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Modified Apparatus for the Measurement of Colour and Its Application to the Determination of the Colour Sensations

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X. *Modified Apparatus for the Measurement of Colour and its Application to the Determination of the Colour Sensations.*

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PART I.

(1.) *Introductory.*

In a paper contributed to the 'Phil. Trans.' in 1899 on Colour Vision, the colour sensations in terms of luminosity were given in detail. Since that date a large part of the leisure which I could command outside my official duties has been occupied in revising the measures there given. To effect this revision, a modification of the apparatus I previously employed was carried out. Some slight alteration in the sensation curves was the result, and, though small, ought to be recorded.

The principal alteration that has to be made is in the amount of what may be called "inherent white" which exists in the spectrum colours. The white is due, at all events in part, to the overlapping of the three sensations. It will in the first instance be necessary to describe the change that has been made in the colour-patch apparatus with which my previous measures had been made, since a good deal of the alteration in the blue sensation curve between λ 5900 and λ 5100 is dependent on it.

(2.) *The Colour-patch Apparatus.*

The colour-patch apparatus is now arranged to enable two spectra formed by the same source of light to be used either separately or together. This arrangement allows a comparison of any differing mixtures of spectrum colours to be made, and it also allows the addition of any desired quantity of white light to the colours formed by the aid of either of the two spectra.

In the original apparatus the intensity of the white light used for comparison with the colours varied with the intensity of the spectrum. The mode adopted to secure this result was to use the light reflected from the first surface of the first of the two prisms used in forming the spectrum. The beam of white light so obtained was reflected by a mirror on to the screen, on which the patch of colour was thrown. In the modified apparatus this principle of reflection has been still further utilized. The white light is used as before to form the spectrum to the comparison light, but, in addition, the light, after passing through the two prisms, passes through a halfsilvered mirror, inclined at about 45° to the axis of the lens. The reflected beam is again reflected so as to pursue a course roughly parallel to the main spectrum, so that two similar spectra are placed side by side. The accompanying diagram will show the arrangement.

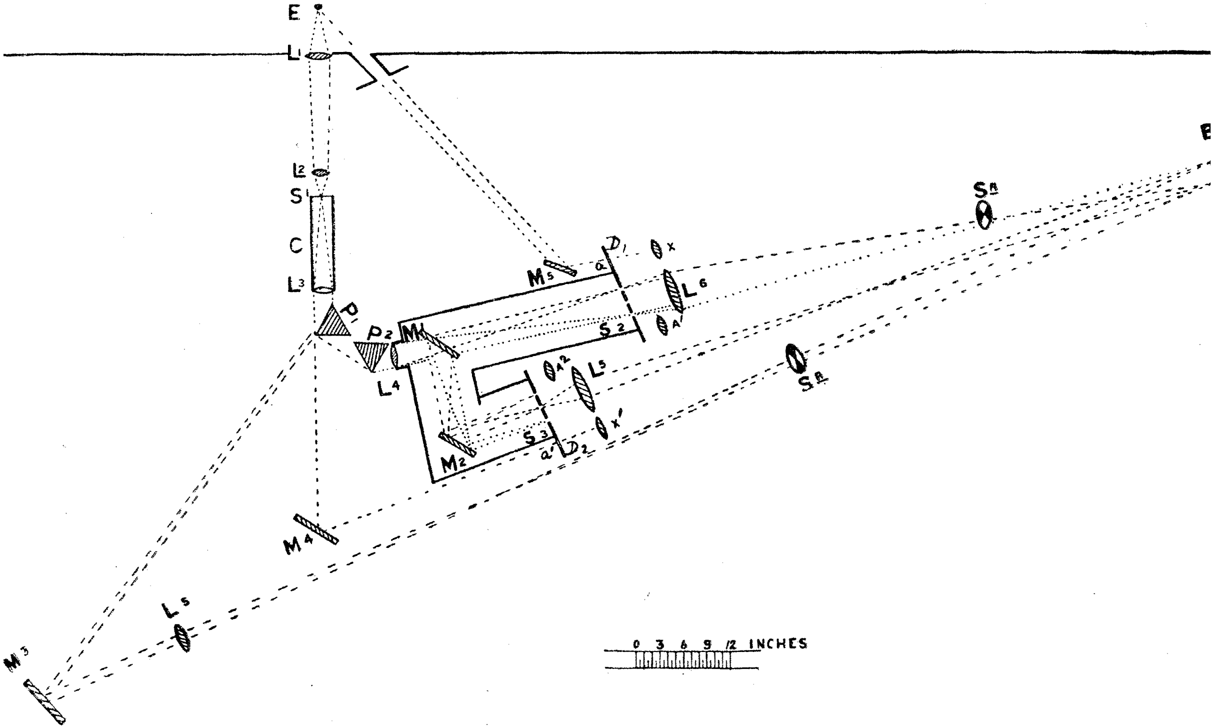
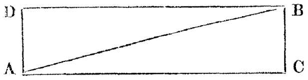


Fig. 1. Diagram of modified apparatus for the colour patch.

As in the apparatus described in "Colour Photometry," Part III. ('Phil. Trans.,' A, 1892), E is the source of light used outside a darkened room, L_1, L_2 are lenses throwing an image of the source of light on the slit S_1 of the collimator C. The parallel beam passes through the prisms P_1, P_2 and is received on a colour-corrected photographic lens, L_4, of sufficient diameter to take in the whole of the light coming through the prisms.

The lens forms a spectrum on a focussing screen at D_1, which can be removed and slits S_2 placed in the image. L_6 collects the colours and gives an image of the face of the prism P_1 on the screen B. When slits are placed at D_1, the image is of the mixed colours passing through them.

Behind the lens L_4 is placed a semi-silvered mirror M_1, reflecting, as nearly as may be, the same amount of light as is transmitted through it. If the mirror be on a plate of glass with parallel sides, it should be as thin as possible, to avoid any serious mixture of colour in the second spectrum due to the reflection of the unsilvered surface. If a plate be made up of two thin prisms, as in margin, with the surface AB of one of them silvered, the transmitted beam is not deviated, and the beams reflected from DB and AC are diverted and not used.



The reflection from the semi-silvered mirror M_1 falls on a silvered mirror, M_2, which reflects the beam in such a direction that it falls on B, the image of the spectrum being thrown on D_2, in which are slits, S_3. The image of P_1 is thrown on B by the lens L_5. A beam of white light is reflected from the face of P_1 by M_3 (which may be either a silvered mirror or plain) and is also focussed on B, so that we have the patches from both spectra and from the white light falling over one another on B. By means of rods correctly placed, a colour or colours from either spectrum can be isolated and be mixed with any proportion of white by using sectors as shown. There are slides carrying the slits at D_1 and D_2, and to them are attached transparent scales. In the case of D_1 a beam of white light falls on the mirror M_5, as shown, and passes through the transparent scale at "*a*," and a lens X throws a magnified image of the graduation on a distant white screen, on which a zero mark is drawn. This enables the transparent half-millimetre scale to be read to a tenth of that unit. In a similar way the scale at "*a*" is magnified by X′ by a beam of light falling on M_4. When the scale readings are not required, the sources of light illuminating them are covered up.

Again the small lenses A^1 and A^2 are mounted in a sliding arrangement and can be moved in front of lenses L_5 and L_6. When a slit is drawn in front of A^1 or A^2 the image of the aperture is magnified on a distant screen, carrying a scale, and the width of the slits can be accurately ascertained by noting on such scale the reading of the breadth (say) of $\frac{1}{2}$ millim. width of slit. This is the instrument with which the following measures were made.

(3.) *Is there a 4th Sensation in the Violet?*

As in my previous investigations, the red at the red lithium line was used as exciting only the red sensation, and the violet at λ 4100 was also employed as a provisional sensation, since it excited only the blue and the red sensations.

