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COLOUR VISION AND ITS ANOMALIES*

BY

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IN allotting to me the subject of Colour Vision, Dr. Wilmer has set me a very difficult task, and it will be one of my objects to prove to you how difficult it is. I regard this as the more necessary because various enthusiasts have propounded theories of colour vision which profess to explain everything, thus resembling quack remedies which cure all ills.

First, then, what is colour? It would seem very easy to answer this question. The sky is blue, grass is green, and strawberries are red. Nobody who speaks the English language will deny the accuracy of these and cognate statements. So that in common everyday parlance we must logically conclude that colour is an attribute of things. But, if so, it is not at all difficult to demonstrate that it is a very variable attribute. In this delightful country of yours you must often have sat out on your verandahs whilst twilight has stolen over the landscape. If you have been able to tear yourselves away from your philosophical meditations to make a few scientific observations you may have noticed that as twilight became deeper the red flowers first ceased to look red and later on the grass and the leaves ceased to look green. The red soon became black, and the green grey. And if you plucked a few leaves and held them close, though you could quite well see their

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shapes they still looked a ghostly grey. If you were very observant you might notice that whereas the red geraniums looked much brighter than the green grass in daylight, as twilight advanced the grey grass looked much brighter than the black geraniums. Something very curious had happened to the colours of these objects, so that one might begin to be a little doubtful about colour being a mere attribute of things.

Many years ago, about 1675, Sir Isaac Newton let a small beam of sunlight into a dark room through a hole in the shutter and allowed the beam to fall upon a glass prism. The light which emerged from the prism, when received on a white surface was seen to be spread out into what is now called a spectrum. It had ceased to be white, but showed all the colours of the rainbow. The rays which were on the side of the apex of the prism, and were therefore least refracted, were red; then followed orange, yellow, green, blue and violet. So Newton proved for the first time that white light can be split up into all the colours of the rainbow. So it obviously follows logically that colour is an attribute, not of objects, but of light. We have already had our logic upset once, so perhaps we had better be careful this time. Logic has always been ridiculously over-rated. It was fully developed in Plato's and Aristotle's times, but no great discoveries were made with its aid until it was made subservient to experiment, until in fact induction was combined with deduction.

And we shall find that our logic has again been at fault. For since Newton's time it has been shown that the luminous spectrum is only a very tiny bit of the whole spectrum, which stretches out on each side for distances which have never even yet been determined. What *has* been shown is that exactly the same type of radiation—in the physical and mathematical sense—exists on each side of the luminous spectrum, and that it gives rise on the one side to invisible ultra-violet radiation, X-rays, γ -rays of radium, and so on, whilst on the other side it gives rise to invisible heat radiation and beyond that to the Hertzian waves which are used in wireless telegraphy. If colour is an attribute of radiation why is it limited to an almost insignificant little patch?

Physicists have spent an immense amount of time and trouble on these various forms of radiation. They have made spectra with prisms and also discovered that they can make them with finely ruled so-called diffraction gratings, and it will interest you to know that the finest diffraction gratings were first made in Baltimore by Rowland (1882), who succeeded in ruling gratings with 43,000 lines to the inch.

If one takes a thermopile and passes it along a prismatic spectrum from the violet end towards the red end one finds that the rise in temperature which is thus measured increases as the red end is

approached, and it still goes on increasing beyond the red end. There is no abrupt change at the spot where colour ceases to be visible.

If one allows the spectrum to fall on a photographic plate the silver is deposited least at the red end and most at and beyond the violet end. There is again no abrupt change where the colour ceases to be visible.

If rays from a spectrum are allowed to fall on a frog's eye electrical currents are set up in the retina and optic nerve. Ultra-violet radiation a little way beyond the violet end will not produce any result, because the rays never reach the retina, being absorbed by the cornea and the lens.

So we see that the effect produced by radiation depends not only on the nature of the radiation, but also upon the nature of the receptive medium.

