From the Author

LIGHT AND COLOUR PERCEPTION.

By F. W. EDRIDGE-GREEN, M.D., F.R.C.S.

Reprinted from the Edinburgh Medical Journal. *Edinburgh and London*, Young J. Pentland, *April*, 1901.

LIGHT AND COLOUR PERCEPTION.

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I will first give a short outline of the theory which I have adopted in order to explain the phenomena of vision. This theory, in addition to being supported by anatomical facts, explains all the extremely complicated phenomena of sight, including those facts which are confessedly incompatible with any other theory. I have assumed that the cones of the retina are insensitive to light, just as, in fact, the optic nerve fibres themselves must be. I regard the cones simply as the terminations of the optic nerve fibres in the retina. I think that it is extremely probable that we shall find that the rods are not connected with the optic nerve fibres, or at any rate in a different manner to the cones. This hypothesis at once disposes of the main objection, which made Kühne say that the visual purple could not be essential to vision, and could not be the visual substance. According to this hypothesis, therefore, light falling upon the retina liberates the visual purple (rose) from the rods, just as heat melts an ointment, and a photograph is formed, the cones conveying the impression of the photograph to the brain. It will be seen, therefore, that the cones are only sensitive to chemical changes in the visual purple, and not to light itself in the sense of conveying any light sensation to the brain. They are sensitive in one way, namely, that when light falls upon them, it causes the inner limbs to contract, but this change has been noted when light falls on the other eye or on the skin. This may be one of the ways by which the visual purple is drawn out; and support is lent to this view by the fact that my experiments on the disappearance of lights can be best made with only one eye, and when no light is allowed to fall on any part of the body with the exception of that which falls on the fovea centralis. In darkness, therefore, the visual purple is in the rods, and the yellow spot of the retina corresponds to the sensitive plate of a photographic apparatus, which is prepared by light, immediately it is required for use. On waking from sleep in the middle of the night, the field of vision often appears absolutely dark for some seconds, though there may be sufficient light by which to recognise objects. I have noted that just preceding vision, in the centre of the field appear a number of rose-coloured circles, and round this centre a great number of rose-coloured and green circles, which interlaced and appeared to be rapidly moving, the appearance being very similar to the subjective sensation caused by intermittent light. I have made numerous experiments, which show that light may fall on the fovea centralis without producing any sensation.[1] Fig. 1 shows the retina at rest, the visual purple being in the rods. Fig. 2 shows the retina when light has fallen upon it and in the act of seeing. It is easy to suppose that light acting upon the visual purple effects chemical changes in it, that these chemical changes excite the ends of the cones, and a sensation of light is conveyed to the brain. Fig. 1 shows the connection of a cone of the retina *b*, with a ganglion cell *c*, of the centre for visual memory; *d* is a cell of the colour-perceiving centre; *e*, a cell of the form-perceiving centre.

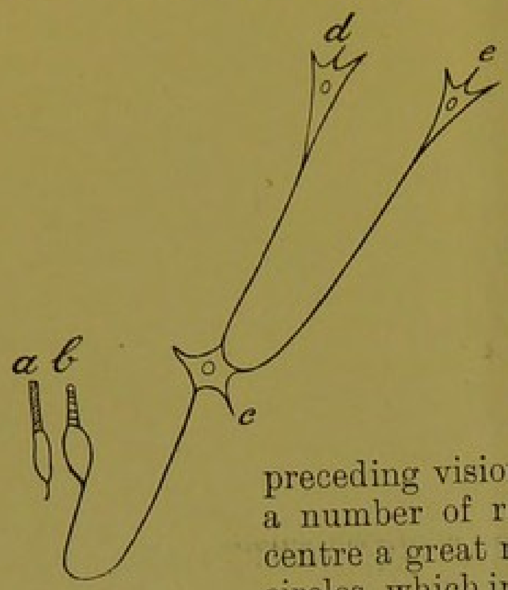

Fig. 1.

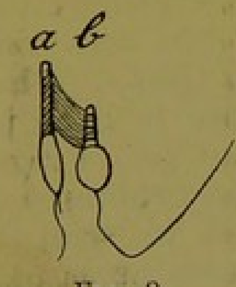

Fig. 2.

