May 23, 1901.

Sir WILLIAM HUGGINS, K.C.B., D.C.L., President, in the Chair.

A List of the Presents received was laid on the table, and thanks ordered for them.

Professor James Gordon MacGregor was admitted into the Society.

The following Papers were read:—

I. "On the Presence of a Glycolytic Enzyme in Muscle." By Sir LAUDER BRUNTON, F.R.S., and HERBERT RHODES.

II. "On Negative After-images and their Relation to certain other Visual Phenomena." By S. BIDWELL, F.R.S.

III. "The Solar Activity 1833–1900." By Dr. W. J. S. LOCKYER. Communicated by Sir NORMAN LOCKYER, K.C.B., F.R.S.

IV. "A Comparative Crystallographical Study of the Double Selenates of the Series $R_2M(SeO_4)_2,6H_2O$.—Salts in which M is Magnesium." By A. E. TUTTON, F.R.S.

V. "On the Intimate Structure of Crystals. Part V.—Cubic Crystals with Octahedral Cleavage." By Professor W. J. SOLLAS, F.R.S.

VI. "Preliminary Statement on the Prothalli of *Ophioglossum pendulum*, L., *Helminthostachys zeylanica*, Hook., and *Psilotum sp.*" By Dr. W. H. LANG. Communicated by Professor BOWER, F.R.S.

The Society adjourned over the Whitsuntide Recess to Thursday, June 6.

"On Negative After-images, and their Relation to certain other Visual Phenomena." By SHELFORD BIDWELL, M.A., Sc.D., F.R.S. Received May 1,—Read May 23, 1901.

I. *Preliminary.*

In a former communication I described a curious phenomenon due to the formation of negative after-images following brief retinal excitation after a period of darkness.* The effect is conveniently demonstrated by the aid of a disc, partly black and partly white,

* 'Roy. Soc. Proc.,' 1897, vol. 61, p. 268.

having an open sector, as shown in fig. 1. If such a disc is caused to turn five or six times in a second, while its surface is strongly illuminated, a coloured object placed behind it and viewed intermittently through the open sector, generally appears to assume an entirely different hue, which is approximately complementary to the true colour of the object: a piece of red ribbon, for example, is seen as greenish-blue and a green one as pink.

FIG. 1.

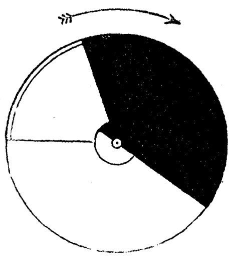
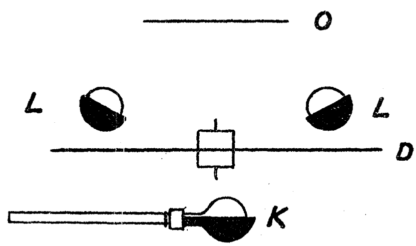


FIG. 2.



The tints thus produced are referred to in the paper as "pale" ones. I have since found that their intensity may in most cases be greatly increased if the object is illuminated more strongly than the disc. The best arrangement for the purpose is indicated in plan in fig. 2, where O is the coloured object, *e.g.*, a design painted on a card, L, L are two incandescent electric lamps of fifty candle-power, and K is a third lamp of thirty-two candle-power, supported horizontally a little above the axis of the disc: all three lamps are fitted with metal hoods to screen the light from the observer's eyes. The distance of the lamp K from the disc may be varied until the best results are obtained. When only a single lamp is used for illuminating both the object and the disc (as in the original arrangement), the light portion of the disc should be covered with paper of a pale neutral tint (not bluish), reflecting about half as much light as ordinary white paper; for experiments in bright diffused daylight, the paper may advantageously be of a pale yellowish-grey or buff tint. The dark part of the disc should be covered with good black velvet, and the open sector should extend to about 70°, instead of only 45°, as recommended in the former paper.

A number of observations made from time to time with the apparatus as thus modified have shown that the "pulsative" after-images, as they will be called, differ in several important respects from the "ordinary" negative after-images seen upon a white or grey background after the gaze has been fixed for some seconds upon a coloured object. The colours of the pulsative after-images produced by certain hues of red and of green may appear far more intense or saturated than those of the ordinary negative after-images excited by the same

primary colours under similar conditions of illumination; in particular, the greenish-blue into which bright red appears to be transformed is singularly strong and luminous. This is a matter for some surprise, since it might naturally be expected that the intermittent impressions of the exciting colour, even though not consciously perceived, would be compounded with and tend to enfeeble the complementary hue of the after-image. On the other hand, when the exciting colour is blue or yellow, it is found difficult to obtain a satisfactory pulsative after-image. The complement of blue is an orange-yellow, which is also the hue of the ordinary after-image. But the pulsative image excited by blue, especially if the colour is at all bright, is in most cases an impure pink or salmon of feeble intensity. By using dull greyish-blue pigments I have succeeded in obtaining a very fair yellow, which is further improved if a little lamp-black is added to the paint. But in such cases the formation of yellow is no doubt chiefly attributable to the inferior luminosity of the pigment, for a perfectly neutral-grey wash of lamp-black will itself give a yellow image, an effect which is probably due merely to intermittent illumination of feeble intensity. When a yellow pigment is the exciting colour, the hue of the pulsative image is not the complementary blue-violet but a pale purple, only just perceptibly bluer than the subjective purple excited by green. A pulsative image which is really blue has never been obtained from any pigment whatever, the nearest approach being the greenish-blue excited by orange, or the bluish-purple which follows yellow. It has been found equally impossible to obtain either a true red or a true green in the pulsative image. All greens, ranging from yellow-green to green-blue, are transformed into some form of purple, including rose and pink. Purple produces in the pulsative image almost the same kind of blue-green as red, quite different from the pale grass-green colour characterising the ordinary after-image of a purple object.

