[*From the* PROCEEDINGS OF THE ROYAL SOCIETY, B, VOL. 82, 1910.]

8

The Relation of Light Perception to Colour Perception.

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

[*Reprinted from the* PROCEEDINGS OF THE ROYAL SOCIETY, B. Vol. 82]

The Relation of Light Perception to Colour Perception.

By F. W. EDRIDGE-GREEN, M.D., F.R.C.S., Beit Medical Research Fellow.

(Communicated by Prof. E. H. Starling, F.R.S. Received June 3,—Read June 30, 1910.)

(From the Institute of Physiology, University College.)

Since the majority of the theories of *colour* perception which have been propounded have been really theories of *light* perception, the two subjects, namely, colour and light perception, though really quite distinct, have become so interwoven in the discussion of the question that many seem quite incapable of distinguishing the two. Yet it may be easily shown that light perception and colour perception are quite distinct. In fact, we can divide cases of colour blindness into two classes, according as the defect is (*a*) one of light perception, or (*b*) one of colour perception or differentiation without any defect in light perception. Of course, both defects may be present in the same individual.

The investigation of these two classes of defective vision is much facilitated by the use of a spectrometer which I have devised for the purpose, and which is so arranged as to make it possible to expose to view in the eye-piece the portion of a spectrum between any two desired wave-lengths. It consists of the usual parts of a prism spectroscope, *i.e.* a collimator with adjustable slit, prism, and telescope with eye-piece of the following dimensions:—

Focal length of collimator and telescope object glasses = $7\frac{1}{8}$ inches (180 mm.).
Clear aperture of collimator and telescope object glasses = $\frac{7}{8}$ inch (22 mm.).
Slit, 7 mm. effective length of jaw, with wedge for reducing the effective length of the slit, protective cap, comparison prism, and screw adjustment for the slit width, with divided head.

The prism is of flint glass, 1·65 refractive index for D. Eye-piece, Ramsden form, focussing on to the shutters described below.

In the focal plane of the telescope are two adjustable shutters with vertical edges, the shutters being carried by levers which rotate about centres near the object glass of the telescope. The shutters can be moved into the field from right and left respectively, each by its own micrometer screw, and to each screw is attached a drum, the one being on the right and the other on the left of the telescope. On each of these drums is cut a helical slot in which runs an index, and the drum is engraved in such a manner that the reading of the index gives directly in wave-lengths the position in the spectrum of the corresponding shutter.

Thus it will be seen that if, for instance, the reading on the left drumhead is 5320 and that on the right drumhead is 5950, the region of the spectrum from λ 5320 to λ 5950 is exposed to view in the eye-piece.*

The instrument is used as follows:—As far as possible a known quality and intensity of light should be employed. A small oil lamp is quite suitable for the purpose. The observer should first ascertain the exact position of the termination of the red end of the spectrum, the left-hand shutter being moved across until every trace of red just disappears. The position of the pointer on the left-hand drum is noted, and the wave-length recorded. The left drum is then moved so that the shutter is more towards the middle of the spectrum. The right-hand drum is then moved until the pointer indicates the wave-length recorded as the termination of the red end of the spectrum. The observer then moves the left-hand shutter in and out until he obtains the largest portion of red which appears absolutely monochromatic to him, no notice being taken of variations in *brightness*, but only in *hue*. The position of the index on the left-hand drum is recorded. The left-hand shutter is then moved more towards the violet end of the spectrum, the right-hand shutter being placed at the position previously occupied by the left-hand shutter. In this way the whole of the spectrum is traversed until the termination of the violet end of the spectrum is finally ascertained with the right-hand shutter. The variation of the size of the patches and the termination of the spectrum with different intensities of light can be noted.

The instrument can also be used for ascertaining the exact position and size of the neutral patches in dichromics, the position of greatest luminosity, and the size and extent of pure colours. When it is used to test colour-blindness, the examinee should first be shown some portion of the interior of the spectrum, and then asked to name the various colours which he sees. In this way he will have no clue to the colours which are being shown him.