We also learn that when the so-called luminous radiation falls on the retina it sets up electrical currents. Now there is ample evidence to prove that these electrical currents are a concomitant of nervous impulses. In themselves they show a change in the form of energy, and it is a fundamental rule of physics that change of energy occurs only when energy is absorbed by a substance. We may therefore consider it conclusively proved that the luminous spectrum sets up physiological changes in the form of nervous impulses.

When nervous impulses are set up they do something. In many cases they cause changes in the consciousness of the individual. How they do this nobody knows. These effects, when they occur, are called psychological effects.

Hence we learn that colour is not a mere attribute of things, nor of light, but that it also involves physiological impulses and psychological effects. Colour, you see, is becoming rather a complicated business.

Ultimately you will all agree, colour, being an event in perception, which is a fundamental feature of consciousness, is a purely psychological fact. Without consciousness there is no colour. On the other hand, using the term colour in a broad sense, we may say with Clerk-Maxwell (1871) that, "all vision is colour vision, for it is only by observing differences of colour that we distinguish the forms of objects." He was only repeating what had already been said by that extraordinary genius Goethe (1810): "The eye sees no form, inasmuch as light, shade, and colour together constitute that which to our vision distinguishes object from object, and the parts of an object from each other."

Colour vision then is a form of perception, and like all forms of perception it is the ultimate result of physiological impulses set up by physical stimuli. The investigation of colour vision, therefore,

demands a somewhat advanced knowledge of physics, physiology and psychology.

It is obvious that the investigation of the problem can be approached from two sides. We can alter the physical stimuli in various ways and study the psychological results—a method which I have called the synthetic method: or we can take the psychological facts as data and attempt to analyse them—the analytical method. Both have been exhaustively pursued, but as might be expected more fruitful results have been obtained from the former than the latter.

The first great step in the investigation was taken by the physicists, who naturally adopted the first method, sometimes falling into error through ignorance of physiological and psychological factors. Newton himself (1704) set the ball rolling by isolating little bits of the spectrum, mixing them together, and observing results. And here it is important to lay stress on the fact that he adopted the best scientific method: for by so doing he was dealing with the purest and simplest stimuli that can be obtained. Many people have fallen into grievous error by their deductions from impure or mixed stimuli, for nearly all the colours of nature and art are impure, in the sense that they are themselves mixed colours. After Newton countless experimenters have confirmed and extended his results, among whom Clerk-Maxwell deserves special mention.

What happens if we mix pure colours? Let us consider a luminous spectrum, such as that produced by white light passed through a glass prism or spectroscope. On the wave-theory of light the various parts can be accurately defined by the wave-lengths of the rays. The limit of the visible spectrum to normal eyes is about $760\ \mu\mu$ at the red end to $396\ \mu\mu$ at the violet end. It will be noticed that as compared with sound waves in air the ether vibrations of the luminous spectrum extend over rather less than one octave. In the solar spectrum there are certain black lines, discovered by Fraunhofer, and caused by the vapour of incandescent metals, which afford the means for very accurately calibrating any spectrum. Of these lines the most important for our purpose are:—lithium, $670\ \mu\mu$ (red), sodium, $589\ \mu\mu$ (orange), and thallium, $530\ \mu\mu$ (green).

Pure colours can be mixed by allowing parts of the spectrum to pass through narrow slits in an opaque screen and focussing the combined rays on the eye or on a white reflecting surface. If we start with two colours from the red end of the spectrum, *e.g.*, $670\ \mu\mu$ (red) and $580\ \mu\mu$ (yellow) it is found that any mixture can be accurately matched with that derived from some spectral colour between those wave-lengths. The exact position, *i.e.*, the wave-length, of this colour depends upon the relative amounts of the two colours in the

mixture. If there is an excess of red the resultant mixture will match a colour nearer the red than the yellow-green. Moreover, the position of the colour will be accurately represented by the mass centre of the weights of the two components, *i.e.*, by the centre of gravity, as Newton showed. All colour sensations in this region are therefore functions of a single variable and can be represented on a straight line.