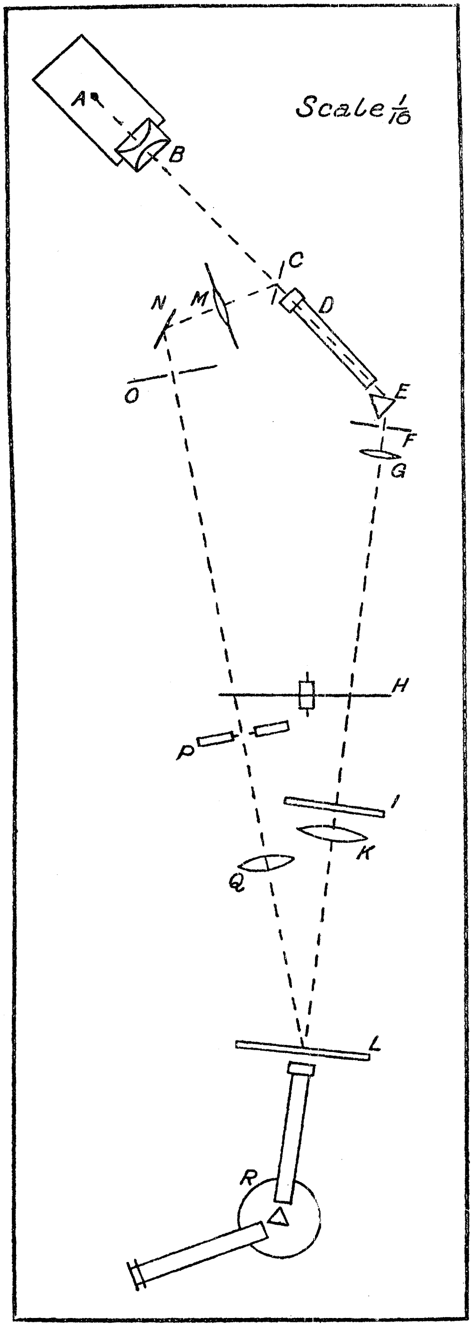
The effects observed with the apparatus described above may be shortly summarised in the statement that the pulsative image of a colour in which red predominates is blue-green, that of dull blue is yellow, and that of any other colour (including bright blue) is purple or purplish-grey. In the experiments to be described in the present paper, spectrum colours were used instead of pigments, being blended into uniform mixtures by means of a simple form of Sir W. Abney's well known "colour-patch" apparatus.*

II. *Methods of Experiment.*

Method I.—The arrangement for generating pulsative after-images when the blended spectrum colours are projected upon a screen is shown

* 'Phil. Trans.,' 1886, Part II, p. 423.

Fig. 3.



in fig. 3, on a scale of one-sixteenth. By means of the condenser B, the image of the positive crater of the electric arc A is projected upon the slit of the collimator D. The emergent parallel rays are refracted by the prism E, and thence pass successively through a circular aperture in the diaphragm F, through the achromatic lens G, and through an opening in the rotating disc H (which renders the light intermittent) until they reach the slit-screen I, upon the face of which the spectrum is focussed by the lens G. The screen contains three adjustable vertical slits, the position of which can be varied; one, two, or three selected portions of the spectrum may be allowed to pass through the slits to the large lens K, which is arranged to project a sharp image of the circular aperture in the diaphragm F upon the white screen L. This image constitutes the "colour-patch"; it is illuminated by a uniform mixture of the spectrum-rays transmitted by the slit-screen.

In front of the collimator-slit D is placed a mirror C, from the back of which a strip of the silver, 20 mm. long and 4 mm. wide, has been removed. So much of the unabsorbed light from the electric arc as does not pass through the clear glass to the collimator-slit is reflected, as shown by the dotted line, through the lens M to the mirror N; thence it is again reflected through an aperture in the diaphragm O (where an image of the condenser B is formed by the lens M); it then passes (intermittently) through an opening near the circumference of the rotating disc H to the wooden screen P, upon which an elliptical image, about 12 cm. by 4·5 cm., of the positive crater is formed. The image is crossed by a dark vertical band, corresponding to the space of clear glass in the mirror C. An opening in the screen P is furnished with an iris-diaphragm, the aperture of which can be varied from 2 mm. to 30 mm. The mirror N is so placed that a portion of the image of the crater on one side or the other of the dark band may cover the iris-diaphragm. A lens Q focusses an image of the aperture in the iris-diaphragm upon the screen L, the disc of white light thus formed being concentric with the colour-patch.

The following are details of the apparatus: The collimator-slit is adjustable by a screw having a divided head; the achromatic lens at the other end has a clear aperture of 2·86 cm. ($1\frac{1}{8}$ inch) and a focal length of 25·4 cm. (10 inches). The extra dense flint-glass prism E has a refracting angle of 60°, and its faces are 5·1 cm. (2 inches) square. The diameter of the circular aperture in the diaphragm F is 2·3 cm. ($\frac{9}{10}$ inch). The focal length of the achromatic lens G is 76 cm. (30 inches), and its diameter 5·1 cm. (2 inches).

The zinc disc, H, as seen from the lantern, is represented in fig. 4. Its diameter is 34 cm.; the opening near the centre extends to 45° and that near the circumference to 135°; both could be varied by movable zinc sectors, but the angles specified were found to be generally the most effective. The disc is driven by an electric motor in

circuit with a variable resistance, the latter being adjusted so that the speed of rotation may be a little higher than is required for the experiment; a short-circuit key within reach of the observer's hand enables him to vary the speed at will or to keep it sensibly constant. A wire attached at right angles to the axis of the disc taps a strip of card at every revolution, producing a succession of audible clicks, which can, when desired, be compared with the taps of a metronome beating seconds. The most usual speed is from five to six turns per second. The disc apparatus is supported at such a height from the table that when the disc is turning in the direction of the arrow the spectrum projected upon the screen I (fig. 3) is eclipsed at the moment when the iris-diaphragm in the screen P is beginning to be exposed to the white light. During about one-half of a revolution both the diaphragm and the slits are shielded by the disc. The width of the spectrum projected upon the slit-screen I (fig. 3) is 2·9 cm., and its visible length in a dimly lighted room about 7 cm.; the measured distance between λ 6870 (Fraunhofer line B) and λ 4115 (iron line between *g* and H) was approximately 6·1 cm.

FIG. 4.

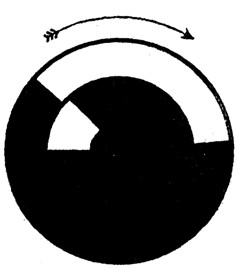
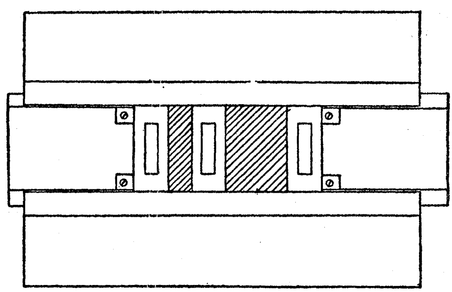


FIG. 5.