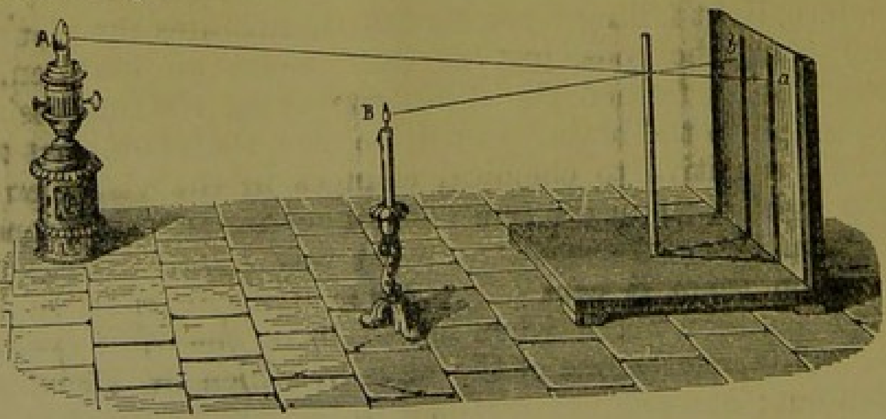

Fig. 3.

It is not at all necessary that we should assume that there are

[1] *Ophth. Rev.*, London, October 1900.

any special substances in the retina, such as the hypothetical substances of the retinal theories of colour vision. It is easy to suppose that light in decomposing the visual purple gives rise to nerve impulses which differ in character (for instance, wave length), just as the physical light waves differ themselves in wave length. A varying degree of acidity would be almost sufficient for our purpose. Therefore, in the impulse itself, we have the physiological basis of light, and in the quality of the impulse the physiological basis of colour. It will be seen from this basis that there is no reason why we should not see an innumerable series of colours. But this is not the case either with the colour or any other perceptive faculty. A very simple experiment will suffice to demonstrate this point (see Fig. 3). Let a equal the light thrown on the screen by the light A, and b that thrown by the light B. The portions of the screen free from shadows receive $a+b$, whilst the shadows receive light from only one source. It is, however, easy to adjust the lights so that one shadow is quite invisible. The same applies to colour.

It will be seen that the nerve cell conveys to the mind information concerning the physical stimuli within the power of perceiving differences possessed by that cell. It is obvious that the psycho-physical theory could be applied in another way; that is, we could assume that the nerve impulses caused by a certain colour differed from other nerve impulses in a different manner from the range of the spectrum; for instance, that yellow and blue differed more than any other two colours. But the facts show that the simplest form of the psycho-physical theory is true—that is, that the nerve impulses differ in accordance with the physical light series.

THE PHYSICAL SERIES OF COLOUR.—It is evident that before we can have a psycho-physical series (that is, a physical series as it appears to the mind), we must have a physical series; and this is admirably represented in the case of colour by the solar spectrum. This is the most perfect example of a physical series which can be obtained. By dispersion, the sun's light is spread out in the form of a series, the wave lengths of the units gradually diminishing from the red to the violet. The presence of gaps in the solar spectrum, in the shape of Fraünhofer's lines, shows that the spectrum is pure, and that the rays of light do not overlap.

The points of greatest difference may be obtained by measurement of the wave lengths. It is evident that the two points of greatest difference do not come within the visual range at all, because the waves in the infra-red present a greater physical contrast to those in the ultra-violet than any two rays in the visible spectrum. If we take the portion of the physical series represented by the spectrum, the two points of greatest physical difference are the first visible ray of red and the last visible ray of violet. The third point of greatest physical difference will be the centre of the spectrum. The next two points will be found between the third point of difference and the ends of the spectrum. These and subsequent points can be found with the aid of mathematics.