Complications arise when we pass beyond these limits. If a yellow is mixed with a blue-green the resultant mixture, though resembling a pure intermediate colour, does not match it perfectly. The match is made perfect by adding a certain proportion of white light to the pure spectral intermediate. In other words the mixture is paler, or less saturated, than the spectral match. As the distance between the mixing colours is increased the saturation becomes continuously less, until, finally, at one distance two colours are obtained which, when mixed, yield a sensation of white, free from all traces of colour sensation. Such colours are called *complementary* colours.

There is a range in the green from about $560\ \mu\mu$ to $492\ \mu\mu$ which possesses no spectral complementary. White can only be obtained from green by mixing it with both red and violet, *i.e.*, purple.

The whole gamut of purples is obtained by mixing appropriate quantities of extreme red and violet: they are all functions of a single variable and can be represented on a straight line. Each purple has its complementary in the green zone of the spectrum between $560\ \mu\mu$ and $492\ \mu\mu$.

The experiments on the mixture of pure spectral colours have proved conclusively that, with the qualifications about to be mentioned, every colour sensation can be produced by the mixture of not more than three spectral colours, on the condition that the three colours are so chosen that neither can be obtained by mixture of the other two. The qualifications are:—(1) that a perfect match is only obtained in many cases by adding a certain amount of white light to the comparison colours, *i.e.*, that the mixed colours produce a perfect match as regards hue, but are what is called less saturated; (2) that brown, olive-green, and greys possessing some coloured hue can only be obtained by mixing black with a spectral colour or mixture of colours.

Subject to these qualifications, within a certain average range of intensities, every conceivable light or light mixture gives rise to a sensation which can be accurately matched by the sensation produced by a suitable mixture of only three lights. In other words, from the point of view of physical stimuli *normal colour vision is trichromatic*. It cannot be too dogmatically emphasized that this law is entirely independent of any theory of colour vision. It is a statement of facts derived from logical induction. It is true

that it is the chief source of a theory which has naturally, but somewhat unfortunately, been called the trichromatic theory. It is better to call it the three components theory. Whether this theory will ultimately prove to be an exhaustive explanation of the facts of colour vision or not, those facts upon which it is primarily based are so striking and fundamental that in my opinion no theory is likely to prove valid in which they do not form a predominant characteristic.

Seeing that the range of luminous vibrations extends to approximately one octave it was natural that an explanation of the facts should be sought in some analogy to sound and hearing. All such attempts have egregiously failed and are now discredited. Apart from that, however, just as the organ of Corti is regarded as responding to individual frequencies of vibration, so it is conceivable that the visual mechanism may possess receptor organs responsive to individual ethereal frequencies. Such a mechanism would be extraordinarily complex, and there is no evidence, anatomical or other, that it exists. The trichromatism of normal colour vision, however, simplifies the problem, as was first suggested by Thomas Young (1801). For three receptive organs—Young unfortunately predicated three “nerve fibres”—all of which responded in suitably varying degree to every frequency of the luminous spectrum, would account for all the facts of colour mixture. Three names are outstanding in the history of the three components theory, Helmholtz, Clerk-Maxwell, and Abney. To them we owe the determination of the three hypothetical so-called sensation curves.

There are two methods whereby these curves can be determined. That adopted by Helmholtz (and worked out by his assistant, König) and by Clerk-Maxwell takes colour or hue as the fundamental criterion for matching. That adopted by Abney and his colleagues takes luminosity or brightness as the criterion. This is a valid criterion because it has been shown within the limits of experimental error that the luminosity of the white light formed by the mixture of all the rays of any given spectrum is equivalent to the sum of the luminosities of the individual parts of the same spectrum.

The “sensation curves” as determined by König, with corrections by Exner, are shown in Fig. 1. Those determined by Abney and Watson in Fig. 2. The curves determined by different observers are not strictly comparable unless corrected for the energy distribution of the given spectrum, as was done by König, and by Abney and Watson. Even so, it is much to be desired that they should be re-determined with all the precautions which further experience has indicated. It is hoped that this will be accomplished shortly by a new apparatus devised by Wright,

working for the Physiology of Vision Committee of the Medical Research Council (*Trans. Optical Soc.*, XXIX, 225, 1928).

Seeing that these curves are founded upon the facts of colour mixture they afford a hypothetical explanation of these facts, and

FIG. 1.