The slit-screen is shown diagrammatically in fig. 5. It consists of a mahogany board, having cut in it an oblong window, 10·4 cm. by 2·7 cm., over which the three brass slit-frames slide between grooved guides above and below. Each slit-frame is 1·8 cm. wide, and has an aperture of 2·5 cm. by 0·6 cm. The slit-jaws (not shown in the diagram) are attached to the front surfaces of the brass frames, and are adjustable in the parallel-ruler fashion, one of every pair being fixed to its frame; the slits can be opened to 0·55 cm. The two outermost slit-frames are attached by screws to sliding shutters, which serve to cover such portions of the window right and left of the slit-frames as would otherwise be open to the light. The spaces between the middle slit-frame and the two outer ones are closed by opaque black ribbons (shaded in the diagram), constituting miniature spring-roller blinds. The axes of the spring rollers are so placed (perpendicularly behind one edge of a

slit-frame) that even when the slit-frames are in contact with one another, and the slits are opened to their widest extent, no obstruction to the passage of the light through the slits is presented by the rollers. Each slit-frame can be moved independently to any desired position, and clamped with a set-screw. On the other side of the slit-screen a second pair of guides is fixed, each having three parallel saw-cut grooves in it. These guides carry rectangular pieces of sheet zinc of various widths, which may be used to shield temporarily one or more of the slits when it is desirable that its adjustment shall not be disturbed. In some experiments it is necessary to use larger portions of the spectrum than can be transmitted by the slits; the slit-frames are then removed from the screen, and the spectrum dealt with solely by means of the zinc plates. Pieces of zinc sliding in different pairs of grooves may be made to overlap one another, thus providing screens or openings of almost any desired width with very little trouble.

The diameter of the lens generally used at K, fig. 3, is 10·2 cm. (4 inches), and its focal length 30·5 cm. (12 inches), the diameter of the circular colour-patch projected upon the screen being then only about 1·5 cm. This size was, however, amply sufficient for most purposes, and with a larger image the necessary luminosity could not always be obtained. Sometimes a lens having a focal length of 40·6 cm. (16 inches) was used at K, the diameter of the patch then being 2 cm.

The focal length of the lens M is 12·7 cm. (5 inches); it is surrounded by a broad diaphragm to screen off stray light. O is a device known to photographers as a "rotating diaphragm"; it has eight apertures ranging from 0·21 cm. to 1·42 cm. in diameter, any one of which can be placed in the path of the beam of light. Its object is to vary the luminosity of the white-light disc projected upon the screen L. The lens Q has a diameter of 6·5 cm. and a focal length of 16·5 cm. ($6\frac{1}{2}$ inches).

Wave-lengths of the Colour-patch Light.—No attempt was made to standardise the spectrum projected upon the slit-screen, the wave-lengths of the light illuminating the colour-patch being determined, when necessary, by means of the spectroscope R, fig. 3. The opaque white screen L being removed, a screen of ground-glass is put in its place, and the slit of the spectroscope is brought near the bright image on the glass. The purpose served by the ground-glass is to diffuse the light, so that any element of the light transmitted by the slit-screen may be at once examined without the need of turning the spectroscope in its direction. The spectroscope has a six-inch circle with a vernier reading to minutes; the prism is of extra dense Jena glass, the refractive index for D being 1·693. To ascertain the constitution of a colour-patch, the deviations corresponding to the two extremes of the one or more coloured bands seen in the spectroscope are determined,

and the related wave-lengths are derived from a large-scale curve. When it is desired to form a colour-patch consisting of a mixture of light of given limiting wave-lengths, the slits in the slit-screen are moved and adjusted until the limits of the bright bands seen in the spectroscope coincide with the vertical cross-wire when the telescope is set at the proper predetermined angles.

Illumination and Luminosity.—It should be remarked that the colour of an object, self-luminous or illuminated, is not completely specified by a mere statement of the wave-lengths of the light which it emits or reflects. This fact is of course well known, but it is doubtful whether sufficient importance is always attached to it; it has many times been strikingly brought to my notice in the course of the experiments under consideration. A complete account of the colour-conditions should include a determination of the luminosity expressed in terms of some standard unit; unfortunately, however, this cannot easily be given. In order to furnish data for approximately estimating the luminosity of the projected colour-patch when illuminated by selected spectral rays, a rough photometric measurement was made of the illumination of the white colour-patch produced by the whole recombined spectrum, a "focus" electric lamp of 25·5 standard candle-power being employed for the comparison. It was found that when the width of the collimator-slit was 0·5 mm. (the width usually employed), the illumination was equal to that due to 8800 standard candles at a distance of 1 metre, or, as it may be called, to 8800 "candle-metres." Taking the luminosity-sensation due to this illumination as the unit or standard of reference, the relative luminosity of a patch lighted by rays taken from any parts of the spectrum can be deduced from Abney's luminosity-curve for the normal electric-light spectrum.* For example, a purple colour-patch was formed by combining the red between λ 6380 and λ 6600 with the blue-violet between λ 4250 and λ 4370. The area enclosed by the curve and the ordinates meeting the horizontal axis at 6380 and 6600 was found to be 0·0361 of the whole, and the corresponding area for the blue-violet 0·0027. The luminosity of the purple patch relatively to that of a piece of white cardboard illuminated by 8800 candles at 1 metre was therefore 0·0361 + 0·0027 = 0·0388. The variation from time to time of the intensity of the source of light, though no doubt considerable, is for the present purpose unimportant.

Approximate values for the illumination of the white disc due to light reflected by the mirror C, fig. 3, and passing through the apertures in the diaphragm O, are given in the following table.

* 'Phil. Trans.,' A, vol. 193 (1899), p. 282.

Table I.