Since my last paper on the subject was published, BURCH, in his paper in the 'Phil. Trans.' (B, vol. 191, 1899) has given it as his opinion that besides the red, blue, and green sensations there is a 4th sensation excited by the violet. Before using the violet as a provisional sensation, it became necessary to ascertain if this 4th sensation really existed, and various experiments were made with this object. From the first I was sceptical as to the 4th colour sensation, as it appeared to me to be unnecessary, and was a departure from the simplicity with which nature usually works. Amongst the experiments tried was that of fatiguing one of my own eyes with strong red light, and by a simple artifice immediately afterwards viewing a patch of violet light, keeping the unfatigued eye closed. The violet became a bright blue, whilst to the unfatigued eye it was of its natural violet hue. Not satisfied with my own vision, I got several unbiased persons to repeat this experiment, and they invariably stated that the patch became blue. A red-blind person matched without any difficulty the blue lithium line* with the violet near H, though he described the former as rather paler than the latter, a description which the colour-vision theory indicates as probable. Using my two eyes, one fatigued and the other not, I endeavoured to obtain a measure of the amount of red sensation destroyed, but owing to the mixture of white in the blue the match was never perfect, as the fatigue passed away before the match was made, and when white was added to the blue, it too had lost part of its red, and the "fatigued" violet appeared too green.

These experiments and others went to prove the absence of the 4th sensation, and if further proof were required, it would be found in the ease with which the violet, when white is added to it, can be matched with a mixture of red and blue near the blue lithium line. I have therefore felt justified in using the violet as a temporary sensation in all my measures, reducing it to its components of red and blue in my final results.

(4.) *Fixed Points in the Spectrum.*

Several points in the spectrum could be readily found. Thus the complementary colour to the red in the blue-green is a fixed point, as is the complementary colour to the violet. The complementary colour to the blue (near the blue lithium line) is also known. For other preliminary details a reference should be made to my previous paper.

(5.) *Determination of the White in the Colour which only excites the Green Sensation with White.*

In my previous investigations I was unable to match spectral orange to which white could be added with mixtures of red and the green, but had to use the light transmitted through a solution of bichromate of potash placed in the path of the white (reflected) beam as representing an orange. By a suitable arrangement white could be added to it, till the mixtures were of the same colour. A small quantity of white had then to be added to the spectral orange to match the colour and the bichromate solution. From the two amounts of white added, the amount of white necessary to add to the spectral orange in order for it to match the mixture of red and green was deduced. With the apparatus now employed the determination of the amount of white to be added to the orange was made direct. There was also an advantage in these direct determinations with the spectrum colour, as more than one shade of orange could be used as checks to one another.

The results of the many measures made show that a slight correction has now to be made to my previous determination.

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* It will be noted further on that the blue lithium excites only the blue sensation and that of white.

(6.) *Amount of Blue Sensation in Yellow and Yellow-green.*

In reviewing my previous measures of the amount of blue sensation in the yellow and yellow-green of the spectrum, I was struck with the variation of results obtained on different occasions, and though every care was taken at the time, I am led to think that the amount of this sensation was under estimated, though at the most the quantity is but small. This part of the spectrum has occupied my attention for a considerable time, and the determination of the blue sensation in this region has been conducted on perfectly different lines to that formerly employed, which was to make an equation by mixing the colour under consideration with red and violet in sufficient quantities to form white, and then to equate it with the standard equation. The equations were formed, but no great stress is laid on the correctness of the blue sensation found, but only on the correct proportion of red and green sensation. The corrected value of the blue sensation was found by the following plan :—

Slits were placed in the red and green at the standard positions red Li and SSN 37·5 (standard scale number) in the green and as good a match as possible was made by mixtures of the two colours with the intermediate spectral colours, to which a little white was added. The amount of white added was not considered, but only the white inherent in the green. This last was deducted from the green and the percentage of red and green sensations in each colour calculated without taking into account the white which was due to the presence of the blue sensation. From the equations were obtained the percentage of red and green when the *white present in each colour was included*, and by the last measures the percentage of red and green when such *white was excluded.* From these different percentages it was easy to calculate the amount of blue sensation present, for it only exists in the "inherent white." On subsequently considering the sensation curves of equal stimulation as given by KŒNIG and myself, my attention was called to the fact that at the place where the red and blue curves cut a large and very sudden increase of white inherent in the colour should be seen, so large indeed that it would never escape notice. The colour at that point ought to be much paler than colours close to it, but such is not the case. The new measures show that there is no sudden rise in the amount of white present in any colour, and that the maximum of white is at SSN (standard scale number) 43 (λ 5427) and not at 37·5 (λ 5150). This point will be referred to later.

(7.) *Measures from the Blue-green to the Violet.*

The measures taken from the blue-green to the violet were made by the same method as described in the paper above mentioned, but the process was much simplified. The colour whose percentage composition had to be measured was isolated by a slit placed in one spectrum, and a slit in the other spectrum moved till a complementary colour was found which, when mixed with the former, gave a match to white. The luminosity of each was taken separately when the match was complete. The composition of the part of the spectrum from the yellow to orange was already known, and the complementary colour found was converted into the percentage components of red and green. This enabled an equation in two standard colours and the unknown colour to be formed. When equated to the standard equation, the percentage composition of the last was found. When the colours in one spectrum approach the violet, the movement of the scale in the other spectrum to find the complementary colours is very small, and the magnified scale, formed as described, was of great assistance, since a vernier could be used when required.

(8.) *The Composition of the Violet.*

This remains as given in my previous paper of 1899. Many measures were made in this region of the spectrum, and the percentage of red to blue remains as before.

The following are some of the principal measures :—

(9.) *Inherent White Light in* SSN 37·5.

To find the amount of inherent white in SSN (standard scale number) 37·5. Taking an orange below D at SSN 50·2, it is found that in luminosities

RS. 37·5. Orange. White.
41 + 55 = 57 + 39.

As there is no white in RS (red sensation), it follows that the 39 white is in 55 (37·5), or that the

Orange. RS. GS.
57 = 41 + 16,

and that there is $\frac{16}{55}$ of GS (green sensation) in 55 (37·5); that is, there is 29·5 per cent. of GS in (37·5).

Taking another orange near D at SSN 50·05, it was found that

RS. (37·5.) Orange. White.
48·7 + 45·8 = 63 + 31·5,

as before

RS. GS.
48·7 + 14·3 = 63.

That is to say, there is 31·2 per cent. of GS in (37·5). Other measures, and they were many, gave

31 per cent., 31·8 per cent., 30·8 per cent., 29·8 per cent., 32·4 per cent., &c.,

and the mean gave 31 per cent. (very closely) of green sensation in the colour, and this number was adopted.

(10.) *The Standard Equation.*

Four separate series of 50 equations each were made with slits at the red lithium line (37·5) and (4) in the violet. The mean of each series gave the following results, using 31 per cent. of GS in (37·5) :—

RS. GS. V. White.
68·48 + 30·16 + 1·36 = 100
68·18 + 30·50 + 1·32 = 100
68·62 + 29·93 + 1·45 = 100
68·44 + 30·17 + 1·39 = 100.

The mean taken to one place of decimals gave

RS. GS. V. W.
68·4 + 30·2 + 1·4 = 100,

and this equation was adopted as the standard equation for white. It will be noticed that this is somewhat different to the equation given in the former paper, but this is accounted for by the fact that the white of the comparison lights in the two cases are not quite identical, selective absorption by the glass used for reflection being far greater in the former measures than in the latter. The percentage of white in (37·5) also differs.

(11.) *Red and Green Sensations from* SSN's 58 *to* 49.

The red and green sensations in this part of the spectrum were determined by placing one slit in the red lithium colour and another in the yellow-orange of one spectrum, and matching the intermediate colours thrown on the screen from the second spectrum. The composition of the yellows and orange used had been previously determined by mixing the colour of the red lithium with (37·5) SSN :—

SSN. RS. GS.
56·2 = 95·6 + 4·4
55·1 = 92·6 + 7·4
54·05 = 90 + 10·0
*54 = 90·6 + 9·4
52·75 = 86·8 + 13·2
*52·6 = 86 + 14·0
51·6 = 80 + 20·0
*51·6 = 80·2 + 19·8
50·9 = 79·3 + 20·7
50·65 = 78·2 + 21·8
*50·55 = 78 + 22
*49·7 = 75·7 + 24·3
*49·3 = 73·6 + 26·4
49·25 = 71·5 + 28·5

SSN. RS. GS.
56 = 96·5 + 3·5
55 = 93·1 + 6·9
54 = 90·5 + 9·5
*54 = 90·6 + 9·4
52 = 84·2 + 15·8
*52 = 83·9 + 16·1
51 = 78·7 + 21·3
*51 = 78·9 + 21·1
50 = 75·0 + 25·1
49 = 70·0 + 30·0

The numbers marked * were taken with a slit at D, the others at 49·0 SSN.