Tested with this instrument a normal individual will, as a rule, name six distinct colours (viz., red, orange, yellow, green, blue, violet), and will mark out by means of the shutters about 18 monochromatic patches. Occasionally we come across individuals with a greater power of differentiating hues, to whom, as to Newton, there is a distinct colour between the blue and violet, which Newton called indigo. Such individuals will mark out a greater number of monochromatic patches, from 22 up to 29. The limited number of monochromatic patches which can be marked out in this way is

* This spectrometer has been constructed for me by Adam Hilger, Ltd., and was purchased with a grant made by the Government Grant Committee of the Royal Society.

at first surprising when we consider how insensibly one part of the spectrum seems to shade into the next when the whole of the spectrum is looked at. The number and position of the patches present, however, great uniformity from one case to another.

I propose to deal with a certain number of cases of defective colour vision as investigated by this instrument, and to show how we may differentiate those defects due to failure of light perception from those due to failure of colour or hue perception.

1. *Defective Light Perception with Normal Colour Perception.*

As an illustration of this class I may mention a case I have recently examined in which there was shortening of the red end of the spectrum with absolutely normal hue perception. A boy wishing to enter the Navy had been examined with the Holmgren test and certified to have normal colour perception. He was rejected, however, with the lantern test. He was then sent to me. I found his hue perception quite normal. He matched and named colours with ease and accuracy. When tested with the spectrometer, however, I found that his spectrum for bright light was shortened to λ 700, the limit for normal individuals being about λ 760 to λ 780. He had also defective perception for the red rays adjacent to the shortened portion. When examined with my lantern* he failed altogether to see the standard red light No. 2 at about 20 feet distance, though he could clearly see the aperture through which the light came. The bright red light consisting almost exclusively of rays from λ 625 to λ 731 was not even visible to him as light.

In the latest reports of the Board of Trade there are several cases of men who have passed the green test of Holmgren, but have failed with the rose test and have therefore been designated completely red-blind. These cases are probably similar to the boy whose condition I have just described. Such cases are undoubtedly red-blind for the rays which are not seen, but not in the sense of the Young-Helmholtz or Hering theories. This boy was in a similar position to a person who is unable to hear very low notes on an organ. Such persons may have absolutely normal perception of tone differences above a certain number of vibrations per second, and in the same way these cases of so-called red blindness may have a normal appreciation of colour differences for all the spectrum except the least refrangible rays, which do not influence their retinas at all. In the same way, just as certain individuals may be deaf to the highest notes of music, so there is a class of

* This is described in my book on 'Colour Blindness and Colour Perception' (International Scientific Series), 1909, p. 264.

persons whose spectrum is shortened at the violet end. Although such cases will have an appreciation of colour differences as good as that of the average individual, their colour sense will not be identical with the latter.

This will be evident if we consider the influence of a shortened spectrum upon colour vision. The first evident fact is that bodies reflecting only light, the rays of which occupy the missing portion of the spectrum, appear black. Nearly all colours are compound, that is to say, the coloured body reflects other rays than those of the colour seen. Thus a blue-green glass may transmit the green, blue, and violet rays of the spectrum. Let us suppose that we have a substance reflecting the green, blue, and three-quarters of the violet, the colour of the body to a normal person being green. Then if we had another substance which reflected the whole of the violet, it would appear blue. But with a person who could not perceive the terminal fourth of the violet the colour would look exactly the same as the green one, and as he could not distinguish between the two, he would be in continual difficulty with blues and greens. All coloured objects reflecting rays occupying the missing portion appear darker than they do to the normal sighted, and are always matched with darker colours belonging to a point more internal. Thus a dichromic with a shortened red end of the spectrum matches a red with a darker green.