Aperture No.	Diameter. mm.	Candle-metres.
1	14·2	5600
2	11·4	3600
3	8·6	2050
4	5 4	800
5	4 0	440
6	3 2	280
7	2 4	160
8	2 1	120

Method II.—It is shown in fig. 6 how the colour-patch may be viewed directly by means of a Huyghens' eyepiece. A diaphragm having an aperture of 1 cm. is fixed in front of the prism (F, fig. 3) and is seen in the eyepiece when properly placed as a sharply defined bright disc illuminated by the coloured rays passing the slit-screen I. The apparent diameter of the disc is about one-fourth of that of the field of view. Its coloration is sensibly uniform, but the method cannot be used to combine widely separated portions of the spectrum, and only a single slit was generally opened. The white light, which in the production of the pulsative after-image alternates with the coloured light, passes through the iris-diaphragm P, and the lens Q to the silvered mirror S; thence it is reflected to the unsilvered mirror T of thin plate glass, which directs some of the light upon the eyepiece V. For most observations pieces of ground-glass were placed behind the iris-diaphragm P and before the collimator-slit in order to subdue the light.

Method III.—The apparatus is arranged as in fig. 3, but for the white cardboard screen there is substituted a piece of ground-glass covered with opaque paper, in which is cut a circular opening 1 cm. in diameter, the colour-patch and the concentric white-light disc being projected upon the opening. At a distance of 9 or 10 cm. behind the glass is placed a Huyghens' eyepiece, its position being such that the field of view is just filled with the coloured light. By the aid of this device observations can be made much more satisfactorily than when the image upon the ground-glass is viewed merely by the unassisted eye. Rays from any part of the spectrum can be combined; but the absence of a surrounding white ground with which to compare the colour of the pulsative after-image is often found to be inconvenient. For some of the experiments a screen of thick brown paper attached to the rocking arm of a metronome was arranged to eclipse the spectrum rays periodically, without obstructing the white light; thus the pulsative image and the white light were seen in the eyepiece alternately, each for a period of a little more than one second, and it

became easier to judge of the colour of the image. The iris-diaphragm was covered with ground-glass.

Method IV.—This is not a colour-patch method, but an ordinary spectroscopic one, the unmixed spectrum as dispersed by the prism being viewed through a tubeless telescope. The eyepiece V (fig. 7)

FIG. 6.

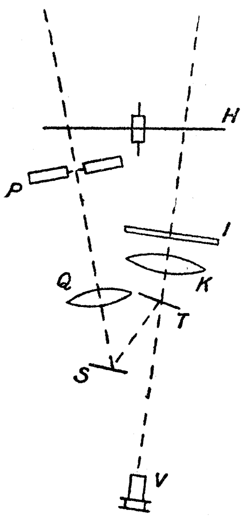
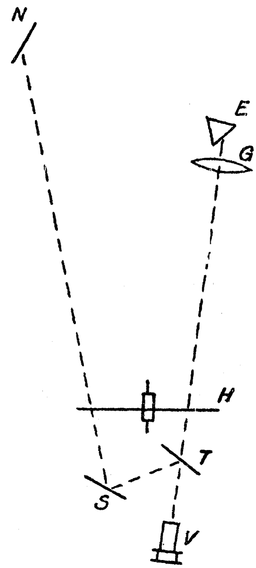


FIG. 7.



occupies the place of the slit-screen behind the disc H; white light is reflected into the eyepiece by the silvered mirror S and the clear plate-glass T, as in Method II. A sheet of ground-glass takes the place of the iris-diaphragm, which is removed. The arrangement is in all essential respects similar to that adopted by Mr. Burch,* except that the reflected white light is derived from the electric arc instead of from the sky, its intensity being capable of wide variation. About one-third of the whole length of the spectrum can be seen at once; the eyepiece is so directed that the spectrum may occupy only the lower half of the field, while the white light, when admitted, fills the whole of it.

Ordinary Negative After-images.—The apparatus, whether arranged for the projection of a colour-patch upon a screen or for observation with an eyepiece, is exceedingly well adapted for the study of ordinary negative after-images. The zinc disc H is set so that a coloured image is formed upon a black ground; after this has been gazed at for 10 or 20 seconds, it is obliterated by turning the disc through a

* 'Roy. Soc. Proc.,' vol. 66, p. 215.

small angle, a white patch of any desired luminosity appearing in its place. The hues of the negative images seen upon the white patch are often very different from those of the pulsative images formed when the disc is rotating continuously.

III. *Pulsative Images due to Various Colours.*

Red.—A red colour-patch formed on the screen by a combination of rays extending from the extreme limit of the spectrum to λ 6450 gives no pulsative after-image at all, the white-light disc, whatever may be its intensity, appearing white throughout. If the slit is further opened to admit rays up to λ 6320 a faint blue-green image is seen upon the white-light disc, provided that the latter is not too strongly illuminated; with apertures greater than No. 5 of the diaphragm O, fig. 3, the blue-green image disappears. The absence of a pulsative image after a low red is, no doubt, in great measure due to the superior persistence of this hue, for the ordinary after-image is quite distinct.

In general the pulsative images of red, or of red and orange mixed, are of a blue-green tint, exceeding in brightness and apparent saturation those due to any other exciting colours. Perhaps the strongest effect was observed when the colour-patch was illuminated by rays from about λ 6100 to λ 6550, aperture No. 4 of the rotating diaphragm being used for the white-light disc. No pulsative image of the red can, however, be formed unless the luminosity of the patch is fairly great.

With the eyepiece methods a feeble pulsative image was excited by red in the neighbourhood of the B line. Its hue appeared bluish with a slight tinge of green. In other respects the results for red were similar to those obtained by Method I.

Orange.—A colour-patch was formed by mixing rays from λ 5800 to λ 6150. Its ordinary after-image was bright sky-blue. The pulsative image upon the screen appeared a rather dull blue-green with aperture No. 2 of the rotating diaphragm and green-blue with apertures 3 and 4. The eyepiece method showed the colour as blue-green, paler than that excited by red.

Yellow.—The ordinary after-image of a patch of yellow, λ 5700 to λ 5890, was blue-violet. The tint of the pulsative image on the screen was a pale nearly neutral grey, pinkish when the illumination was weak, bluish when it was strong. A slightly more orange yellow, λ 5700 to λ 5980, gave an image of nearly the same character but a little stronger. When the eyepiece methods II and III were employed with yellow, the pulsative images were exceedingly feeble, and generally appeared to contain a trace of pink. The image due to a greenish-yellow, λ 5590 to λ 5740, was more decidedly pink or pale purple. Similar effects were obtained when the exciting yellow

was produced by mixing red and green rays. An orange-yellow, made by combining the spectrum rays from the extreme red to λ 5340 in the green, had a slate-coloured or nearly neutral pulsative image; the addition of a very little more green turned the image pink.