As special accuracy was necessary between SSN's 48 to 50, a large series of measures was taken at this part of the spectrum. This necessity arose from the fact that a great part of the complementary colours between the greenish-blue and the violet lay in this part of the spectrum, and their composition could only be accurately determined when the exact percentage of RS and GS was known.

(12.) *Red and Green Sensations from* SSN's 49 *to* 37·5.

The equations were formed, as stated before, in the ordinary manner, keeping the slits in the red and violet at the standard places and altering the position of the green slit.

As an example, the value of SSN 45·8 was found as follows:—

$$\overset{\text{RS.}}{38\cdot8}+\overset{(45\cdot8.)}{16\cdot8}+\overset{\text{V.}}{2\cdot03}=\text{White},$$

or

$$\overset{\text{RS.}}{18\cdot6}+\overset{45\cdot8.}{80\cdot4}+\overset{\text{V.}}{1}=\overset{\text{W.}}{100},$$

but

$$\overset{\text{RS.}}{68\cdot4}+\overset{\text{GS.}}{30\cdot2}+\overset{\text{V.}}{1\cdot4}=\overset{\text{W.}}{100}\ \text{(standard equation)},$$

therefore

$$\overset{45\cdot8.}{100}=\overset{\text{RS.}}{61\cdot9}+\overset{\text{GS.}}{37\cdot6}+\overset{\text{V.}}{\cdot5}.$$

Similarly SSN's (40·5), (43), and (47·5) were found

$$\overset{(40\cdot5.)}{100}=\overset{\text{RS.}}{51\cdot68}+\overset{\text{GS.}}{47\cdot49}+\overset{\text{V.}}{\cdot83}.$$

$$\overset{(43.)}{100}=\overset{\text{RS.}}{56\cdot9}+\overset{\text{GS.}}{42\cdot5}+\overset{\text{V.}}{\cdot60}.$$

$$\overset{(47\cdot5.)}{100}=\overset{\text{RS.}}{66\cdot20}+\overset{\text{GS.}}{33\cdot5}+\overset{\text{V.}}{\cdot30}.$$

The more accurate values of the violet were determined as described by matching the intermediate colours between SSN's 49 and (37·5) of one spectrum by mixtures of these standard colours. Using luminosities, we get

$$\begin{array}{rcrcl}
\text{SSN.} & & \text{R.} & & \text{G. }(37\cdot5.)\\
38 & = & 2\cdot62 & + & 97\cdot38\\
40 & = & 9\cdot66 & + & 90\cdot34\\
42 & = & 17\cdot16 & + & 82\cdot84\\
44 & = & 24\cdot45 & + & 75\cdot55\\
46 & = & 31\cdot31 & + & 68\cdot69\\
48 & = & 39\cdot41 & + & 60\cdot59.
\end{array}$$

Deducting 69 per cent. of white from the green (SSN 37·5), we get the following R and G sensations in luminosities :—

Table I.

SSN.	RS.	GS.
38 =	8	+92
40 =	25·7	+74·3
42 =	40·1	+59·9
44 =	51·1	+48·9
46 =	59·2	+40·8
48 =	67·1	+32·0.

From the plotted curves of the red sensations and green sensations at this part of the spectrum we get the following figures :—

Table II.

SSN.	RS.	GS.
38 =	47·9	+51·2
40 =	51·0	+48·5
42 =	54·9	+44·7
44 =	57·7	+41·9
46 =	62	+37·6
48 =	67	+32·9.

Any slight corrections due to alterations found in the violet were made in the green sensations. The violet was calculated from Table I. and Table II. as follows :—There is a certain quantity of red sensation and of green sensation which with the violet forms white. From the standard equation we know that the luminosity of the red sensation is 2·265 times larger than the green sensation and 49 times larger than the violet in the white. If x be the factor of red in Table I. (which is only due to the excess of red beyond that required to form white), then the same factor must be used with the green. The red sensation in Table II. (which takes into account the white present in the colour) must have deducted from it the red of Table II. × x, and the resulting amount must equal the green in Table II. less the green in Table I. × x and multiplied by $\frac{68 \cdot 4}{30 \cdot 2}$ or 2·265.

Let R be the red in Table I., R_1 the red in Table II., G the green in Table I., and G_1 the green in Table II. Then

$$R - xR_1 = (G - xG_1)\, 2 \cdot 265.$$

From this equation we derive x. When x is found, we have a known amount of red on the left-hand side of the equation, which is the amount which combines

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with green and violet to form the white, and $\frac{R-xR_1}{49}$ gives us the amount of violet. Take, as an example, SSN (42):

$$\overset{\text{RS.}}{54\cdot9}-\overset{\text{RS.}}{40\cdot1x}=(\overset{\text{GS.}}{44\cdot7}-\overset{\text{GS.}}{59\cdot92x})\,2\cdot265.$$

From this we get

$$x=\cdot484\quad\text{and}\quad\frac{54\cdot9-40\cdot1\times\cdot484}{49}=\cdot726,$$

the amount of violet present in SSN 42.

The scale numbers in Tables I. and II. were thus treated and the violet as shown in Table III. was so obtained.

(13.) *Colour Sensations in* SSN (37·5).

The amount of white light in (37·5) has already been determined as 69 per cent. It only remains to add this amount of white to the green in the standard equation and equate it when so altered to the standard equation.

When the luminosity of the GS is increased by 69 per cent. the equation becomes

$$\overset{\text{RS.}}{40\cdot91}+\overset{(37\cdot5.)}{58\cdot27}+\overset{\text{V.}}{\cdot84}=\overset{\text{W.}}{100},\ \text{the standard equation being}\ \overset{\text{RS.}}{68\cdot4}+\overset{\text{GS.}}{30\cdot2}+\overset{\text{V.}}{1\cdot4}=100.$$

These give us the composition of

$$\overset{(37\cdot5.)}{100}=\overset{\text{RS.}}{47\cdot19}+\overset{\text{GS.}}{51\cdot85}+\overset{\text{V.}}{\cdot96}.$$

(14.) *Determination of* SSN's *from* 36 *to* 12.

The method described above was adopted to determine the SSN's 36 to 12. The following is an example:—

$$\overset{(54.)}{53\cdot4}+\overset{(34\cdot9.)}{46\cdot6}=\overset{\text{W.}}{100}\quad\ldots\ldots\ldots\quad(\text{i.}),$$

But

$$\overset{(54.)}{100}=\overset{\text{RS.}}{90\cdot5}+\overset{\text{GS.}}{9\cdot5}\quad\ldots\ldots\ldots\quad(\text{ii.}).$$

From (ii.), (i.) becomes

$$\overset{\text{RS.}}{48\cdot33}+\overset{\text{GS.}}{5\cdot08}+\overset{(34\cdot9.)}{46\cdot6}=\overset{\text{W.}}{100}.$$

Equating with the standard equation we get

$$\overset{(34\cdot9.)}{100}=\overset{\text{RS.}}{43\cdot07}+\overset{\text{GS.}}{53\cdot93}+\overset{\text{V.}}{3\cdot0}.$$

Another example may be given of SSN 25·5. The equation is

$$\underset{\text{RS.}}{\overset{(49\cdot05.)}{96}} + \underset{\text{GS.}}{\overset{(25\cdot5.)}{4\cdot0}} = 100.$$

In 49·05 there is 70·1 + 29·9, and the equation becomes, after equating with the standard equation,

$$\overset{(25\cdot5.)}{100} = \overset{\text{RS.}}{27\cdot5} + \overset{\text{GS.}}{37\cdot5} + \overset{\text{V.}}{35}.$$

Similarly it was found that

$$\overset{(27\cdot1.)}{100} = \overset{\text{RS.}}{30\cdot8} + \overset{\text{GS}}{45\cdot9} + \overset{\text{V.}}{23\cdot3}, \qquad \overset{(18\cdot6.)}{100} = \overset{\text{RS.}}{11\cdot3} + \overset{\text{GS.}}{7\cdot3} + \overset{\text{V.}}{81\cdot5},$$

$$\overset{(23\cdot7.)}{100} = \overset{\text{RS.}}{\cdot24} + \overset{\text{GS.}}{24} + \overset{\text{V.}}{52}, \qquad \overset{(15\cdot5.)}{100} = \overset{\text{RS.}}{4\cdot6} + \overset{\text{GS.}}{2\cdot1} + 93\cdot3.$$

Beyond SSN's 14 and 12 respectively, where the red and green sensations vanish, the violet alone remains, but having different intensities.