The Psycho-Physical Series of Colour.—When a physical series has been obtained, the mental impression of this series constitutes a psycho-physical series. The appearance of the spectrum to any person constitutes the psycho-physical colour series for that person. The question then is, What is the appearance of the spectrum to the majority of persons? Most persons say that they can see six definite colours in this spectrum—red, orange, yellow, green, blue, and violet; and that one colour appears to shade off into those adjacent to it. We can examine the spectrum in another way—that is, by only observing a small portion at a time, either using shutters to a spectroscope, or letting the spectrum pass through a slit which only allows a small portion to pass. When the spectrum is viewed in this way, it appears to be made up of a series of monochromatic bands. The size of these monochromatic bands differs with different persons; that is, a band which is monochromatic to one person is not necessarily monochromatic to another. These bands are absolutely monochromatic; that is, if a portion of green were taken, the observer could not say which was the yellow and which was the blue side of the portion of light shown. But we know that the portion of light, though apparently monochromatic, contains rays of light which differ very considerably in wave length, therefore we have a number of physical units which cannot be distinguished from each other. These units are seen under the most favourable circumstances for the detection of any difference, the adjacent colours being excluded, and yet they appear alike. The first obvious inference to be drawn from this is, that the rays of light occupying a monochromatic band are identical for the observer, as far as perception is concerned. In the psycho-physical colour series, therefore, the absolute psycho-physical colour units are portions of the spectrum which appear—when the remainder of the spectrum is shut off—monochromatic. For example, take the several varieties of green which we can distinguish. As the band of colour appears monochromatic, we could substitute an equal number of any one of the rays of light entering into its formation, without altering its appearance as far as colour is concerned. From this it is evident that nearly all the experiments which have been made by physicists with regard to colour will have to be looked at from a psycho-physical standpoint, as this is a source of error which appears to have been very generally overlooked. As we can only tell an absolute psycho-physical colour unit from the adjacent units by carefully comparing them, it is evident that the difference between them is not sufficient for practical purposes, so we come to the approximate psycho-physical colour units—that is to say, colours which can be easily distinguished from each other without comparison.

These approximate psycho-physical units, for a normal-sighted person, are six in number—red, orange, yellow, green, blue, and violet.

Fig. 4 represents a spectrum as seen by a normal-sighted person. A and B represents the centre points of approximate psycho-physical units, green and blue; that is, colours corresponding to these portions of the spectrum would be easily distinguished without comparison. The rays included between A and C form an absolute psycho-physical unit; that is, the portion included between A and C appears monochromatic. If shutters were used to the eyepiece of the spectroscope, the observer would not be able to say which was the yellow and which was the blue side of the portion of light shown. If, however, he were shown the coloured band from A to D, he would be able to distinguish between the colour at A and B and that at D. But if he were shown a colour corresponding to D, and were asked to which

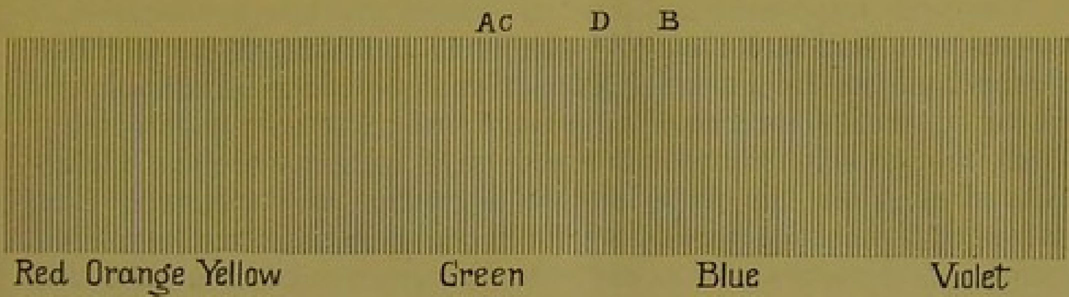

FIG. 4.

portion of the spectrum it corresponded, without being allowed to compare it with other colours, he would find great difficulty in indicating the right position. There are therefore six definite points of difference in the spectrum to a normal-sighted observer, corresponding to the centre of each of the colours—red, orange, yellow, green, blue, and violet. As each of the colours at these points must, by the presence of the adjacent points, blend with each other, we have the approximate psycho-physical units formed. It will be seen that if the size of the absolute psycho-physical units, as AC, be increased, the size of the approximate units will also be increased. As the spectrum remains the same length, the increase in size of the approximate units results in their rearrangement and diminution in number, and hence colour-blindness; five instead of six distinct points are seen in the spectrum. In the next degree four, and so on, until total colour-blindness is reached.

