrum, but with normal discrimination will pass all the older tests for colour-blindness with ease. The portion of the spectrum which is not seen has to be subtracted from white light and any colour which reflects or transmits these rays. In order to ascertain why it is that these men can pass the older tests the red was cut out of the spectrum and various tests viewed with the re-combined light. It was found that even when the red had been cut off as far as the yellow many pseudo-isochromatic plates could be read with ease. As an example, not only of the accuracy of my classification but also of method of testing, we can take the class of the heptachromic or those who see seven colours in the spectrum. Houstoun mentioned several cases, and three gave the junction of the blue and the seventh colour at $465\mu\mu$, all the readings being made rapidly and without hesitation. He states: "At this part of the spectrum I see only blue merging into violet, and I find it extremely difficult to say where the one begins and the other ends, getting anything between 437 and $460\mu\mu$." It is therefore obvious that a man cannot pick out a colour which he cannot see, neither will he be able to recognise the colour of the light when shown in the lantern.

This lecture only deals with facts, as it is intended to help those who have to test for colour-blindness. The facts, however, were obtained by prediction from my theory, indeed every prediction of this theory has been found to be a fact. Classifications of colour-blindness based on the old theories are completely erroneous. I have often stated to supporters of the trichromatic theory that there is no fact supporting this theory and have received the reply, "There is the fact that red and green, when mixed, make yellow, but the theory was constructed to explain the fact that all colours could be matched with three selected spectral colours." It is totally wrong to assume that the retino-cerebral apparatus is similarly constituted. A far better explanation of the fact is that when the red-green region of the trichromic has been replaced by the yellow of the tetrachromic, red and green, when mixed, make yellow, instead of the red-green of a previous stage of evolution.

There are about twenty-five per cent. of men who are colour defective, but only about five or six per cent. dangerous, and this number could be diminished by careful selection of the lights employed. A tetrachromic who sees four colours in the spectrum and whose chief defect is to confuse green and blue would be only dangerous if he had to distinguish between these colours. I have spent five hours without making a man of this kind make a single mistake between the red, green, and white lights.

If the persons to be tested have to distinguish between the standard red and green lights, these lights should be used as the basis of the test: because, if any other test were used, we should still have the same problem before us, from a practical point of view. A sailor might (with reason) object to any other test, and say that because he cannot distinguish between a green and a grey wool, there is no reason why he should be unable to distinguish between the red and green lights. If other lights are used, as for instance orange, yellow-green and purple, as is the case on some railways, these must be included in the test, so that it may be shown that the examinee can distinguish between them.

It will be seen from the above that the colour-blind person names colours in accordance with his colour perception and does not guess. Though with an inexperienced examiner he may name a number of colours correctly, how different will be the case when he is examined by an examiner with a knowledge of the facts of colour-blindness! An examiner of this kind can now ask him to name colours with a certainty as to the mistakes he will make. An examination of one of each of the three chief varieties of dangerous colour-blindness will show definitely the value of colour names. A dichromic regards a certain green as white and a corresponding purple also as white. When shown these colours, why should he call them anything except the white which he sees? If the green be made yellower he will immediately call it green, if made bluer he will call it blue. Again, the dichromic regards orange and a certain green as identical, therefore when asked to name an orange he will reply emphatically "green," often adding, "I know that colour; it is the colour of grass." The trichromic who sees yellow as red-green miscalls this colour red or green. Dark yellow should be chosen, and if a red be shown first the yellow will be called green, and if a green be shown first then the yellow will be called red. Those with shortening of the red end of the spectrum may be shown a red light which they do not see at all and say so. They may be shown a pink which appears to them a definite blue, as indeed it does to a normal sighted person, when examined through a blue-green glass.

Now a colour-blind person is quite as honest as other members of the community, and certainly does not wish to enter a profession for which he is obviously incompetent. A man who cannot see a red light at all, obviously belongs to the most dangerous class of colour blindness. Yet those belonging to this class can pass most of the old tests with ease. Again and again have men of this class been examined by me with a certificate from a well-known ophthalmic surgeon stating that their colour vision was perfectly normal. A man of this kind will look at a red light at a distance of 20 ft. and declare that there is nothing there, though he may remark that he can see the hole in the lantern. He is then not annoyed at being rejected, but thankful that he has found out his defect in time.

Let us suppose that a man of this kind, though I have never met with such a case, should desire to get through the test by trickery and guessing, how is he

to set about it? How can he tell when a red light is being shown him, or when there is really nothing there, the lantern can be clicked without altering the colour and the light obscured at will? How can he pick out a pink from twenty blues when all appear identical to him? The point to be emphasized specially is that there is no chance; his detection is a certainty every time. It is exactly the same with the trichromics, who are so difficult to detect by the older tests. The efficiency of the wool test is increased enormously by the use of colour names. A man is being examined, and has just passed the wool test with the greatest ease. He is now asked to pick out all the greens, and amongst those selected are several shades of orange and yellow-browns. When asked, "Why did you not put these with the test green?" he replies, "They are a different kind of green."

Colours are called pseudo-isochromatic when they are distinguished easily by normal-sighted persons, but are regarded as identical by certain classes of the colour-blind.

The pseudo-isochromatic tests in common use are those of Stilling and Ishihara and my Card Test. In order to ascertain the relative merits of these three tests, fifty consecutive referred, or appeal, cases were examined at the Board of Trade, with the following results. It should be noted that none of these cases was examined by me alone; in all of them at least three persons, and often more, were present at the examinations. In every case Captain Ellery or Captain Dowdy and the Recorder were present. Each candidate was first examined by the pseudo-isochromatic tests and the fact whether he was dangerously colour-blind or not was ascertained subsequently.

Seventeen of the fifty cases were passed and thirty-three rejected. Of the thirty-three who failed, nineteen failed with all three pseudo-isochromatic tests, but fourteen of those rejected passed Ishihara completely, and thirteen passed Stilling. Of those who were passed thirteen showed defects with my Card Test, and of those who failed all were rejected by my Card Test, in most cases failing very badly, as, for instance, not reading Card eight, a yellow-green C on an orange ground. The explanation of the difference is that a test for a dichromic will not necessarily detect a trichromic and those with shortening of the red end of the spectrum; both are obviously dangerous, as shown by the examination with the lantern and spectral tests. In my Card Test also the pattern is the same on every card, so that the examinee has to judge by colour alone and cannot follow the design of the artist.

An important point to note is that a test which is difficult to the normal-sighted is not necessarily difficult to the colour-blind. This is shown by the number of colour-blind persons who can read Stilling's plates numbers nine and ten, the reading of which is supposed to indicate very good colour perception. In fact a test may be constructed which can be read by the colour-blind, but not by the normal-sighted.

Nagel's anomaloscope is not a satisfactory test, since a man may be anomalous without being colour-blind, and 90 per cent. of the colour-blind agree with the normal equation.

Further details will be found in my books "The Physiology of Vision," G. Bell & Sons, London, 1920, and "Science and Pseudo-Science," John Bale & Sons, London, 1933.