(15.) *Formation of the Sensation Curves.*

From the foregoing equations curves of violet-green sensation and red sensation were plotted, and any small irregularity was smoothed. The ordinates thus found are given in the following Table III., in Columns IV., V., and VI.

Columns I., II., and III. represent (i) the standard scale numbers of the prismatic spectrum (the same as used in my previous paper), (ii) the wave-lengths, and (iii) the luminosity of the spectrum of the crater of the electric (arc) light as judged by the centre of the eye.

Columns VII., VIII., and IX. are the luminosities of the colours in terms of the red sensation (RS), the green sensation (GS), and the violet (V). These are obtained by multiplying IV., V., and VI. by Column III. and dividing by 100.

In Columns X., XI., and XII. are given the percentage composition of the different rays in terms of RS, GS, and BS (the blue sensation). These are obtained by reducing the violet sensation to $\frac{28}{100}$ of its value in Column VI. (which is the percentage of blue which the violet contains), and adding $\frac{72}{100}$ of the violet to the red in Column IV. GS is the same in Columns V. and XI.

Columns XIII., XIV., and XV. are the luminosities of RS, GS, and BS as contained in the different colours, and are obtained, as before, by multiplying XI., XII., and XIII. by the luminosities in Column III. and dividing by 100. Column XVI. is Column XIV. multiplied by 2·3, and Column XVII. is Column XV. multiplied by 178.

TABLE III.

I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.	XIII.	XIV.	XV.	XVI.	XVII.
Scale number.	λ.	Luminosity of spectrum.	Percentage composition.			Luminosity.			Percentage composition.			Luminosity.			GS × 2·3.	BS × 178.
			RS.	GS.	V.	RS.	GS.	V.	RS.	GS.	BS.	RS.	GS.	BS.		
64	7217	·5	100	—	—	·5	—	—	100	—	—	·5	—	—	—	—
62	6957	2	100	—	—	2	—	—	100	—	—	2	—	—	—	—
60	6728	7	100	—	—	7	—	—	100	—	—	7	—	—	—	—
58	6521	21	99	1	—	20·79	·21	—	99	1	—	20·79	·21	—	·48	—
56	6330	50	95·5	4·5	—	47·75	2·25	—	95·5	4·5	—	47·75	2·25	—	5·17	—
54	6152	80	90·5	9·5	—	72·40	7·60	—	90·5	9·5	—	72·40	7·60	—	17·48	—
52	5996	96	84·2	15·8	—	80·83	15·17	—	84·2	15·8	—	80·64	15·36	—	35·38	—
50	5850	100	75	25	—	75	25	—	75	25	—	75	25	—	57·5	—
48	5720	97	67	32·9	·107	65	31·9	·103	67·12	32·9	·030	65·16	31·78	·029	73·1	5·3
46	5596	87	62	37·63	·370	53·94	32·74	·322	62·3	37·60	·104	54·20	32·70	·090	75·21	16·
44	5481	75	57·7	41·74	·565	43·77	30·81	·422	58·1	41·74	·158	43·75	30·81	·118	70·86	21·03
42	5373	62·5	54·9	44·4	·700	34·31	27·75	·445	55·4	44·4	·196	34·61	27·75	·122	63·82	21·80
40	5270	50	51	48·2	·800	25·50	24·10	·400	51·57	48·20	·224	25·80	24·09	·112	55·40	20
38	5172	36	48	51·1	·900	17·28	18·40	·324	48·65	51·1	·252	17·50	18·43	·091	42·30	16·14
36	5085	24	45	53·5	1·500	10·80	12·84	·360	46·08	53·5	·420	11·09	12·83	·101	29·51	18
34	5002	14·2	41·55	55·34	3·11	5·82	7·94	·442	43·79	55·34	·870	6·22	78·6	·124	18·08	22
32	4924	8·5	37·8	56·13	6·07	3·27	4·71	·516	42·17	56·13	1·700	3·58	4·77	·145	10·97	25·74
30	4848	5·7	34·10	54·60	11·28	2	3·08	·620	42·24	54·60	3·160	2·45	3·08	·174	7·08	30·12
28	4776	4	30·71	50·54	18·75	1·25	2·03	·720	44·36	50·54	5·200	1·76	2·03	·202	4·83	35·96
26	4707	2·8	27·70	41·30	31	·78	1·15	·868	50·02	41·30	8·680	1·41	1·15	·243	2·64	43·25
24	4639	1·95	24	28	48	·48	·53	·935	58·56	28	13·44	1·15	·53	·262	1·22	46·63
22	4578	1·4	20·2	16·3	63	·28	·24	·882	65·56	16·3	17·64	·91	·27	·247	·48	43·96
20	4517	1·1	16	8	76	·165	·10	·836	70·72	8	21·28	·77	·10	·234	·23	41·65
18	4459	·86	11·4	4·6	84	·098	·04	·720	71·88	4·6	23·52	·62	·04	·202	·092	36·49
16	4404	·70	6	2	92	·047	·01	·648	72	2	25·76	·51	·01	·180	·023	32·04
14	4349	·56	1·5	·5	98	—	—	·550	72	·5	27·44	·392	—	·154	—	27·41
12	4296	·45	—	—	100	—	—	·450	72	—	28	·334	—	·126	—	22·43
10	4245	·35	—	—	100	—	—	·350	72	—	28	·253	—	·098	—	17·44
8	4198	·26	—	—	100	—	—	·260	72	—	28	·187	—	·073	—	12·49
6	4151	·18	—	—	100	—	—	·180	72	—	28	·130	—	·051	—	9·08
4	4106	·14	—	—	100	—	—	·140	72	—	28	·101	—	·039	—	6·91
2	4062	·10	—	—	100	—	—	·100	72	—	28	·076	—	·028	—	5·00
0	4010	·06	—	—	100	—	—	·060	72	—	28	·057	—	·022	—	3·92
											Areas .	579	248	3·26	572	581

The areas of the curves given by Columns XIII., XVI., and XVII. are equal, and represent equal stimuli of all three sensations. A mixture of the three colours, each being represented by ordinates of the same height, makes white. The points where the red and green curves cut the blue curve are the points in the spectrum which the green-blind and the red-blind match with white.