THEORIES OF COLOUR PERCEPTION.—I will now review a certain number of the well-known facts of colour vision, and show the inferences which may be drawn from each set of facts, each inference and deduction being limited as much as possible by other known facts and deductions. In constructing a theory, if any facts be absolutely inconsistent with the theory, the theory should be rejected, no matter how plausibly other facts are explained by it.

1. *Colour mixing.*—If we take certain proportions of spectral red, green, and violet, we can make white light or any other colour. If we stopped at this point, we could deduce, as Helmholtz has done, that there were three primary colour sensations, in which case the curves constructed by him admirably represent the theoretical position. But we can equally deduce from these facts that red, green, and violet are the primary points of difference perceived by the colour-perceiving centre, and that the mixture of spectral colours only gives rise to the perception of subsidiary points of difference within the power of perceiving differences possessed by that centre. Let us therefore see whether the curves are intrinsically correct, judged only by the other known facts of colour-mixing.

The first important fact is, that there are many colour-blind persons who will make exactly the same matches, as far as shade is concerned, as the normal-sighted, therefore colour-blindness cannot be due to the absence of a hypothetical set of colour-perceiving fibres, though this is how it is represented in many books. Helmholtz at once saw the force of this argument, and suggested that instead of the colour-perceiving fibres being absent, they responded to light in the same way as one of the other sets of fibres. But this hypothesis does not surmount the difficulty with reference to the perception of shade, because it seems incomprehensible that, when the hypothetical red fibres were acted upon by green light in the same way as the green fibres, the perception of luminosity should be the same as the normal-sighted. Rood has shown that the luminosity curves for the normal-sighted differ. I regard all luminosity curves as only giving information as to the action of light on the visual substance, and not as affording any information with regard to the perception of colour. The colour-blindness of the peripheral parts of the retina, and the fact that this disappears with brighter colours, while white does not change its colour, has to be explained. We have also to account for the well-known fact that normal-sighted persons may be made colour-blind, and colour-blind persons made to see like the normal-sighted, by hypnotism. It would be impossible to replace a missing set of fibres, but it is very easy to understand how an ill-developed perceptive centre might, under a condition of excitement, recognise differences in the same way as a better developed centre under normal conditions, just as a normal-sighted person can recognise spectral colours with the peripheral parts of his retina.

Though I do not believe that colour vision is trichromic, in the sense used by the physicists—that is to say, that there are three definite fundamental sensations which are capable of acting independently of each other—it is easy to give a simple explanation of the apparent trichromatism which exists. There are two elements of trichromatism which exist, which may act independently or in association with each other. One is in the brain, and the other in the retina. The one in the brain is that red, green, and violet are the three primary points of difference; and that for the retina, the fact that visual purple and its complementary pure green may be divided theoretically into three parts, that is, orange, or red and violet, or blue, the constituents of purple (rose) and green. In the latter case, it will be noticed that green must have a value equal to the other two constituents, which, as a matter of fact, as shown by the colour-mixing equations, it has. But even had the experiments been consistent with the three-fibre hypothesis, this would not prove the truth of the theory, which would have to be rejected as totally inconsistent with other facts. Many natural phenomena can be explained in various ways, but in order to arrive at a true conclusion we must make crucial experiments, which point in which direction the truth lies.

There are many more facts of colour-mixing which are quite incompatible with the three fundamental sensations. For instance, orange and violet make dark rose, not red ; and blue and red make rose, not violet. It now remains for me to explain how the facts of colour-mixing may be interpreted by the psycho-physical theory. This will, however, be clearer after the reader has read the portion of the article on colour-blindness. According to the psycho-physical theory, any person can only see a certain number of colours. In trichromic cases the space between red and green is seen as red-green, but as the colour sense became further developed a new colour, yellow, was seen, and so a mixture of red and green could only give rise, in the normal-sighted, to a sensation of yellow, the colour which had replaced the red-green of an anterior state of development. I shall not again allude to the trichromic theory, as the objections I have raised to it and other theories have never been answered; but I wished, in the above few remarks, to show that the theory was not even in perfect accordance with the primary facts on which it was based. This is very evident on comparing the sets of curves by any two observers; the difference between them is very marked.

2. *Some peculiarities of the yellow spot of the retina.*—The peculiarities of the yellow spot, even those mentioned by Helmholtz, in the first and second editions of his "Physiological Optics," appear to be very little known. I have already mentioned the fact that light may fall on the fovea centralis without producing any sensation. A very simple experiment will convince the reader.