R, G, and B, sensation curves. These are König and Dieterici's curves corrected to new determinations of the points of section, *a*, *b*, *c*, *d*. Abscissae, wave-lengths of the interference spectrum of the arc light; ordinates, arbitrary scale (F. Exner.)

FIG. 2.

Normal sensation curves on equal area scale. (Abney and Watson.)

they point the way towards the explanation of many other obscure points with regard to the spectrum. For example, they indicate quantitatively the degree of unsaturation of spectral colours; for it is only near the extreme ends of the spectrum that the colours are saturated, whereas in the green part they are very unsaturated. Moreover—and this is a point which I wish specially to stress on account of its importance in colour blindness—they give quantitative estimates of the three components to the luminosity of

FIG. 3.

Luminosity curves of persons having normal and reduced red and green sensations. Abscissae, wave-lengths of the prismatic spectrum of the arc light; ordinates, arbitrary scale. (Watson.)

FIG. 4.

— Average photopic luminosity curve of 18 observers.
 --- König's photopic luminosity curve (equality of brightness method.)
 Thürmel's photopic luminosity curve (flicker method.) (Ives.)

individual wave-lengths: added together they determine the form of the curve of distribution of brightness or luminosity in the spectrum (Fig. 3). This agrees with the luminosity curve of the spectrum as determined by ordinary photometric methods (Fig. 4).

Though the three components theory explains the facts of colour mixture, there are other facts of colour vision which it explains with greater difficulty; and indeed Helmholtz wrongly admitted its failure to explain these facts and resorted to psychological explanations.

Let us look at the problem of colour vision from another point of view. Let us regard it merely as a naive phenomenon of consciousness. I look at a spectrum and I see a rainbow of colours. If I analyse my sensations the first thing that strikes me is that there are only four colours in the spectrum which I can regard as utterly dissimilar from each other. All the others appear to me to be mixtures of two of these psychologically fundamental colours. The four colours are red, yellow, green, and blue. Psychologically, as merely naive perceptions, orange is clearly a mixture of red and yellow; on each side of the green are greenish yellow and greenish blue; and beyond the blue is a violet which my experience of purples leads me to suspect is a blue with a tinge of red in it. Many people would say that green is a mixture of yellow and blue, but this is a fallacy founded on the artist's method of obtaining green by mixing yellow and blue pigments. One cannot see yellow and blue in green in the same way that one can see red and yellow in orange.

Now there are many common facts of colour vision which are grouped together under the term contrast, or better, induction. There are two kinds of induction—temporal and spatial: the former is generally called successive contrast, and the latter simultaneous contrast. If I stare at a red patch on a white background for a few seconds and then close my eyes I shall then almost certainly see a greenish patch of the same shape, and this greenish patch will be approximately the complementary colour to the red. If instead of closing my eyes I look at a differently coloured surface, its normal colour will be modified as if by the addition of the complementary colour of the primary stimulus. The obvious inference is that the physiological and psychological conditions of the receptor mechanism have been changed by the primary stimulus in such a way that its excitability has been lowered for a succeeding stimulus of the same nature and enhanced for one of a complementary nature.

Moreover, the change is not confined to the area stimulated: a reciprocal effect is observed on neighbouring areas. A patch of grey paper on a white background looks darker than a patch of the same paper on a black background (Goethe). Similarly a patch

of colour on a grey background induces a complementary response from the surrounding grey.

There seems, therefore, to be some sort of antagonism between the two pairs of psychologically fundamental colours—red and green, and yellow and blue. Such reciprocal actions are common in other nervous physiological phenomena. They led Hering to propound a general physiological theory for them, of which the visual part has survived longest. According to this opponent colours theory green and blue set up assimilative or anabolic changes in the visual apparatus; red and yellow dissimilative or katabolic changes.

The theory, being founded on the facts of induction, explains them at any rate plausibly, but has the grave objection that the trichromatic character of normal vision, as shown by colour mixtures, plays no preponderant rôle. Moreover, it is repugnant to the physiologist's mind to imagine that diametrically opposed metabolic processes should produce phenomena so clearly of the same fundamental character as the perception of, say, red and green.