Green.—A colour-patch sufficiently illuminated by green rays taken from any part of the spectrum between greenish-yellow and greenish-blue inclusive (about λ 5750 to λ 5050) produced a pink or dilute purple pulsative image; the purple was strongest when the exciting colour was a full green, but it never reached an intensity equal to that of the blue-green excited by red when the conditions were most favourable. On the other hand, there can be no question that a purple pulsative image after green is much more easily produced than a blue-green one after red, a fact which tends to indicate that, at least after a short period of repose, the colour-sense organs become fatigued more quickly by green light than by red. It seems to be generally believed that the red sensation is more readily exhausted than the green.* Rood,† however, attributes the "well-known intolerance of all full greens to the fact that green light exhausts the nervous power of the eye sooner than light of any other colour," this exhaustion being "proved by the observation that the after-pictures . . . are more vivid with green than with the other colours." The results of my own observations lead me to think that while after a prolonged gaze at brightly illuminated colours, blue-green after red is more conspicuous than purple after green, the opposite may be the case when the exposure has been brief or the illumination feeble. In the case of the pulsative image, however, account must be taken not only of fatigue, but also of persistence and of the latent period during which the first impact of light upon the eye fails to produce any recognisable sensation.

Blue.—Though the ordinary after-image of blue is orange, the pulsative image upon the screen was generally seen as some form of impure purple, variously described as dull pink, salmon, or flesh colour. The same was often the case when the eyepiece methods were employed. Among the blues tested were a mixture of λ 4700 to λ 4950, and one of λ 4550 to λ 4760, besides many others of which the limiting wave-lengths were not determined. By Method II a good orange-yellow image could always be produced from the last-named blue, provided that the illumination was sufficiently strong and the various luminosities carefully adjusted.

Blue-violet and Violet.—The ordinary after-image is yellow. The screen method showed scarcely any image at all for light of wave-lengths less than about λ 4500. With the eyepiece methods the image

* Foster, 'Text-book of Physiology,' 6th edition, p. 1382.

† 'Modern Chromatics,' 2nd edition, p. 295.

usually appeared as a pale bluish-pink, which could be closely matched by blue-violet diluted with much white. The persistence of violet impressions is very great, and it is not unlikely that the bluish-pink image was due merely to the intermingled action of the violet and white-light rays (as in a Maxwell's disc), and was not a true pulsative after-image. In the circumstances mentioned in the last paragraph, when blue light gave an orange pulsative image, blue-violet also gave a yellow one, the persistence of blue-violet being less with strong than with weak illumination.

Purple.—A bright purple was made by combining red, λ 6180 to λ 6810, with blue-violet, λ 4330 to λ 4420. The ordinary after-image of the red alone was blue-green, and that of the purple grass-green. The pulsative image of the purple formed on the screen was, however, blue-green, and when the slit admitting the blue-violet light was alternately covered and uncovered, no change in the colour of the image could be detected.

IV. *Pulsative After-image of White.*

Recombined Spectrum.—If the slit-frames and their appurtenances are removed from the slit-screen I, fig. 3, the whole spectrum is recombined by the lens K, and forms upon the screen L a white "colour-patch," the illumination of which can be varied in a known manner by changing the width of the collimator-slit. The illumination of the "white-light disc" (which, during an experiment, alternates with the white "colour-patch") can also be adjusted to certain known intensities. A large number of experiments, which need not be described in detail, were made with various illuminations of the white colour-patch and of the white-light disc. The colour of the pulsative images of the white patch, which is not in general neutral like that of the ordinary after-image, was found to depend not only upon the absolute values of the two illuminations but also upon their ratios. Broadly speaking, it may be stated that with feeble illumination the patch appeared yellow (probably only an effect of weak intermittent light), with very strong illumination it was a neutral grey, and with all such intensities of illumination as are ordinarily employed it appeared a more or less decided purple.

In my former paper reference was made to the purple tint assumed by a white card when seen through the original black and white disc, and a distinguished physiologist, who saw the effect, expressed the opinion that the colour might be due to the "visual purple." In the light of the observations described in the present paper, it seemed possible that the phenomenon might be explained by the hypothesis that the purple was really an after-image of the green component which, according to the Young-Helmholtz theory, is contained in the

white light. All the various components set up fatigue after a moment's action, but green more than the others; if, therefore, the green stimulus were diminished to an extent corresponding to the excess of fatigue which it produced, the tint of the pulsative image might be expected to become neutral, like that of the ordinary negative after-image. Different parts of the green portion of the spectrum were accordingly cut out by interposing strips of black card of various widths, and it was found that when the green rays from λ 5030 to λ 5470 were intercepted, the tint of the pulsative image was absolutely neutral.

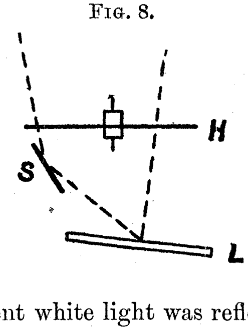
White compounded from Red and Blue-green.—Such a white always gave a pink pulsative image—a fact which confirms the inference derived from previously described observations that the blue-green sensation is, after an interval of repose, more readily fatigued than the red sensation.

White compounded from Yellow and Blue.—A white colour-patch was formed by combining a blue of λ 4530 to λ 4710 with a yellow of λ 5650 to λ 5860. The colour of the pulsative image was rather doubtful, but an artist (who did not know what to expect) unhesitatingly pronounced it to be yellow. Since the Young-Helmholtz theory supposes that yellow excites the green sensation, this result was unexpected. It is also opposed to the usually received opinion that the sensation of yellow is more readily exhausted than that of blue.*

V. *Pulsative Images of Complete Spectrum.*

The spectrum was projected upon a screen covered with white cardboard, which was put in the place of the slit-screen, as shown in fig. 8.

FIG. 8.