(1) If we look at two small isolated stars of equal magnitude, either may be made to disappear by looking fixedly at it, whilst the other remains conspicuously visible. I found that the phenomenon was most marked on a dark night, and when the star looked at was in a portion of the sky comparatively free from other stars, when only one eye was used. On a very dark night, a considerable number of small stars occupying the centre of the field of vision may be made to disappear, whilst stars occupying other areas of the field of vision are plainly visible. (2) Other lights or objects, when small and with dark surroundings—as, for instance, a piece of white cardboard on black velvet—may be made to disappear in a similar manner. (3) No change can be observed if a very bright light, a group of stars, or a uniformly illuminated surface, be made the object of the experiment. (4) If we look at an illuminated object through a pin-hole in a piece of black cardboard, surrounded by black velvet, we find that, unless it be very bright, it will not be visible at all. On moving the eye, so that the image does not fall on the centre of the retina, the object appears brighter.

When these experiments are made with a lantern, the result is very startling. One moment we are looking at a bright light, and the next have the sensation of having become quite blind, the sensation of absolute blackness being greater than can be obtained in any other way. Just before the light disappears, it appears to pulsate, appearing and disappearing as if a rose diaphragm were shut and opened before it, except that the reappearance of the light is always from without inwards. The same appearance may be seen with the stars on a dark night. I have made a great number of experiments in order to find out which colour disappears quickest, but these experiments require special apparatus. The chief essentials in making a bright light disappear are to use only one eye, and to have the surroundings of the light absolutely dark. In my experiments which I make at night I use a specially constructed lantern, which I view through four open doors, so that all extraneous light can be as far as possible excluded. The practical importance of these experiments is obvious, as a sailor, on looking at a supposed light, and seeing nothing there, might think he was mistaken, and so an accident might arise. These facts ought to be generally known to seafaring men.

It is not generally known, though Helmholtz mentions the fact, and also states that it is quite unexplainable, that a perceptible interval elapses before we are able to see with the yellow spot. When once the fact has been noted, it is very easy to see the phenomenon under almost all circumstances; but in order to see it best, one eye should be used, and the surface looked at should not be too brightly illuminated. On opening the eye quickly, the portion of the field of vision corresponding to the macula will be seen as an oval black spot, and light will appear to invade it from without inwards, the fovea centralis being the last point to convey a sensation of light. This experiment demonstrates the diffusion into the yellow spot of the visual substance. It may also be noted that, on shutting the eyes, vision is most persistent at the fovea centralis, just as we should theoretically expect, as it would take longer for the visual purple to return to the rods from the fovea.

I have made many experiments with a perimeter, in order to ascertain at which point of the retina a piece of paper, painted with luminous paint, appeared brightest. I found the connected points made an oval figure, the smaller diameter of which occupied the vertical direction, and was 10° on either side of the point of fixation. The long diameter was in a horizontal direction, and occupied a position from 15° to 20° on either side of the point of fixation.

There are many other phenomena connected with the yellow spot, and which equally support the theory. For instance, under intermittent light the yellow spot appears as a black patch, with a purple substance moving rapidly towards it from adjacent parts. If we look at a bright light reflected from metal, so that there is darkness on one side and light on the other, on the light side there appear to be innumerable little purple rivers, which seem to be moving rapidly towards the central spot. The purple appears to move in minute spots, and the space between them appears green.

3. *After-images.*—After-images may be divided into positive and negative. Positive after-images are those in which the bright parts of the objects seen appear bright in the after-image, the reverse being the case in negative after-images. The first important fact to be noted in regard to after-images is that positive after-images are favoured by darkness and negative after-images by light. This fact can be easily verified, and is of the greatest importance in the study of the subject. The colour of a positive after-image varies according to the duration and intensity of the primary stimulus. If this is very short, and the light moderate, we have a momentary glimpse of a purplish white light, which rapidly fades away from without inwards. If the duration of the stimulus be rather longer, and particularly if the eyes have been first kept closed, and afterwards are shut and covered by the hands, a dull purple is seen, which increases in intensity up to a certain point, and then fades away from without inwards, without changing colour or becoming negative. The same purple after-image is seen after every spectral colour and white light. It is most difficult to obtain after spectral red. If the duration of the primary stimulus be slightly longer, a well-defined yellow after-image is seen, which instantly changes to purple, which then passes through the same changes as before. The yellow after-

image is very well defined and the purple after-image is ill defined, but both are positive. If the duration of the primary stimulus be slightly longer and the light bright, as for instance the film of an incandescent electric light, the positive purple after-image will be surrounded by a halo of its complementary, namely, pure green.