It will be noticed that a shortened spectrum, especially if one end only be affected, may interfere very little with the general appreciation of shade. If, for instance, we take a case in which the red end of the spectrum is shortened, so that only three-quarters of the red of the normal sighted is seen, then all bodies which equally reflect or transmit these rays can be correctly compared, because a similar portion of light has been removed from each. It is only when one colour reflects or transmits the rays occupying the shortened portion and the other does not that there is any definite interference with the appreciation of shade. Again, if neither colour reflects or transmits rays occupying the shortened portion of the spectrum, there will obviously be no interference with the appreciation of shade.

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 missing portion of the spectrum, only the violet is visible to him, and so the pink appears 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 missing 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 consist only of rays occupying the missing portion of the spectrum.

The same remarks which I have made for a shortened spectrum apply to cases in which there is defect of light perception through absorption or any other cause. The person having the defect is placed in a similar position to a normal-sighted person with those particular rays removed or reduced to the same intensity.

Another effect of shortening of the spectrum when it is sufficient to interfere with the difference perception which appears to be inherent in the central nervous system is that the colours appear to be moved in the direction of the unshortened portion. For instance, we find the neutral point of the dichromic with shortening of the red end of the spectrum further towards the violet end of the spectrum in comparison with a case in which the spectrum is of normal length. In the same way a trichromic with a shortened red end of the spectrum has the junction of the red and green nearer the violet end than in a case where there is no shortening.

The point that I specially wish to emphasise is that, though every case in which there is defective light perception can be explained by a defective sensibility to light of certain wave-length, not a single case of the very large number of persons that I have examined can be explained on the older theories, that is, the defect of light perception cannot be explained on the assumption that there is a defect in a light-perceiving substance which is sensitive to rays of light from a considerable range of the spectrum.

2. *Cases in which there is Defective Colour Perception.*

Even in cases where there is actual colour blindness or deficiency of hue perception it is equally important to differentiate between the perception of light and the perception of hue. Let us take as example a case which at first sight appears to be in support of the older theories, a case of so-called red-blindness, in which there is dichromic vision with considerable shortening of the red end of the spectrum. It can be easily shown that the defect which has caused the non-perception of certain red rays has not caused the dichromatism. A case of this kind will put a bright rose with a dark blue, a bright red with a dark green, designate a dark red leather as black, and find difficulty in seeing in a red light. On examining such a case it will be found that the shortening of the red end of the spectrum may be abrupt or more or less diffuse, that is, there may be defective perception of red over a much larger area. It will, however, be found that the light perception is absolutely normal immediately adjacent to the portion in which there is defective light perception. For instance, the red may be shortened to λ 680; at λ 670 the perception of red may be defective to about half the normal, and at λ 660 it may be quite normal. If we now test such a case with spectral colours from λ 660 onwards to the violet end of the spectrum, we find that their luminosity, *i.e.*, differences of light and shade, is identical with the normal. Thus the subtraction of the element which causes the non-perception of certain rays cannot be responsible for the dichromic vision which extends from λ 660 to λ 385.

In estimating defects of light perception, colours should be directly compared in order to ascertain their comparative luminosity. For instance, light of λ 589 can be compared with light of λ 570 and λ 535. A comparison with white light gives rise to results which are very fallacious. Not only have the missing red rays to be subtracted, but if the individual have a spectrum which is lengthened at the violet end or is more sensitive to any other rays than the normal, a co-efficient corresponding to these rays must be added. Therefore if α represent the missing red rays and β the added violet rays, the formula of white light as seen by the individual in question, as compared with the normal, will be white $-\alpha+\beta$.