It has long been known that many men show peculiarities of colour vision distinguishing them from the normal. The colour blindness of the great chemist, John Dalton, first led the attention of scientists to the analysis of the sensations of the colour blind (1798). So great was the stir produced by Dalton's defect that colour blindness was long known as Daltonism.

The vast majority of congenitally colour-blind people manifest their defect most clearly by making mistakes, often grotesque to the normal, in the names which they give to colours in which light of long wave-length predominates. As a result they have difficulty in distinguishing between red and green. Thus, Dalton said that blood looked to him like bottle-green, and grass appeared very little different from red. A laurel leaf was a good match to a stick of red sealing-wax. He was an earnest Quaker, and Quakers object to bright colours. Yet Dalton, having received the degree of D.C.L. at Oxford, wore the scarlet gown for several days, in happy unconsciousness of the effect he produced in the street.

Colour blindness might be regarded as a harmless idiosyncrasy if it were not that red and green are favourite colours for navigation lights and railway signals. It was indeed owing to a serious railway accident which occurred in Norway, and which was suspected of being due to the colour blindness of an engine driver, that Holmgren investigated the subject and devised his wool-test for its discovery. What makes the defect more dangerous is the fact that most colour blind people are quite honestly unaware of it, and attribute their mistakes to the stupidity of other people. Abney, in his Tyndall lectures, records the case of an old

gentleman of 74 who stated that " he was sitting on a black velvet chair, whereas the seat was a deep crimson plush. He laughed at his daughter's description of the mistake he made, and declared he was only colour ignorant, and that she was the one who was colour blind." I, myself, once had a conversation with a highly placed officer in a foreign navy who told me that he was not colour blind, though he admitted he had difficulty in distinguishing strawberries among the leaves of the plant.

Congenital colour blindness affects vision with each eye, and consequently we have no means whatever of knowing what the actual sensations of the colour blind are as compared with the normal sensations. It is true that a number of cases of unilateral congenital colour blindness have been reported in the literature, but it is doubtful if any of them are genuinely congenital, for defects of colour vision are often due to acquired pathological causes.

It follows from this fact that we can place no reliance on the names which these people give to colours. The names they give are those which they have learnt from popular usage and which have arisen as descriptive of normal colour sensations. In every day life the names they give are often correct, though they often exhibit a hesitation which is suggestive to the expert. Owing to the polemics which have centred around the question of colour naming it is necessary to add that colour names are certainly of importance in determining whether a man is dangerous as a navigator or engine driver; for if he calls a red light green, or vice versa, he is obviously dangerous.

Seeing that we cannot depend upon the accuracy of the terminology of the colour blind we must adopt other means for proving the nature of their abnormality. I have no hesitation in saying that the surest method is that of comparing their matches of spectral colours in various combinations. Only by this method are we quite certain of the exact nature of the stimuli which we are employing to excite their visual sense. For pigments—such as wools, cards, and so on,—and even transparent glasses reflect or transmit such complex radiations that error is likely to arise. At the same time, bad cases can easily be detected by less accurate methods: but it should never be forgotten that partial cases, such as are quite common, may also be dangerous.

When we test a large number of colour blind people—and they are not difficult to find, for at least 4 per cent. of males are badly colour blind—we find that it is not difficult to obtain two quite distinct groups, both of which match reds with greens. But the matches they make are quite different. One group which, if the numbers are large, will be the smaller group, match a slightly bluish-red with a dark green, *e.g.*, scarlet with olive-green: these

are the people who cannot distinguish by colour the difference between cherries or strawberries and their leaves. The other, larger group match a much bluer red with a green which has about the same brightness to the normal, *e.g.*, a pink with a pale green.

The majority of our victims, however, will not make such egregious errors, although most of them will make mistakes which are found to be of the same type. In 1881, the late Lord Rayleigh made the important discovery that many people with apparently normal colour vision require different amounts of red or green in their colour mixtures from the majority. His observations were confirmed by Donders, and have been amply verified. He used as his test the match of the yellow of the sodium line ($589\mu\mu$) with the yellow which is produced by the suitable admixture of lithium red ($670\mu\mu$) and thallium green ($530\mu\mu$). Whilst a few of these anomalous people required more red than the normal, most of them required more green. This is the test which is used in Nagel's anomaloscope.