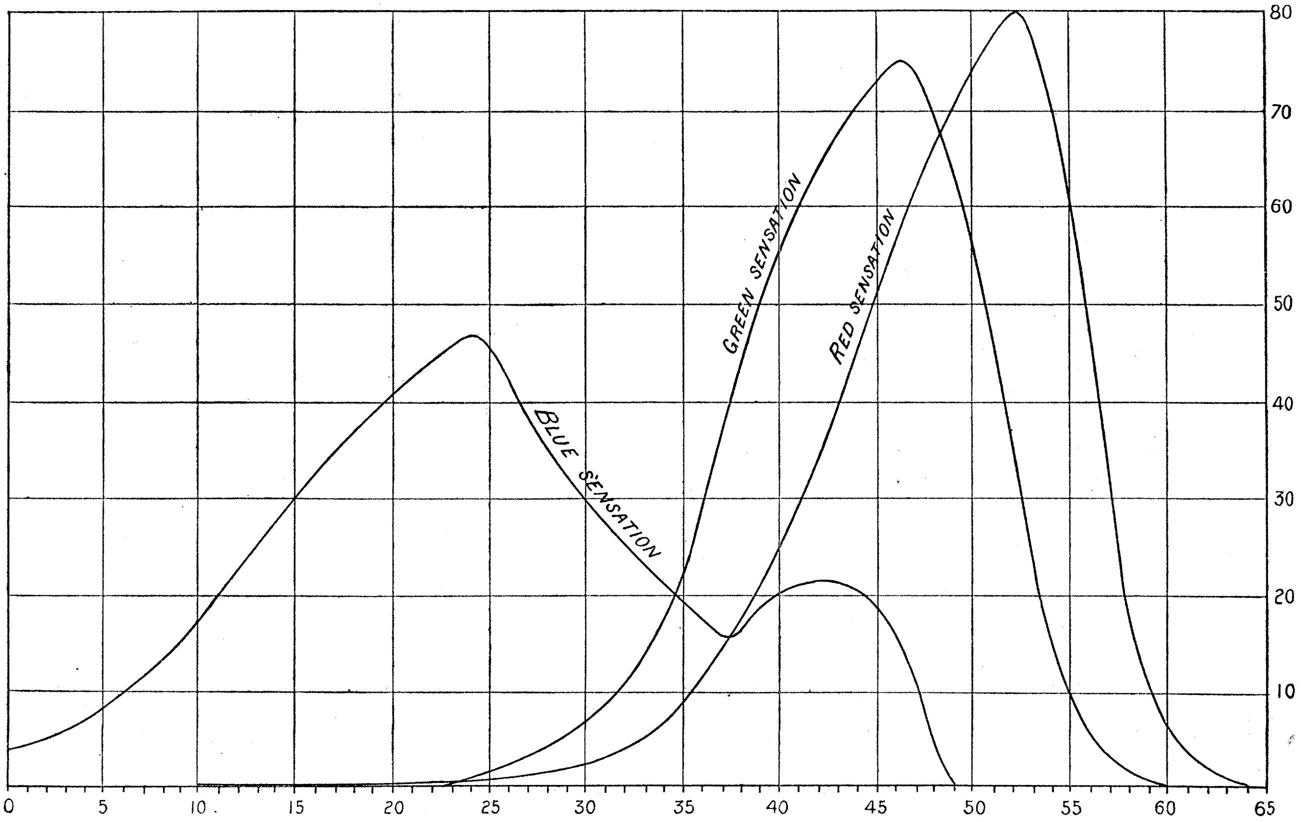

Fig. 2. Sensation curves having equal areas (equal ordinates at any point make white).

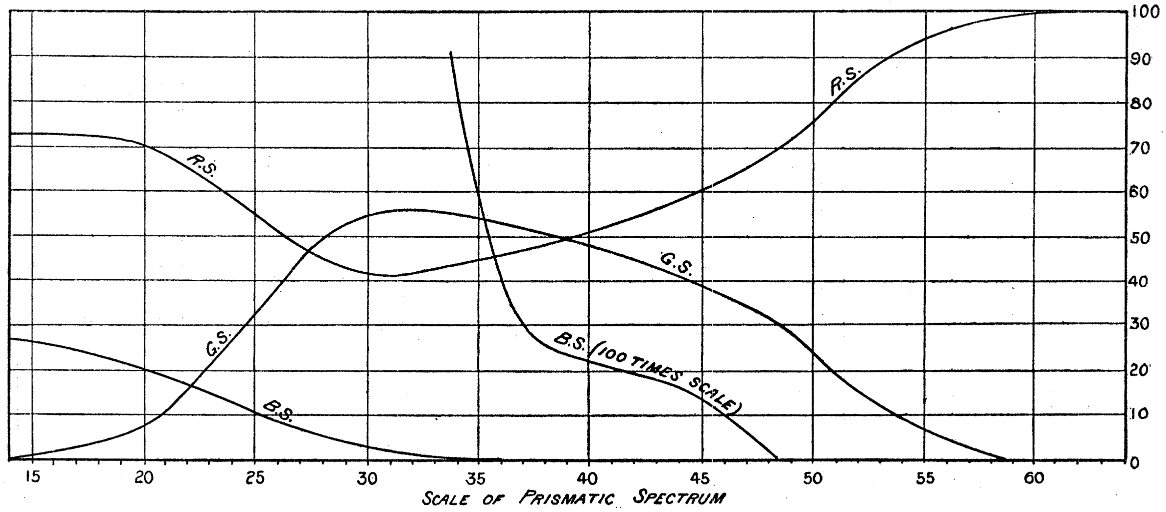

Fig. 3. Percentage composition in luminosities of red, green, and blue sensations of the spectrum colours.

(16.) *Determination of Colour Sensations and White.*

The results given in Table III. are carried still further in Table IV. In it Column I., is as before, the standard scale number. Columns II., III., IV., V. are RS, GS, BS, and (white) W. These are obtained from Columns XIII., XVI., and XVII. of Table III. From SSN (standard scale number) 64 to 49 no white is present

TABLE IV.

I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.
SSN.	Luminosity of sensation together with the white.				Percentage composition of the sensations, white being deducted.			Colour mixtures.		
	RS.	GS.	BS.	W.	RS.	GS.	BS.	R.	G.	B.
64	·2	—	—	—	100	—	—	100	—	—
62	2	—	—	—	100	—	—	100	—	—
60	7	—	—	—	100	—	—	100	—	—
58	20·79	·21	—	—	99	1	—	97·2	2·8	—
56	47·75	2·25	—	—	95·5	4·5	—	86·8	13·2	—
54	72·40	7·60	—	—	90·5	9·5	—	74·7	25·3	—
52	80·64	15·36	—	—	84·2	15·8	—	62	38	—
50	75	25	—	—	75	25	—	48·4	51·6	—
48	60	29·5	—	7·5	67·1	32·9	—	38·7	61·3	—
46	38·2	25·7	—	23·1	59·9	40·1	—	31·5	68·5	—
44	22·5	21·6	—	30·9	51·1	48·9	—	24·3	75·7	—
42	12·8	18·2	—	31·5	40·1	59·9	—	17·6	82·4	—
40	5·8	15·4	—	28·8	27·4	72·6	—	10	98	—
38	1·4	11·4	—	24·5	10·9	89·1	—	3·5	96·5	—
36	—	8	·031	16	—	99·6	·386	—	99·87	·13
34	—	5·1	·088	9	—	98·31	1·69	—	99·47	·53
32	—	3·2	·125	5·2	—	96·24	3·76	—	98·09	1·91
30	—	2·12	·155	3·43	—	93·18	6·82	—	97·78	2·22
28	—	1·33	·192	2·48	—	87·37	12·63	—	95·71	4·29
26	—	·53	·235	2·03	—	68·8	31·6	—	87·56	12·44
24	—	·03	·250	1·66	—	10·5	89·5	—	27·42	72·58
22	·43	—	·245	·73	15	—	85	15	—	85
20	·54	—	·235	·33	69·7	—	30·3	69·7	—	30·3
18	·51	—	·201	·15	71·8	—	28·2	72	—	28
16	·49	—	·180	·03	73·1	—	26·9	72	—	28
14	·39	—	·154	—	72	—	28	72	—	28
12	·334	—	·126	—	72	—	28	72	—	28
10	·253	—	·098	—	72	—	28	72	—	28
8	·187	—	·073	—	72	—	28	72	—	28
6	·130	—	·051	—	72	—	28	72	—	28
4	·101	—	·039	—	72	—	28	72	—	28
2	·072	—	·028	—	72	—	28	72	—	28
0	·057	—	·022	—	72	—	28	72	—	28
Areas .	450	192	2·53	187						

in the colours, but at 48 some small quantity of white is shown to exist, and it is found to SSN 16. Taking SSN (40) as an example, in Table III. this colour has for its components in the columns showing equal stimuli

RS.	GS × 2·3.	BS × 178.
25·80,	55·40,	20.

As equal ordinates make white, the smallest ordinate, 20 in that case, is deducted from the other two and we have

RS.		GS × 2·3.
5·80	and	35·40.

Thus after deducting 28·8 of white, the amount of RS is 5·8 and of GS $\frac{35\cdot 40}{2\cdot 3}$ or 15·4, so that the colour at SSN (40) is given by the equation

RS.	GS.	W.	SSN (40).
5·8 +	15·4 +	28·8 =	50.