The phenomena of contrasts are explained on the view that, colour being a point of difference, this becomes more marked on comparison, the perceptive centre being in the most favourable position for the detection of any difference. If we contrast a yellow with a greenish yellow, the yellow inclines to orange, and the greenish yellow to yellowish green. This could not be explained by assuming that the colours differ by the addition of the complementary to each, as the complementary of yellow is blue, and this mixed with yellow would make white instead of orange-yellow.

There is one fact which is more quoted than any other as evidence of definite substances in the retina representing fundamental sensations, that is, that after looking at blue-green the red of the spectrum appears a more saturated red than when seen under ordinary circumstances. But the same occurs with all physiological sensations, and no theory of fundamental sensations has been applied to these. For instance, warm water feels warmer if we have had our hands previously in cold water, and if one hand be put in cold water and the other in hot, and then both are plunged into lukewarm water, the water feels hot to the one hand and cold to the other. A sweet substance tastes much sweeter if we have previously tasted a sour liquid. A high note is positively disagreeable in its shrillness if the previous part of the tune has been played in the bass. These facts are only evidence of the fatigue which takes place in all parts of the nervous system, and which gives rise to a false standard of comparison. I am glad to be able to say that the number of those who believe in definite retinal substances corresponding to different colours, diminishes every day.

Space will not permit me to go further into the domain of physiological optics, especially as the explanation is in most cases obvious. For instance, adaptation of the retina corresponds to the accumulation of the visual purple, in addition to the fact that all the structures become more sensitive. The variation in the luminosity curve with light of different intensity is similar to that found with other photo-chemical substances. The perception of light of low luminosity being seen as white is what we should expect, the cerebral cells not being able to perceive any difference between the feeble stimuli. It will be noticed that we have disorders corresponding to defects in each part of the apparatus, as night-blindness, day-blindness, central scotoma, defects of colour perception without defects of form perception, etc.

The colour-blind may be divided into two distinct classes, which are independent of each other.

The first class includes those who are not able to see certain rays of the spectrum. There are two subdivisions of this class of colour-blind persons—

1. Those who are found to have the red end of the spectrum shortened.

2. Those who have the violet end of the spectrum shortened.

Persons belonging to the first subdivision are not able to recognise a red light at a distance as easily as the normal-sighted, and in extreme cases it is not visible at all.

The shortened portion of the spectrum is indistinguishable from black ; that is to say, not only is the red or violet not perceived as a colour, but it is not seen at all.

It now remains to consider the influence of a shortened spectrum upon colour vision. The first evident fact is, that bodies reflecting light, the rays of which occupy the shortened portion of the spectrum only, appear black.

A very common mistake, due to shortening of the red end of the spectrum, is the confusion of pink and blue. If a person with considerable shortening of the red end of the spectrum is shown a pink which is made up of a mixture of red and violet, the red consisting of rays occupying the extreme left of the spectrum, only the violet is visible to him, and so the pink appears as a violet without a trace of red. This pink is therefore matched with a violet or blue very much darker than itself.

Mistakes which are due to shortening of the spectrum may be remedied if we subtract the rays occupying the shortened portion from the colour of confusion. For instance, if we take a blue and a pink which have been put together as identical by a person with a shortened red end of the spectrum, and look at them through a glass which is opaque to the red but transparent to the remaining rays of the spectrum, both will appear alike in hue and shade.

A person with considerable shortening of the red end of the spectrum will look at a red light (which is so dazzlingly bright to a normal-sighted person as to make his eyes ache after looking at it closely for a few seconds) at a distance of a few inches, and remark that there is nothing visible, and that the whole is absolutely black. It is obvious that the light must only consist of rays occupying the shortened portion of the spectrum.