How are all these cases to be explained—or *can* they be explained—on either of the two theories which have been mentioned?

Exhaustive testing of the very bad cases with a large variety of spectral matches has shown that in both groups every spectral colour can be accurately matched by suitable mixtures of only two colours. Their whole gamut of colour sensations can therefore be referred to a function of two variables, and they are therefore called dichromats. They can be explained on the three components theory on the hypothesis that one of the three components is absent. In the smaller group the "red" curve is absent; in the larger group the "green" curve is absent. Hence, though both confuse reds and greens, the former were called "red-blind" and the latter "green-blind." These are abominable terms and have led to endless trouble. Von Kries replaced them by protanopes and deuteranopes respectively; but it is a great pity that Rivers's purely descriptive terms, scoterythrous and photerythrous have not been adopted, because they are free from all theoretical implications, and merely express the fact that the first group see reds much darker than normal people do, whereas the second group see them in nearly the same brightness as normal people.

Hering said that both groups are "red-green blind," and he attributed the differences to differences in the amount of their macular pigmentation. This explanation has been quite conclusively disproved; and so far as I know, no satisfactory explanation on the Hering theory is forthcoming.

The milder cases are obviously trichromats, but they are abnormal and are called anomalous trichromats. They are

explained on the three components theory as due, not to absence of, but to deficient reaction of, one of the components. It is as though two of the sensation curves were normal and the third had all its ordinates reduced in the same proportion. If the "red" curve is

FIG. 5.

Gauging curves for dichromats: "warm" curves. *S* and *M*, two protanopes; *N* and *St*, two deuteranopes. Abscissae, arbitrary scale of prismatic spectrum of gaslight, indicating certain wave lengths; ordinates, arbitrary scale. (v. Kries.)

thus affected they are anomalous protanopes, if the "green" curve, anomalous deuteranopes.

One of the most striking facts about colour blindness was deduced by Seebeck in 1837 from the three components theory and has been proved to be generally correct; *viz.*, that the colour matches made by people of normal colour vision are also valid matches for the colour blind. This fact shows that the colour blind have not got any extra variable which the normal have not got. On

the contrary there is some quality of sensation lacking in them which the normal sighted possess. Colour blindness is in fact a reduction form of normal colour vision, which is exactly what the theoretical explanation suggests.

There are many other features of colour blindness which the theory suggests, and which have been strikingly verified in

FIG. 6.

Gauging curves for dichromats: "cold" curves. Same observers as in Fig. 5. (v. Kries.)

practice. Thus, if either the "red" or "green" curve were entirely absent it ought to be possible to match every spectral colour by suitable admixture of only two spectral colours if these be chosen sufficiently far apart. This can of course only be expected in very bad cases of colour blindness, but in them it has been found to be true (Figs. 5 and 6). As a matter of fact it will be seen from the curves that from the red end up to about $530 \mu\text{m}$ each spectral light can be matched with a red of say, $645 \mu\text{m}$, by suitably altering the slit widths, whereas, beyond that point it is necessary to add blue of, say, $460 \mu\text{m}$. The "red" curves show distinctly the difference in the two groups, the protanopic maximum being at $571 \mu\text{m}$, the deuteranopic at $603 \mu\text{m}$. The protanopes therefore require far more red for their matches than do the deuteranopes. This is strikingly brought out by matching

sodium yellow (589 $\mu\mu$) with lithium red (670 $\mu\mu$) when it is found that the protanopes require on an average five times as much red as the deuteranopes (von Kries).

The low stimulus value of red for protanopes accounts for the abnormally low luminosity of the red end of the spectrum to them, and for the "shortening of the red end of the spectrum" in this class of dichromats. The luminosity curves of the two groups are therefore very different from each other and from the normal.