In the same way the equations to the other colours of the different SN's were found, and fig. 4 gives the curves of RS, GS, BS, and W. It will be seen that all the curves are smooth, and not one is abrupt, which is the case where the old numbers in my paper of 1898 for the BS are treated in the same way, more especially in the green and white curves.

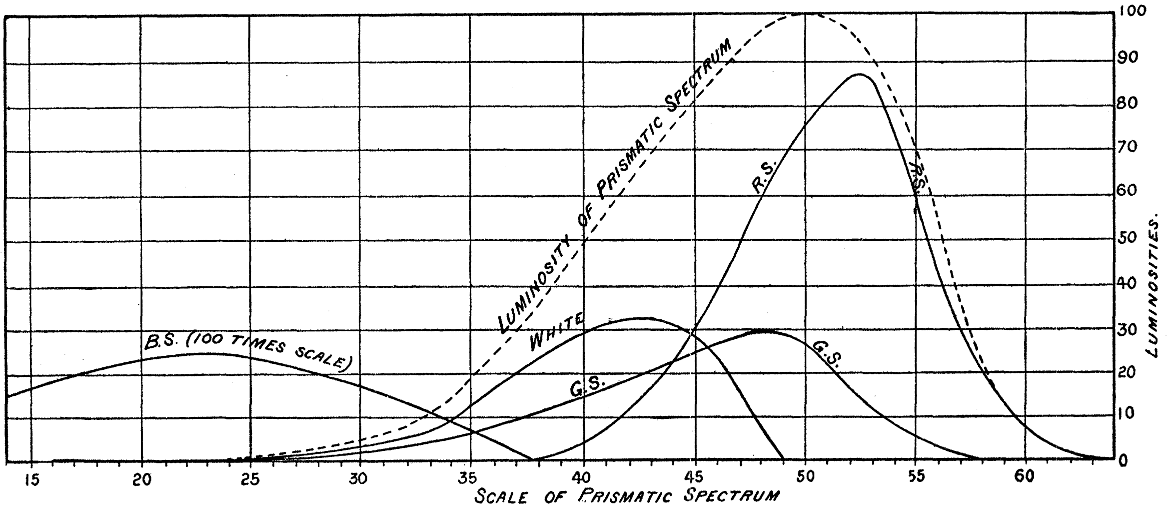

Fig. 4. Luminosity curves of red, green, blue and white sensations of the prismatic spectrum of the crater (positive pole) of the arc light.

Columns VI., VII., and VIII., Table IV., give the percentage composition in terms of RS and GS, GS and BS, and of RS and BS of the different colours. These columns are useful when we are considering the accurate calculation of the colours of pigments either reflected or transmitted.

Columns IX., X., and XI. give the percentage composition of the different colours of the spectrum in terms of the three *colours* which best represent the colour sensations when white is deducted from them, viz., red lithium, SSN 37·5, and SSN 23·2.

In reference to this table it may be remarked that of the whole spectrum ·225 is white and ·775 colour. This shows that the white in the colours is by no means a negligible quantity.

(17.) *Significance of the Inherent White.*

In regarding the table, Column V., for white, it will be remarked that the maximum amount of white is near SSN (42). In 'Colour Photometry,' Part III. ('Phil. Trans.,' 1892), it was shown that in this region the light disappeared last when the intensity was reduced. It was also shown that the maximum luminosity of a very feeble colourless spectrum was near this point, and in the concluding page of my last paper on the colour sensations, I pointed out that the presence of the fundamental sensation of light, which is white, must be taken into account in any theory of colour vision. The fact that in these slightly revised measures we get more than indications that white exists in the region where the fundamental sensation has been shown also to exist, leads one to believe that we are in some way separating this sensation from the three-colour sensations. What seems to confirm this view is that when a very bright spectrum, such as is given by sunlight, is measured, there is a tendency for the proportion of white in the region SSN's 48 to 16 to diminish. This is what we should expect to find, since fixed amplitude of wave colour vanishes at some, as also does the fundamental light at a lesser amplitude, be the spectrum feeble or brilliant.

(18.) *The Normal Spectrum Curves.*

Table V. gives the sensation curves for the normal spectrum, and is shown in the same manner as it was in my previously quoted paper.

Table V.—Normal Spectrum.

Wave-length.	Spectrum luminosity.	Percentage composition.			Luminosity.				
		RS.	GS.	BS.	RS.	GS.	BS.	GS × 2·38.	BS × 146.
6800	1	100	—	—	1	—	—	—	—
6700	6	100	—	—	6	—	—	—	—
6600	10	99·7	·3	—	9·97	·03	—	·070	—
6500	17	98·5	1·5	—	16·74	·26	—	·6	—
6400	26	97	·30	—	25·22	·78	—	1·9	—
6300	41	95	·50	—	38·95	2·05	—	4·9	—
6200	59	92	8	—	54·28	4·72	—	11·2	—
6100	75	88·5	11·5	—	66·25	8·75	—	20·8	—
6000	85	84	16	—	71·4	13·60	—	32·4	—
5900	93	78·5	21·5	—	72·93	20·70	—	48·7	—
5800	99	72	28	—	71·28	27·72	—	66	—
5700	100	66·2	33·8	·028	66·20	33·80	·028	80·4	·050
5600	95	62·2	37·7	·104	59·09	35·91	·099	85·4	·145
5500	89	58·5	41·4	·150	52·06	36·84	·133	87·8	19·4
5400	80	55·2	44·6	·185	44·96	34·88	·148	83·1	21·6
5300	70	52·7	47·1	·215	36·89	32·97	·150	78·5	21·9
5200	54	49·5	50·3	·243	26·73	27·16	·131	64·1	19·1
5100	30	46·5	53·1	·400	13·95	15·93	·120	37·8	17·5
5000	18	43·8	55·3	·860	7·88	9·95	·155	23·7	22·6
4900	11	42	56	2·00	4·62	6·16	·220	14·7	32·1
4800	7·5	43	52·4	4·6	3·23	3·93	·345	9·4	50·3
4700	5	50	41·3	8·7	2·50	2·06	·435	4·9	63·5
4600	3·5	62	21·8	16·2	2·17	·76	·567	1·8	82·7
4500	2·7	72	7·3	21·7	1·94	·20	·586	·5	85·5
4400	2·1	72	2·2	25·8	1·51	·05	·542	·1	79·1
4300	1·7	72	—	28	1·22	—	·476	—	69·5
4200	1·3	72	—	28	·94	—	·367	—	53·6
4100	1	72	—	28	·72	—	·280	—	40·9
4000	·75	72	—	28	·54	—	·210	—	30·7
3900	·50	72	—	28	·27	—	·140	—	20·4
3800	·25	72	—	28	·13	—	·070	—	10·2

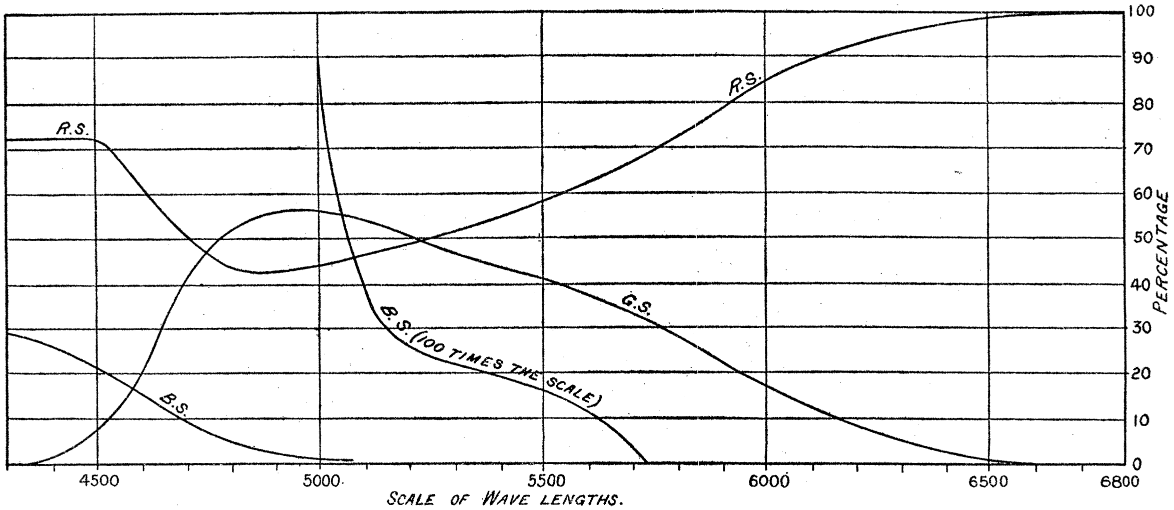

Fig. 5. Percentage composition in luminosities of red, green, and blue sensations of the colours of the normal spectrum.