I have constructed a test for this class of the colour-blind, which consists of a lantern, with slides containing smoked glass, which, like a mist or fog, is most transparent to the red rays at the extreme left of the spectrum. By means of these glasses we can show a red composed of rays from the terminal portion of the spectrum; if the observer fail to see this light, we know that the red end of his spectrum must be shortened, and that he is unfit for the duties in which it is necessary to recognise a red light at a distance.

The strongest objection to the use of a wool test only, is that a person may, through shortening of the spectrum, be unable to distinguish red from black and yet be able to pass the test with ease, as it is obvious that this will not prevent him from matching a light green wool with other green wools.

The second class of the colour-blind make mistakes, not because they cannot see any colour, but because they are not able to perceive the difference between the colours which is perfectly evident to normal-sighted persons.

Both these classes are represented by analogous conditions in the perception of sounds. The first class of the colour-blind are represented by those who are unable to hear very high or very low notes; that is to say, these notes are non-existent to them. The second class are represented by those who possess what is commonly called a defective musical ear. A person with a defective musical ear is not able to say when a violin is in tune with a piano, though he can clearly hear the sounds produced by both instruments. He may recognise the difference between the two when the violin is a tone sharper or flatter than the piano, but not when the interval is only half a tone. In extreme cases no difference is perceived between very high and very low notes.

The same thing is found with regard to the perception of colour. Normal-sighted persons see six distinct colours in the solar spectrum. These are red, orange, yellow, green, blue, and violet. All other colours are plainly modifications of these six, for instance, yellow-green, blue-green, etc.

Those who have a very acute perception of colour can see seven distinct colours or points of difference in the spectrum. The seventh colour is seen between the blue and the violet.

In the first degree of colour-blindness, five instead of six distinct colours are seen, orange having disappeared as a definite colour. In the next degree only four colours are seen, blue having disappeared as a definite colour. Yellow next disappears, three colours being seen. In the next degree only two colours are seen, green having disappeared. With increasing colour-blindness, less and less difference is seen between any part of the spectrum, until only the ends are recognised as being different in colour. Finally, no difference in colour is seen between any part of the spectrum.

I have classified this class of the colour-blind in accordance with the number of colours which they see in the spectrum, but I have not relied upon this examination alone, but confirmed it by other tests; for instance, I have found that a person who could see four colours in the spectrum would classify two hundred pieces of coloured material or skeins of wool as if he saw four colours, and never making mistakes between these four.

An examination with the spectrum, therefore, gives us a complete key to the mistakes made by the colour-blind.

Those who see five colours make the following mistakes:— They always find a difficulty with orange, rarely using the word, and regarding it as a superfluous term. By artificial light they confuse orange with reds, pinks, and browns. They do not see the slight differences between colours which are evident to the normal-sighted. Thus they are rarely able to say, without comparison, whether a certain green is a pure green, or has a shade of blue in it, to use a common expression. In the same way, they confuse crimson and scarlet, and deep purple-violet with violet. They never make mistakes between the colours corresponding to the five points in the spectrum, which they distinguish as different.

In this subdivision, like those which follow, the defect in colour perception is not limited to one part of the spectrum; the colour sense seems to be diminished as a whole.

Those who see four colours in the spectrum make all the mistakes made by those who see five colours, but in a more marked degree. In addition, they do not recognise blue as a definite colour; when told to classify a number of coloured objects, they put the blues with green or violet.

Colour is to them a feeble quality of objects, but they never confuse the four colours (red, yellow, green, and violet) which they have distinguished in the spectrum.

Those who see three colours in the spectrum (red, green, and violet) make all the mistakes made by those who see four colours, and, in addition, do not recognise yellow as a colour, but put it with green or red. They can always distinguish between the three colours they saw in the spectrum.

Those who see only two colours in the spectrum confuse red, orange, yellow, and green on the one hand, and blue-green, blue, and violet on the other. Colours corresponding to the neutral point, and equal mixtures of colours belonging to both sets, are mistaken for grey.

In cases in which shortening of the spectrum is associated with a diminution of the colours seen, the position of the colours is altered. For instance, a person seeing two colours in the spectrum has the position of the neutral point nearer the violet when the red end is shortened, and nearer the red when the violet end is shortened, than in cases in which the spectrum is of the normal length.