Still more difficult to explain on any light perception theory are the cases of so-called green-blindness. These, as I have shown, are simply cases of dichromic vision without shortening of the spectrum, and, indeed, with no defect in light perception in any part of the spectrum. If to such cases we give colours to compare which differ only slightly in shade but are absolutely different in hue, we find that their selection of the lightest or darkest corresponds to that which would be made by a normal individual. A red and a green, or an orange and a green, will be selected which to the normal eye match exactly in shade.*

During two years I examined every case of colour-blindness which came

* These observations are in agreement with those of A. König, who also found that there were considerable variations in the luminosity curve of persons of normal colour perception, whilst a so-called green-blind had almost exactly the same curve as himself and a normal sighted woman. 'Beiträge zur Psychologie und Physiologie der Sinnesorgane,' 1891, p. 311.

to my notice with Rayleigh's colour mixing apparatus, in addition to other methods. In this apparatus a match is made between λ 589 (sodium yellow) and a mixture of λ 670 (lithium red) and λ 535 (thallium green). The results obtained, however, seem to be quite independent of the power possessed by the individuals examined to appreciate differences in colour. In fact, by this apparatus we may obtain abnormal values in persons who have apparently no defect in hue perception, while others who are undoubtedly colour-blind may give results which correspond to that given by the average individual. The results seem to be determined not by varying power of appreciation of hue, but by slight variations in the luminosity curve of different parts of the spectrum in different individuals. Another important factor, probably the chief one, is the state of adaptation of the eye at the time of the observation.

All who have had practical acquaintance with colour-blindness are aware that all dichromics are not equally colour-blind; one will be readily detected by almost any test, whilst another requires the greatest care to detect at all. I find that the cases of dichromic vision vary from almost total colour-blindness to cases bordering on those I have called the trichromic. I give below the monochromatic patches marked out by four dichromics with my spectrometer in similar conditions. The light was 180 meter-candles, the slit the same size in each, and the eyes light-adapted. The size of the patches is measured in micro-millimetres ($\mu\mu$).

No. 1 cannot see any difference between the cactus flower and its leaf, and does not see any difference between the red and green signal lights except at the moment when there is a change from one to the other. It is obvious that this case is much more colour-blind than the ordinary dichromic. On the other hand, a case bordering on the trichromic will see about eight definite patches in the spectrum; make a normal match with Rayleigh's apparatus; pass the Holmgren test with ease; and play pool regularly without on any occasion mistaking the coloured balls. Such a case, when examined with the spectrometer, has eight monochromatic patches instead of the normal eighteen; says that there are only two colours in the spectrum, red and violet, and has a very small neutral patch. It is quite easy to show that such a case is dichromic, as he will match spectral blue-green with a mixture of spectral red and violet: λ 670 + λ 470 = λ 490. How could a defect in a light-perceiving substance have such varying results? If we assume that in these cases there is a varying perception of colour difference, the facts are explained.

It is stated in favour of the Young-Helmholtz theory that with three variables we can produce innumerable variations, the fact that on trial we

Case.	Monochromatic patches.			Remarks.
	No.	λ.	μμ.	
1	1 2	665 498 429	167 69	Patch of greatest luminosity, λ 571—608. Neutral patch, λ 4854—5078.
2	1 2 3 4	635 503 494 482 415	132 9 12 67	Neutral patch, λ 4975—5100.
3	1 2 3 4 5 6	735 605 534 499 492 482 414	130 71 35 7 10 68	Neutral patch, λ 5005—5185.
4	1 2 3 4 5 6 7	775 653 517 506 494 484 473 416	122 136 11 12 10 11 57	Patch of greatest luminosity, λ 587—642. Largest neutral patch, λ 504—515. No defect of light or shade perception. I agreed with all his selections.

can only perceive a limited number of variations in the spectrum being entirely ignored. The same argument would, however, apply to a two-colour theory, since we can make innumerable variations with only two variables. A more important argument, however, against the three-colour theory is to be found in the fact that there is a whole group of cases which possess three definite colour sensations and yet are undoubtedly colour-blind. These I have called the class of trichromics. Such persons may match the Holmgren wools perfectly, though they may make mistakes in *naming* single wools. A very frequent mistake when shown a single skein of yellow wool is to call it red or green, while a blue wool they will call green or violet. Similar mistakes are made with a lantern. When examined with the spectrometer, they will name only three colours as against the six named by an ordinary individual. When questioned, they regard the application of a special name of yellow or blue to definite parts of the spectrum as word-splitting, and would regard the words reddish-green or greenish-violet as more appropriate to the parts of the spectrum in question.