The beam of intermittent white light was reflected upon the screen by means of a mirror and formed an oblong bright patch upon the site of the spectrum. The upper part of the mirror was covered by a screen, so arranged that the site of the spectrum was longitudinally divided into two equal parts, the lower of which was exposed to intermittent

* Foster, *loc. cit.*

white light, while the upper was not. Thus the spectrum and its pulsative image could be seen together, the one above the other. At first sight the pulsative image appeared to contain only two colours—blue-green corresponding to the spectral red and orange, and purple-pink corresponding to the green. Closer inspection revealed a pale grey band between the blue-green and the purple, and a feeble tint of lavender corresponding to the blue of the spectrum. Nothing at all could be seen beneath the violet and the extreme red. The boundaries of the several colours of the pulsative image were found to be roughly as follows:—Blue-green, λ 6800 to λ 6000; grey, λ 6000 to λ 5800; purple, λ 5800 to λ 5000; lavender, λ 5000 to λ 4300.

Observations were also made of the changes undergone by the red and green of the projected spectrum when the illumination was varied by altering the width of the collimator-slit. With a width of 0·06 mm. neither of the spectrum colours was at all affected; they appeared simply as intermittent red and green. With 0·125 mm. the green had become transformed into a purple, intermixed with which a little green could sometimes be glimpsed; this latter completely disappeared when the slit was made 0·2 mm. wide, the apparent colour being with this and all greater widths of slit a steady purple. At the same stage (0·2 mm.) red was still seen as red, though a flicker of blue-green could be detected upon it. At 0·45 mm. red appeared as blue-green with a red flicker, which ceased to be perceptible, except along the extreme edge, when the width of the slit was increased to 0·5 mm. With a slit of 0·94 mm. wide the last trace of red had vanished. Thus the more ready exhaustion of the green sensation is again evidenced.

VI. *Colour Changes with Reversed Cycle.*

If the cycle is reversed by making the zinc disc turn in the opposite direction, most of the spectrum colours undergo remarkable changes. Red becomes rose-purple; orange a diluted crimson; yellow is made much paler, as if veiled by a white haze; green appears as blue-green, and blue-green as blue. Blue and violet are very slightly affected. Very similar effects are observed when the disc described in Section I is turned in the reverse direction. They naturally suggest that white light excites a blue or blue-violet sensation, the persistence of which exceeds that of any other fundamental sensation.

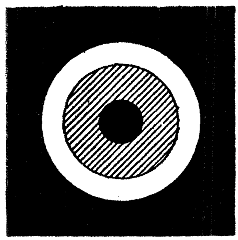
VII. *External and Border Phenomena.*

Some very remarkable and interesting phenomena are exhibited in the region of the visual field immediately adjacent to that upon which a "pulsative after-image" is being produced. It is a matter for surprise that one should be able to perceive after-images without detecting

any indication whatever of the colours to which they are due, but it is perhaps even more surprising to find that parts of the retina upon which the intermittent white light does *not* fall may also be absolutely blind to the exciting colour.

The effect in question is conveniently demonstrated by the arrangement illustrated in fig. 9. A piece of clear glass, upon which is

FIG. 9.



gummed a small circle of black paper or tinfoil, is fixed behind the iris-diaphragm P, fig. 3, and thus a round black spot, 0·6 cm. in diameter, is formed at the centre of the white-light disc projected upon the screen L. In fig. 9 the outer circle represents the white-light disc, the shaded circle the colour-patch, and the inner one the black spot upon the white-light disc. Suppose the colour-patch to be green. When the apparatus is worked, the shaded circle becomes purple; the site of the black spot, being illuminated five or six times in a second by green light, might be expected to appear green; but if viewed from a distance of 30 cm. or more it remains perfectly black throughout; under normal conditions no trace of a flicker of green light can be seen upon it. The apparent width of the blind region adjoining the site of the pulsative image, therefore, exceeds half a degree.

This induced blindness is most conspicuous when the light is green, and hardly less so when it is yellow; it does not occur at all with extreme red nor with violet light, which illuminate the site of the black spot quite strongly; but its absence is certainly not entirely due to the inferior luminosity of those hues. With a very narrow slit green can indeed be seen in the central part of the spot by an observer stationed quite near the screen; but if he is at a distance of 1·5 metre, the green light may be weakened by gradually closing the slit until the pulsative image completely disappears, yet no green is ever seen upon the spot.

The following are the results noted in one experiment, when a slit was moved across the spectrum from end to end. Red was seen upon the spot, at first nearly continuously, then intermittently, until the slit reached about λ 6220, when, unless the illumination was made very

feeble, the spot became uniformly black, remaining so until about λ 5000, at which point a blue flicker began to appear; at λ 4700 the spot had become steadily blue. Blue-violet and violet seemed to illuminate the spot much more steadily than red. It was noticed that as soon as the black spot became distinctly coloured the pulsative image almost disappeared; the weakness of the pulsative images excited by light corresponding to the two ends of the spectrum may therefore probably be accounted for by supposing that the negative after-images become blended either with the primary images, or with positive after-images, or perhaps with both, producing the effect of white.

It was found possible to observe these phenomena not only when the zinc disc was spinning continuously, but even with a single properly timed cycle of (1) darkness; (2) colour-patch; (3) white light; (4) darkness. When the spectrum light was green, there appeared for a moment a bright white disc with a perfectly black central spot, which was surrounded by a well-defined purple annulus (as in fig. 9), the whole being free from any visible trace of green.

When a purple pulsative image excited by green rays was viewed in the eyepiece by Method II, it was seen to be surrounded by a purple corona, which extended considerably beyond the well-defined boundary of the aperture in the diaphragm (F, fig. 3). Sometimes, indeed, when the illumination was strong, the purple of the corona appeared to be fuller or more saturated than that of the image itself. Moreover, a purple haze of greater or less intensity always extended over the whole field of the eyepiece. These phenomena are, of course, to be explained by the "induced" blindness to green light which was demonstrated by the black spot.