The following are the details of a trichromic case of colour-blindness:—

J. C., a man, æt. 33, saw three colours in a bright solar spectrum—red, green, and violet. The orange and yellow, he saw, not as definite colours, but as mixtures of red and green. In the same way he regarded blue as a mixture of green and violet. There was no shortening of either end of the spectrum.

The following is a classification of the wools, silks, cards, and glasses of my classification test. The name at the commencement of each group was the colour-epithet applied by him.

Violet.—Violet, purple, blue-grey, blue, and one blue-green card.
Blue.—Green and blue.
Green.—Green, blue, brown, and yellow.
Yellow.—Yellow, orange, greenish yellow, and yellow-green.
Pink.—Pink and purple.
Light red.—Orange, red, pink, and rose.
Red.—Red, rose, orange, and yellow-brown.
Light brown.—Brown, grey, light green, and buff.
Not named.—Grey, brown, and black.

In making this classification, it was with great difficulty that I persuaded him to name the groups which he has designated as blue, yellow, and light brown, though he named the other groups readily enough.

Tested with my lantern test.—Called yellow "light red"; standard green, "blue"; purple, "violet"; and blue, "violet." (Rejected.) Named pure green, all neutrals, ground glass, ribbed glass, and both reds correctly.

Passed Holmgren's test without touching a confusion colour.

Read Stilling's coloured letters.

Red and blue (20 ft. being normal), at 33 ft. 9 in.

Green (20 ft. being normal), at 38 ft. 2 in.

Yellow (20 ft. being normal), at 42 ft.

The examination with the spectrum gave a key to his colour-perception.—He was never in doubt about red, green, and violet, and always named these colours correctly. Blue, yellow, and orange, he said, ought not to have names, and he was very uncertain about them. His manner when classifying these colours was very characteristic of the indecision he felt regarding them. He would take a blue and put it with the violets, then move it away and put it with the greens. Finally, he put it in another class which contained as many greens as blues.

A man with this colour-perception would be unsafe at sea, because he would be unable to distinguish the front light from the side lights. This is shown by the lantern test. A very interesting point in this case is, that he had a much more marked sense for light of all colours than most normal-sighted. He was able to read Stilling's yellow letters on a black ground at more than twice the normal distance. It is evident, therefore, that quantitative tests which assume that the colour-blind are short-sighted for colours would be useless to apply to a case of this kind.

In a paper in the *Lancet*,[1] I have pointed out the defects of the physical methods of endeavouring to ascertain the colour

[1] *Lancet*, London, August 4, 1900.

sensations of a colour-blind person by measuring the luminosity of the colours he sees. The facts obtained by measuring these colours are very easy to interpret. For instance, it has been shown that the luminosity curve of a totally colour-blind individual, suffering from day-blindness, had a similar shape to the normal curve for light of low luminosity. But this is exactly what we should expect; that is, that a powerful stimulant had the same effect on the defective retina as a feeble stimulus has on a normal-sighted person.

I have, as far as possible, avoided the facts which I have already dealt with in my book on colour-blindness,[1] and paid special attention to those facts which are either crucial in their character, or which present some special points of difficulty. I have not found it necessary to vary my theory in the smallest particular.[2]

All the facts which can be gained from the study of museums and literature point to the view that the sense of light was developed first, and then the sense of colour, those waves which differ from each other most, physically, being first perceived as different, namely, red and violet. It is obvious that if a certain portion of the visual centre be set apart for the perception of colour, when it was very small and ill developed, it would only be able to perceive differences of considerable magnitude, but as more cells were added to the centre, greater and greater power of perceiving differences arose. Many facts show that the fovea and yellow spot are more effectively represented in the cortex than the peripheral parts of the retina. This would explain the partial colour-blindness of the peripheral parts of the retina, especially as very bright colours are recognised. Each nerve cell might at first have been connected with many optic nerve fibres, and the number gradually diminished as evolution proceeded. Then all the degrees of colour-blindness were passed through, until the present stage of the development of the colour sense was reached. These facts show that colour-blindness is only an example of an earlier state in the development of the colour-perceiving centre.

[1] "Colour Blindness and Colour Perception," Internat. Sc. Ser.
[2] "Memory and its Cultivation," *ibid.*