I give below the details of three trichromic cases as examined by the spectrometer.

Monochromatic Patches in Wave-lengths as Marked out by Trichromics 1, 2, and 3.

No. of patches.	Case 1.		Case 2.		Case 3.	
	λ.	δλ.	λ.	δλ.	λ.	δλ
1	7341 6160	1181	7604 6149	1455	7604 6105	1499
2	6037 5877	160	6050 5877	173	6032 5877	155
3	5873 5677	196	5883 5694	189	5877 5765	112
4	5679 5408	271	5694 5453	241	5765 5660	105
5	5411 5309	102	5446 5166	280	5660 5529	131
6	5309 5178	131	5166 4991	175	5529 5323	206
7	5176 5070	106	4991 4916	75	5326 5024	302
8	5070 4969	101	4921 4855	66	5024 4855	169
9	4972 4806	166	4850 4713	137	4850 4713	137
10	4811 4019	792	4713 3853	860	4713 3853	860
	Length of spectrum, 3322 Angström units.		Length of spectrum, 3751 Ångström units.		Length of spectrum, 3751 Ångström units.	

δλ represents the size of the monochromatic patch in Ångström units.

On comparing these three cases, it will be noted that there is a series of very remarkable coincidences. Each presents 10 monochromatic patches, and in each there are two wide patches at the extremities and one in the centre. It will be noticed also that the smaller patches are grouped round this central one. In 1 and 3 there are in each case five intermediate patches on one side and two on the other, but in 1 the five patches are on the violet side and in 3 on the red side.

As far as these intermediate regions are concerned, 3 looks like a reversal of 1. No. 2 has four patches on one side and three on the other. There are also coincidences in the wave-lengths. The first two patches on the violet side in 2 and 3 are exactly alike in size and position. All three coincide at λ 5877. Nos. 2 and 3 have a spectrum of normal length and of exactly the same size, whilst 1 has a spectrum which is shortened at both ends but more shortened on the red side. The centre of the smallest patch of 1 is λ 5543 and the centres of 2 and 3 λ 5306 and λ 5174 respectively. It would appear as if these were three similar cases with different absorption.

We know that the portions of the spectrum which differ are those which are most influenced by the varying pigmentation of the yellow spot. It will be noticed that the total effect is the same, the spectrum being divided into 10 patches in each case, so that what is gained on one side is lost on the other. No. 2 is the spectrum of Sir J. J. Thomson, further details of whose colour perception I have given in the ' Proceedings of the Royal Society,' B, vol. 76, 1905, p. 194. Sir J. J. Thomson, when making the match previously mentioned with Rayleigh's apparatus, put more green than the normal in the mixed colour, but the other two trichromics made the normal match. It is obvious that this alteration in light perception could not produce the defect in colour perception which was found.

By the use of the spectrometer described above, it is easy to detect cases of defective colour perception of a smaller degree than the two classes I have just described. In fact, if we regard the normal individual as hexachromic, we can differentiate classes possessing five and four colour sensations respectively, which may be called pentachromic and tetrachromic. In these cases, the only loss is the power of differentiation of hue. The sensibility to light, *i.e.* to luminosity, may be normal throughout the whole spectrum. These minor cases will, as a rule, match wools perfectly, but may make slight mistakes when asked to name the colours of single skeins. The pentachromic may be regarded as differentiating the colours red, yellow, green, blue, violet, while the tetrachromic would name only the colours red, yellow, green, violet. It is evident that none of these classes can be explained by assuming the absence of any substance or set of percipient elements sensitive to light over a considerable area of the spectrum. Any theory of colour vision must explain the position of the colours and the varying size of the monochromatic patches in each case.

Harrison and Sons, Printers in Ordinary to His late Majesty, St. Martin's Lane.