Since white light can be matched by the dichromat with a suitable mixture of two monochromatic lights, and since all spectral colours can be matched by mixing the same two colours in various proportions, it follows that there is some spectral colour which will match white. This point is called the *neutral point* of the dichromatic spectrum. On the three components theory it must fall at that point in the spectrum where the "blue" sensation curve intersects the remaining—"green" or "red"—sensation curve; *i.e.*, for protanopes at about 500 $\mu\mu$, for deuteranopes at about 515 $\mu\mu$. These points in the blue-green are not far apart and therefore afford no very crucial test for distinguishing between the two groups: and the point is made still more uncertain by variation of macular pigmentation, which being yellow, absorbs a varying amount of the shorter wave-lengths. The complementary colour to the neutral point must also necessarily match white, and hence there is also a neutral purple. This long established fact has been vaunted as a brilliant new discovery in a recent book on colour vision!

Theoretically there ought to be a third form of colour blindness in which the "blue" sensation curve is suppressed. A few such cases have been recorded. Since the defect causes confusion chiefly at the blue end of the spectrum there is little risk of confusion of red and green lights. Moreover, it is very rare. It is to be noted, however, that the defects of colour discrimination associated with pathological conditions, such as detached retina, retinitis, etc., manifest themselves chiefly at this end of the spectrum.

Finally, we can conceive of two out of the three sensation curves being suppressed. Such people would see the whole spectrum as a monochromatic band, probably resembling the scotopic spectrum seen by normal people with feeble illumination and good dark adaptation. Cases of monochromatic vision certainly occur, but some of them at any rate are better explained on different theoretical grounds.

We shall not, of course, expect the anomalous trichromats to behave like true dichromats. They will not match spectral colours with the admixture of two colours only, nor will they have comparable neutral points. We shall, however, expect them, if the

theoretical explanation is correct, to show gradations as regards the distribution of brightness in the spectrum, etc., between normal colour vision and dichromatism: and such is, indeed, found to be the case. Whether *all* forms of defective colour vision in which reds, yellows, and greens are confused can be explained on this theoretical basis is quite another matter, and there is some reason to think that they cannot.

It has been found that anomalous trichromats differ from the normal in being more dependent upon the physical intensities of the lights and upon the size of the areas of retina stimulated. Moreover, they require longer time to make up their minds as to the colours and are more subject to fatigue. Thus, whereas they make gross mistakes with small sources of light—such as a lantern light at a great distance which is quite discriminable to the normal—they may be quite accurate with larger or brighter sources. They, however, seem frequently to have an enhanced capacity for simultaneous contrast.

The nature of their defect is best discovered by matching tests with spectral colours, and one of the most satisfactory is Lord Rayleigh's original test. Although Nagel's anomaloscope is quite efficient for people accustomed to telescopes and other optical instruments it is not altogether satisfactory for other people. In fact, these spectral tests are much best carried out by direct observation of a small white screen, such as a surface of magnesium or zinc oxide, illuminated by the spectral rays, as for example in Abney's apparatus.

The luminosity curves of the colour blind afford a means of actually measuring the amount of the deficiency in those cases which fall into the ordinary categories, as was shown by Abney and Watson (Fig. 3).

Considering the fact that coloured flags and lights have so long been used for signalling purposes it is remarkable that fifty years elapsed after Dalton before any serious campaign was instituted for the elimination of dangerous colour blind people from occupations entailing their use. Dr. George Wilson, Regius Professor of Technology in the University of Edinburgh, communicated a paper in 1853, and published an important book on the subject in 1855. He seems to have been the first to express the suspicion that fatal disasters had resulted to merchant ships and railway trains from mistakes made by colour-blind men; and he was instrumental in inducing the Great Northern Railway Company to test the candidates for admission to its service before they were chosen. It was not until 1875, that a railway accident at Lagerlunda attracted Holmgren's attention to the danger. His researches led to the invention of his famous wool test, and to the first public discussion of the subject in the United States by Dr.

Joy Jeffries, of Boston, in 1877. Jeffries's book on "Colour-Blindness, its Dangers and its Detection," published in 1879, founded largely on Holmgren's writings, but containing also much original work, forms a landmark in the history of the practice of testing for colour blindness.