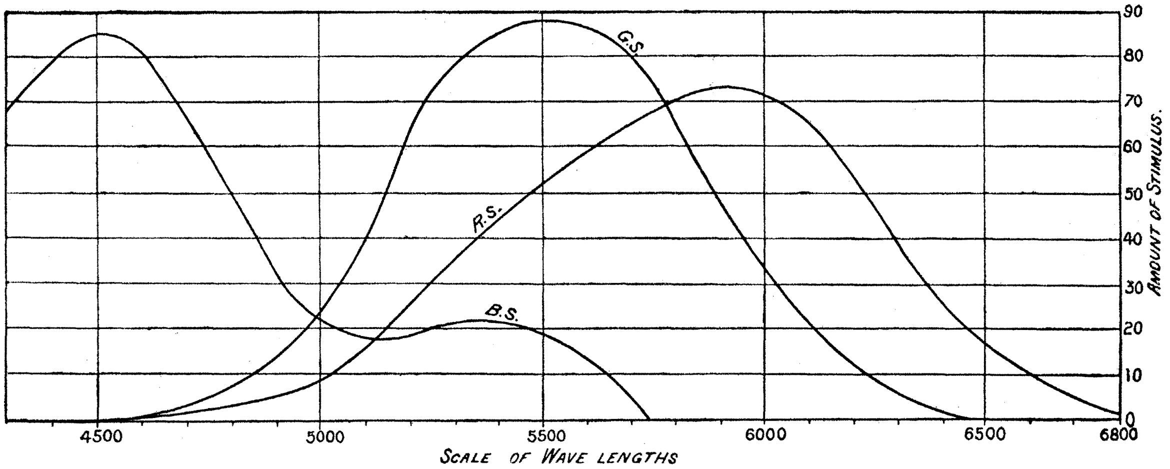

Fig. 6. (Normal spectrum) Curves of equally stimulated red, green, and blue sensations to form white.

PART II.

(19.) *A Colour Defined by a Wave-length, &c.*

In a note "On the Numerical Registration of Colour," which I communicated to the Royal Society ('Proceedings,' vol. 49, 1891), it was indicated that any colour could be accurately defined by a wave-length, its luminosity, and the percentage of white light that it contained. In Table III. we have a very ready means of stating all these with extreme accuracy.

If the percentage of each colour of the spectrum which a coloured medium or a pigment transmits or reflects be known from measurement, then from Table III. we can find the wave-length, the luminosity, and the percentage of white light which the colour contains.

(20.) *Measurement of Spectrum Intensity.*

I have already described the method employed by myself in measuring the intensity of the light transmitted or reflected. Fig. 7 shows the plan. S is the slit moving in

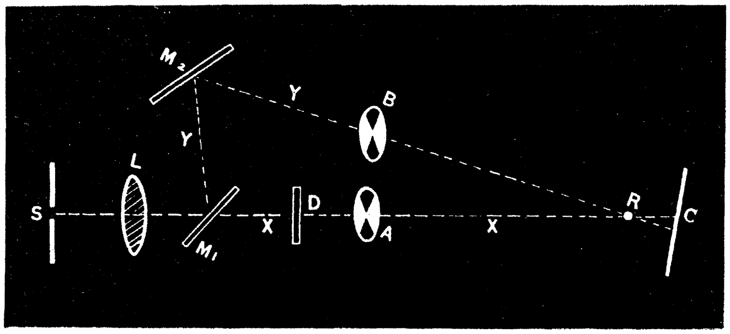

Fig. 7.

the spectrum, L the lens throwing the image of the face of the prism on the screen C. In the path of the ray X a plain glass mirror is inserted reflecting a proportion of the beam to a second silvered mirror M_2, which in its turn reflects the beam Y to C. Sectors can be inserted in one or both of the beams X and Y.

If the colour to be measured is that of a piece of (say) coloured glass, it is inserted at D in the path of the beam X; or if it be a pigment whose colour has to be measured, it is placed at C, so that it is illuminated by X, and a white square placed adjacent to it is illuminated by Y, a rod R being placed in a proper position to throw two shadows touching each other at C. I have found that instead of using one plain mirror at M, it is better to have a bundle of glasses, so that the intensities of the beams X and Y are more equal than when a single glass is employed.

The readings are made by equalizing the brightness of the illuminated shadows first with the colour in position and then without. The two measures give the percentage of light reflected or transmitted from the coloured medium or surface.

(21.) *Measurement of Emerald-green and Chrome-yellow.*

As examples of the way in which Table III. is to be used, the light reflected from emerald-green, Table VI., and from chrome-yellow, Table VII., has been tabulated.

In both tables Column I. shows the standard scale numbers.

In both tables Column II. the relative intensity of the light reflected from the colour compared with that reflected from a white surface.

In both tables Columns III., IV., and V. are copied from X., XI., XII., Table III.

In both tables Columns VI., VII., and VIII. are III., IV., and V. multiplied by the intensities in Column II.

The areas of the curves of RS, GS, and BS in VI., VII., and VIII. for emerald-green are taken and found to be on an empiric scale (which is the same as that of the luminosity of the naked spectrum of the crater of the arc light), RS 202, GS 133, BS 1·418.

GS and BS are multiplied by 2·3 and 178 (the factors for making the sensation curves of equal area) respectively, and found to be 306 and 252 respectively. The lowest of the ordinates is RS 202. This must be deducted from GS × 2·3 and BS × 178, and we have as the remainders 104 and 50. These must be divided by 2·3 and 178, and from these (which are 45·2 and ·28) the percentages of GS and BS are calculated, and are found to be 99·38 and ·62. This, from the diagram and from calculation, gives the dominant colour as SSN 35·64 or λ 5070.

The area of the spectrum curve is 830 on the same scale, and the sum of the three curves is 336. The luminosity of the emerald-green, when white is taken as 100, is $\frac{336}{830} \times 100$, or 40·5. (This is the same as was made by direct measurement.)

The amount of RS and GS and BS used to form the white is 290. The sum of the areas of the three curves is 336. The percentage of white is therefore $\frac{290}{336} \times 100$, or 86·3. The amount of inherent white in SSN 35·64 is 68·5, so that there is 38 per cent. more white in emerald-green than there is in SSN (35·64).

Emerald-green is therefore represented by

SSN 35·64.		W.		Emerald-green.	
62	+	38	=	100.	Luminosity 40·5.

Chrome-yellow was treated in the same manner.

TABLE VI.—Emerald-green Pigment.

I.	II.	III.	IV.	V.	VI.	VII.	VIII.
SSN.	Intensity of colour (white 100).	Composition of white in luminosity.			Composition of green in luminosity.		
		RS.	GS.	BS.	RS.	GS.	BS.
64	3·5	·5	—	—	·02	—	—
62	3·5	2	—	—	·07	—	—
60	3·5	7	—	—	·24	—	—
58	4	20·8	·2	—	·83	—	—
56	5	47·75	2·25	—	2·39	·11	—
54	8	72·4	7·6	—	5·79	·6	—
52	14	80·64	15·36	—	11·3	2·16	—
50	28	75	25	—	21	7	—
48	42	65·16	31·78	·039	27·36	13·34	·017
46	53	54·2	32·7	·090	28·73	17·33	·047
44	63	43·75	30·81	·118	27·56	19·41	·074
42	71	34·61	27·75	·122	24·57	19·7	·086
40	74	25·8	24·09	·112	19·9	17·83	·083
38	74	17·5	18·43	·091	12·95	13·65	·067
36	73	11·09	12·83	·101	8·10	9·34	·074
34	70	6·22	7·86	·124	4·35	5·5	·087
32	65	3·58	4·77	·145	2·31	3·12	·094
30	61	2·45	3·08	·174	1·49	1·84	·106
28	58	1·78	2·03	·202	1·08	1·2	·117
26	53	1·41	1·15	·243	·74	·61	·129
24	46	1·15	·53	·262	·51	·24	·121
22	40	·91	·24	·247	·36	·1	·099
20	32	·77	·1	·234	·24	·03	·075
18	27	·62	·04	·202	·18	·01	·054
16	22	·51	·01	·18	·11	—	·04
14	17	·39	—	·154	·07	—	·026
12	12	·33	—	·126	·04	—	·015
10	5	·25	—	·098	·01	—	·005
8	3·5	·19	—	·073	—	—	·002
				Areas .	202	133	1·418

To find luminosity—

Sum of areas of green = 336.
Sum of areas of white = 830.