Certain border effects of an entirely different character were also observed. If the rays illuminating the circular patch seen in the eyepiece were taken from the red, orange, or yellow regions of the spectrum, the image appeared to be surrounded by a narrow red, or rather crimson, border. Measurements of the composition of different colour-patches which showed this effect include a red of λ 6420 to λ 6600, a reddish-orange of λ 6200 to λ 6280, an orange-yellow of λ 5890 to λ 5990, and a yellow of λ 5740 to λ 5860; in the last case, the border was less conspicuous, but still recognisable with certainty. With a greenish-yellow patch containing rays from λ 5650 to λ 5750 no trace of the crimson border could be detected. It turned out that these crimson borders could be seen when the intermittent white light was screened off, though they were less easily visible against the dark background than against the bright one. They evidently belong to a class of phenomena discussed in a former paper,* in which it was

* 'Roy. Soc. Proc.,' vol. 60, p. 368, "On Subjective Colour-phenomena attending Sudden Changes of Illumination."

shown that when a bright image is suddenly formed upon the retina after a period of darkness, the image generally appears for a moment to be surrounded by a narrow red border. The paper referred to contains an account of an experiment* demonstrating that when the bright object producing the image was looked at through variously coloured glasses, the red border did not appear unless the glass used, when tested spectroscopically, transmitted red light, and it was suggested that the phenomenon was due to sympathetic excitation of the "red nerve fibres" lying immediately outside the portion of the retina exposed to the direct action of the light. The orange and yellow glasses employed in the experiment referred to of course transmitted red light; it is interesting to find that the pure orange and yellow rays of the spectrum, of wave-length not necessarily exceeding about λ 5800, are competent to give rise to the same red borders.

These effects can be exhibited equally well by Methods I and II, the observations being rendered much easier by the aid of a device described in the former paper. A darning needle, blackened with camphor smoke, is cemented vertically across the opening in the diaphragm F, fig. 3, dividing the bright disc which is projected upon the screen or seen in the eyepiece into two equal parts. Each half disc then has its red border, and, if the intervening space is sufficiently narrow, the red borders along the two contiguous vertical edges meet, or possibly even overlap, with the result that the focussed image of the needle should appear to be red. This was the case when the slit was placed in any part of the spectrum between the extreme red and the greenish-yellow. With the slit in the greenish-yellow itself the image of the needle appeared to be almost colourless, but as the full green was approached the colour became a rather dark shade of blue-green, and remained so until the slit reached about λ 4500, near the beginning of the blue-violet, when the needle again became colourless. In a colour-patch formed of the pure blue rays from λ 4600 to λ 4725 the contrasted blue-green hue assumed by the image of the needle was strikingly conspicuous. The border-colour in question cannot easily be observed unless the intensity of the illumination is within certain limits; for, as in the case of the red borders which were discussed in a former paper,† the blue-green hue becomes transformed into its complementary if the light is very strong, and the needle appears reddish. For the green part of the spectrum it is especially necessary that the illumination should be very carefully adjusted; indeed, the phenomenon would probably never have been noticed at all with green light if its remarkable appearance when the light was pure blue had not first attracted attention. For the more refrangible part of the spectrum it is desirable to place in front of the collimator-slit a piece of blue glass

* Experiment IV, *loc. cit.*, p. 372.

† 'Roy. Soc. Proc.,' 1897, vol. 61, p. 268.

which will obstruct the red rays; possible sources of error due to the reflection of red light by the prism are thus avoided. The origin of these blue-green borders is, no doubt, analogous to that of the red borders, but the matter requires more careful and thorough investigation than it has yet received.

Though the image of the needle was colourless when the patch was illuminated by the greenish-yellow rays of the spectrum, it appeared red when the same hue was formed by combining red and green rays. Red borders were also observed with a purple composed of red and blue rays, with a white composed of red, green, and violet rays, and with another white formed by recombining the whole of the spectrum; this last observation was, of course, practically a mere repetition in a slightly different form of the one which formed the chief subject of my previous paper.

No coloured border of the same class has yet been observed when the colour-patch was illuminated by the violet rays of the spectrum, Method II being the one employed. The edge of the yellow pulsative image was fringed with a pale violet rim, which, however, was wholly inside the geometrical boundary of the image and not external to it, as were the red and the blue-green borders. Red was very carefully looked for around the violet, but not found. The so-called "simultaneous contrast" effect was, however, very remarkable, the whole field of the eyepiece appearing of a strong yellow tint; often it was quite as strong as the colour of the image itself, which could only be distinguished from the background by the narrow violet ring surrounding it. An equally remarkable effect was produced when the stimulating light was blue, the "contrast-colour" being, like that of the image, orange.

VIII. *Discussion of the Observations.*

Nature of the Pulsative Image.—The phenomenon which, for brevity, has been termed the "pulsative after-image," may be defined as the negative after-image of a coloured object which is seen against a white ground after a very brief stimulation—1/60 to 1/30 of a second—following a period of repose. A strange peculiarity incidental to the formation of these after-images is, that under suitable conditions of illumination, the true colour of the light to which the phenomenon is due altogether fails to evoke its appropriate sensation and is not perceived at all, the only colour seen being that of the after-image. The difficulty experienced in attempts to find a really definite explanation of this fact, and illustrate it by curves of sensation, is in some degree diminished by the singular observations upon the "black spot." The black spot is, of course, merely a device for exhibiting a certain border effect in a convenient manner. A small disc of green light is

flashed upon a white screen for about a fortieth of a second, and is immediately replaced by a concentric annulus of white light. During this process no green is seen at all; there appears only a purple annulus surrounding an area which is perfectly black. The white light clearly has the effect of restraining the visual sense-organs adjacent to those upon which it falls from responding to the green stimulus. It would seem to follow *a fortiori* that the sense-organs directly acted upon by the white light must be similarly incapacitated from evoking any green sensation. It is not the fact that the green sensation is produced for a moment and then swamped by a more powerful white one so completely as to escape notice; it actually never comes into existence. Nevertheless, the effects of fatigue by green are exhibited, and the physically white annulus is seen as purple.

It may be well to state that when once the necessary apparatus has been set up and the various luminosities adjusted to the order of those specified, the "black spot" observation is an exceedingly easy one. No skilled observer is required for it; it can be made at once by any one whose vision is normal, and the phenomenon can at any time be exhibited with certainty.