Holmgren's wool-test does not quite deserve the obloquy which it has received in some quarters. It is an efficient test for bad cases, but it is true that milder, though still dangerous cases, may escape detection. It is seldom, however, that an expert examiner will not have his suspicions sufficiently aroused by the manner in which the candidate handles the wools to make further tests. Consisting, however, as it does, in the matching of coloured wools it has proved very unpopular with sailors and railway men, who resent a test which savours of effeminacy and seems to have no relation to their actual duties.

A more acceptable test is by means of a lantern showing coloured lights. By its means the practical conditions are more nearly simulated. Lantern tests, however, are at least as liable to lead to mistaken diagnoses unless they are very carefully devised and controlled.

In 1910, as the result of a dispute over a famous case, a Departmental Committee of the Board of Trade was constituted to revise the sight tests for the British Mercantile Marine. That Committee advised the use of a lantern which was constructed according to the specification of three of the members of the Committee. Bearing in mind that the chief guide of the colour blind to the discrimination of red, green, and yellow lights is the relative brightness of these lights *as seen by them*, this lantern uses lights all of which are of the same luminosity. In the hands of the Board of Trade examiners it has proved a very efficient instrument.

Neither Holmgren's wools nor the lantern test is, however, infallible. The decision whether a doubtful case is practically dangerous is often very difficult, and in such cases it cannot be too strongly emphasised that exhaustive tests with spectral colours are absolutely essential.

The possible dangers to travellers by sea and land owing to colour blindness are so obvious that the testing of candidates for the Navy, Mercantile Marine, and Railways is now universal. There is grave reason to fear, however, that the tests usually employed are far from infallible. If this be so it is probable that fatal accidents still arise from this cause. In 1913, the late Mr. Nettleship published a pamphlet "On Cases of Accident to Shipping and on Railways due to Defects of Sight." He collected all the cases he could find in which visual defect was the probable cause of the accident. The list is astonishingly small, and the majority of the cases are inconclusive. It cannot be doubted that

it gives an erroneous, or at any rate an extremely unreliable, estimate of the occurrence and frequency of such accidents. This is due to the facts that in many cases the colour blind navigator or engine driver is himself a victim of the accident, and that, even if he escapes, *he is never re-examined as part of the enquiry into the cause of the accident.*

It is probable, therefore, that an entirely fallacious feeling of security and confidence in the methods of testing is instilled into the public mind. In my opinion, testing for dangerous defects of colour vision in candidates for public services is at present far from satisfactory.

I wish to emphasize most strongly that I am fully aware of the great difficulties which stand in the way of a truly efficient system of tests. I candidly admit that the account which I have given in this address affords but slight indication of the complexities of the subject. The human eye is not a precise physical instrument. On the contrary, it is a highly complex and variable physiological instrument. I have indicated that it is subject to great variations from individual to individual, but it must also be remembered that it varies from moment to moment—that it is subject to adaptation to variations of light stimulation, to temporal variations whereby the responses differ according to previous excitations, to spatial variations whereby the responses differ according to the conditions of excitation of neighbouring retinal areas. There is ample evidence to show that it is a multiplex organ with at least two receptive mechanisms. Facts such as these, which I have not been able to discuss in this address, exasperate the physicists who are accustomed to deal with precise instruments which can at least be expected to exhibit some stability in their performances. The eye probably never behaves twice in exactly the same way. Nevertheless, it does not deserve the opprobrium which Helmholtz once cast upon it.

As you are probably aware colour vision has been a notorious battlefield upon which internecine conflicts have been fought with vigour, and alas, acrimony. It is a feature of clinical medicine that the more obscure the causation of a disease the more numerous and diverse are its vaunted cures. So it is with colour vision, of which it may with much truth be said—*quot homines, tot sententiae*. The theories of colour vision are like the sands upon the sea shore in multitude, and each theorist has his panacea for the infallible detection of dangerous cases of colour blindness. It is not only of the colour blind themselves that Dr. Oliver Wendell Holmes's verses apply :

“ Why should we look our common faith to find,
Where one in every score is colour-blind ?
If here on earth they know not red from green,
Will they see better into things unseen ?”