Luminosity of emerald-green

$$= \frac{336}{830} \times 100 = 40\cdot5.$$

To find the amount of white and the dominant wave-length

RS = 202,
GS = 133,
BS = 1·418,
GS × 2·3 = 306,
BS × 178 = 252.

Residue after forming white

$$\frac{306 - 202}{2\cdot3} = 45\cdot2 \text{ GS},$$

$$\frac{252 - 202}{178} = \cdot23 \text{ BS}.$$

Percentage of GS and BS

GS.		BS.		Emerald-green.
99·33	+	·62	=	100.

This is SSN 35·64 or λ 5070.

TABLE VII.—Chrome-yellow Pigment.

I.	II.	III.	IV.	V.	VI.	VII.	VIII.
SSN.	Intensity of colour (white 100).	Composition of white in luminosities.			Composition of yellow in luminosities.		
		RS.	GS.	BS.	RS.	GS.	BS.
64	100	·5	—	—	·5	—	—
62	100	2	—	—	2	—	—
60	100	7	—	—	7	—	—
58	100	20·8	·2	—	20·8	·20	—
56	100	47·75	2·25	—	47·75	2·25	—
54	100	72·4	7·60	—	72·4	7·60	—
52	100	80·64	15·36	—	80·64	15·36	—
50	100	75	25	—	75	25	—
48	100	65·16	31·70	·039	65·16	31·70	·034
46	100	54·2	32·70	·090	54·20	32·70	·090
44	84	43·75	30·81	·118	36·75	25·88	·099
42	62	34·61	27·75	·122	21·46	17·20	·076
40	42	25·80	24·09	·112	10·83	10·12	·047
38	26	17·50	18·43	·091	4·55	4·78	·024
36	19	11·50	12·83	·101	2·11	2·44	·019
34	16	6·22	7·86	·124	1	1·26	·021
32	14	3·58	4·77	·145	·5	·67	·020
30	12	2·45	3·08	·174	·29	·37	·021
28	11	1·78	2·03	·202	·19	·22	·022
26	11	1·41	1·15	·243	·76	·23	·216
24	11	1·15	·53	·262			
22	11	·91	·24	·247			
20	11	·77	·10	·234			
18	11	·62	·04	·202			
16	11	·51	·01	·180			
14	11	·39	—	·154			
12	11	·33	—	·126			
10	11	·25	—	·098			
8	11	·19	—	·075			
6	11	·13	—	·052			
4	11	·10	—	·039			
2	11	·8	—	·028			
0	11	·6	—	·022			
				Areas .	503·9	178	·694

To find luminosity—

Sum of areas of yellow = 682.
Sum of areas of white = 830.

Luminosity of yellow

$$= \frac{682}{830} \times 100 = 82 \cdot 2,$$

white = 100.

To find the white and dominant wave-length

RS = 504,
GS = 178,
BS = 694,
GS × 2·3 = 409,
BS × 178 = 123.

Residue after forming white

$$504 - 123 = 381 \text{ RS}$$

$$\frac{409 - 123}{2 \cdot 3} = 124.$$

Percentage of RS to GS.

RS.		GS.		Yellow.
75·4	+	24·6	=	100.

Therefore chrome-yellow is 50 SSN, and contains 26 per cent. white.

(22.) *Principles of Three-colour Photography.*

At the present time the accurate determination of colour composition in terms of the three-colour sensations, of pigments, and transparent media, is of great practical importance. There is now a large business carried on in the production of prints by the three-colour process of photography, and up to the present time the colours produced are, with rare exceptions, wanting in truth, probably owing to screens of the wrong colours being used. In order to take the three negatives from which the prints are produced, it is necessary to place screens of different colours (reddish, greenish, and blue) in front of the sensitive plate in order to get distinctive images which will represent the three sensations in the three printings. As to the printing itself, nothing need be said in this communication, but I shall confine myself to the negatives alone. If the negatives are correct, three transparencies from them should give three images, which, if illuminated by the three colours which represent best the three sensations, and superposed, should give the true colours of nature.

Where the three positives are each devoid of deposit at the same part of the image, the mixture of colours should give white, which means that in the negatives the deposits should be equally opaque. This is the starting point of the process.

The deposit being without colour, the different parts of the three component negatives have to be such that the transparencies, when projected on a screen, allow so much of each coloured beam to pass as will give the natural colour by mixture. [It may be remarked that the negatives themselves, if illuminated with the three colours, and the images superposed, should show the complementary colours.] If there were a perfect photographic plate, there would not be much difficulty in calculating directly the colours for the three screens which should be used. As, however, no photographic plate is perfect in one sense, the proper exposing screens have to be ascertained by trial. It is *useless* to make such trials with the spectrum, and I have adopted a system which allows an accurate determination to be made by trial.

(23.) *The Principle on which a Colour Sensitometer is Made.*

The principle I have employed, and which has been outlined before, is as follows:—

If we have to find a screen to take what we may call the red negative (*i.e.*, one in which the opacities of deposit are proportional to the red components of the objects photographed), we may take a variety of pigments, each of which contains red, and utilize them for the purpose. Such pigments may show a diversity of luminosities, and the relative proportions of red, green, and blue will also be very different in each. If (say) squares of paper are covered with the pigments of different colours and photographed through almost any coloured screen we should be unable to say without measuring the different opacities of deposit whether the screen was correct or not. If, however, by some artifice we are able to make all the red components in each of the pigments identical, and then photograph them, it is evident that the only screen which would be correct would be that which would make the opacities of all the images of the different squares of colour the same. The mode I have adopted of reducing the intensities of pigments and making all the luminosities of red, green, or blue the same, is by making annuluses of the different pigments and filling up parts of them with black pigment (the amount of white light reflected from such black being measured and taken into account), and then rotating them round the centre of the disc on which they are fixed.

(24.) *Practical Application of the above Principle.*

The method shown of ascertaining the composition of the colours in terms of the three sensations, and of ascertaining their luminosity, enables us to make an accurate determination of the amount of reduction which the various pigments should undergo. Suppose we wish, for instance, to make the red sensations in the yellow, the green, and the white the same, we should proceed as follows :—

The amount of red, green, and blue sensations in these three on the same empiric scale are—

	RS.	GS.	BS.
White	571	248	3·264
Chrome-yellow	503	178	·694
Emerald-green	202	133	1·418

If we reduce these sensations to colours, from Table IX. then we shall have for (say) the red component in white 342, in chrome-yellow 284, and in emerald-green 79.

In order to reduce all these to show equal red components, the centre of the disc would be occupied by emerald-green pigment. The chrome-yellow would have to be reduced to $\frac{79}{284}$, or ·278 of its normal luminosity, so that ·278 of 360°, or 260° of the annulus, would have to be occupied by dead black.

The white would have to be reduced to $\frac{79}{342}$, or ·231 of its normal luminosity, so that 277° of the annulus would have to be occupied by dead black.

If a green screen had to be obtained the green sensations reduced to green colour would be white 447, chrome-yellow 298, emerald-green 255. Then, as before, emerald-green would occupy the centre of the disc, and chrome-yellow would have to be reduced to $\frac{255}{298}$, or ·856 of its luminosity, and white to $\frac{258}{477}$, or ·534 of its luminosity.

The above will give an idea of the method to be adopted in making what I have called colour sensitometers. Examples have been given only with those pigments which have been considered in the foregoing pages; but naturally there would be many other colours introduced in order, as far as possible, to imitate the spectrum colours.