No explanation of it can, I think, be afforded by the Young-Helmholtz theory of colour-vision in its current form; an independent white sensation must be postulated, as by the theory of Hering. And the observations point to the conclusion, even if they do not of themselves sufficiently prove it, that the latent period for a colour-sensation is very much greater than that for white. For green, under the conditions of my experiment, the latent period must be at least 1/40 second, while for white it can hardly exceed 1/500 second, though the luminosity of the two may be nearly equal. The latent period for red is probably not very different from that for green under similar circumstances, that for blue being considerably greater;* but it is not quite certain whether the red and blue flickers seen upon the black spot are produced before or after the illumination by white light. I am inclined to think that the latter is the case, the negative after-image being followed during the period of darkness by a positive one. In all cases the duration of the latent period probably depends partly, through certainly not wholly, upon the intensity of the illumination.†

If in a darkened room a ray of green light is admitted to the eye for a period of 1/40 second, one sees a flash of green; but assuming

* Some preliminary observations by a method of which I hope to submit an account at a future date indicated that, under the conditions of the experiments, the latent period was for red 0·031 sec., for green 0·028 sec., and for blue 0·040 sec.

† According to Exner, "If the intensities of the illumination of an object increase in geometrical progression, the times necessary for the perception of the same decrease in arithmetical progression," 'Wien. Akad. Sitzber.,' vol. 58, Abtheil II, p. 624, 1868.

that the suppositions which have been put forward are correct, the visible flash is not contemporaneous with the physical illumination. One does not begin to experience the green sensation until after the green ray which excited it has been shut off. What is actually perceived is, in fact, a positive after-image, the duration of which may be considerably longer than that of the stimulus. But if a sufficiently luminous white surface is presented to the eye immediately upon the expiration of the brief period of stimulation by green light, the after-image formed will not be positive but negative, and the only colour perceived will be purple. The fatigue to which the negative image is due must have been set up during the latent period when no image at all was actually perceived. It is noteworthy that if the white background is eclipsed by black before the expiration of the period during which the positive after-image normally continues, the purple negative after-image is seen to be followed by a green positive one, which appears as a bright object upon the dark ground.

One other point requires notice. According to Hering's theory, rays of every wave-length excite not only the sensation of a colour but also that of white. Supposing therefore that the colour-sensation lags behind the white-sensation, we should expect that when the zinc disc is turned, the black spot, even if no colour showed upon it, would appear more or less grey. This, however, is not the fact, at least to any perceptible extent; on the contrary, the spot appears more intensely black when it is illuminated by intermittent green light than it does when the green light is screened off. In the latter case (when no light whatever falls upon it) the spot seems to be veiled by a faint haze, the origin of which I have traced to a phenomenon attending sudden changes of illumination described in a former paper.* The "black spot" phenomena are therefore not fully in accord with either of the leading theories of colour-vision.

Red and Green Borders.—The narrow red and blue-green borders which appear to surround colour-patch images formed from different parts of the spectrum obviously point to the excitation of fundamental red and blue-green colour sensations, the effects of the excitation being sympathetically extended beyond the geometrical boundaries of the images projected upon the retina. Red borders are exhibited by colour-patches formed from any mixture of spectral rays which contains a considerable proportion of red; they also appear around patches illuminated by the simple orange and yellow rays of the spectrum (though with the latter they are feeble) and around white patches. With mixtures of spectral rays from which red, orange, and yellow rays are excluded, they are never seen. A blue-green border, on the other hand, appears only when the green or the blue of the spectrum enters into the combination, the addition of blue-

* See 'Roy. Soc. Proc.,' vol. 60, p. 370, experiment I (2).

violet and violet having no sensible effect, while an admixture of red, orange, or yellow causes the border to become red. The intensity of the red borders is much greater than that of the blue-green, and if the two could occur together, the blue-green would no doubt be overpowered. According to Hering's theory the red and blue-green fundamental sensations, being antagonistic, cannot both be excited at the same time, and it is to be remarked that those spectral rays which are less refrangible than the greenish-yellow produce red borders, while those of refrangibility intermediate between greenish-yellow and blue-violet produce blue-green borders, which is nearly what the Hering theory would require. According to the most recent exponents of the Young-Helmholtz theory, green spectral rays excite the fundamental red sensation to about the same extent as orange-red rays; yet no red border is formed by the green, though that formed by the orange-red is very strong. If the presence of these borders may be taken as affording evidence of the excitation of fundamental colour-sensations, the evidence so far is in favour of Hering's views. But on the other hand the fact that the red borders can be caused by all kinds of white light seems to show that white excites the fundamental red sensation, while there is some evidence in Sections IV and VI that it excites green and blue or violet colour-sensations as well. No indication as to what one or more colour-sensations in addition to red and blue-green are fundamental ones has yet been afforded by the class of border phenomena under discussion.

Simultaneous Contrast.—When a purple pulsative image of a very bright green patch is formed upon a white ground by the eyepiece method, the whole physically white field appears to be strongly purple, a fact which shows conclusively that the phenomenon of simultaneous contrast may in certain cases be absolutely independent of mental judgment. It cannot be that the ground appears purple simply from contrast with green, for no green whatever is consciously perceived; the cause must necessarily be a physiological one. Similar remarks apply to the orange and yellow fields which accompany the pulsative images of blue and violet patches. It is curious that with a red patch the colour of the field is but very slightly affected.

But while these observations show that in certain cases the so-called contrast effects must have a physiological origin, it is beyond question that this is not invariably so. Some of Helmholtz's well-known experiments leave no room for doubt that mental judgment is sometimes the sole cause of contrast phenomena.

Colours of the Pulsative Image.—The chief results of the colour experiments are collected in Table II. One of the most noticeable features is the superior intensity of the pulsative after-images of red and green; another is the intrusiveness of some form of purple. Purple after green is, as before mentioned, more easily obtainable than

any other colour, and if the appearance of purple in the pulsative image may be regarded as a test for the presence of green in the luminous object, then it appears from Nos. 4, 8, and 9 that green is a constituent of yellow, of blue, and of white.

TABLE II.

Ref. No.	Spectrum colours.	Complementary colours.	Pulsative colours.	Remarks on pulsative image.
1	Extreme red	Green-blue ..	Green-blue	The image could only be seen by direct vision. None was formed on the screen.
2	Red	Blue-green....	Blue-green	The most intense of all pulsative colours.
3	Orange......	Blue	Pale blue-green	Green-blue with strongest illumination and direct vision.
4	Yellow......	Blue-violet ..	Nearly neutral	Pinkish with ordinary illumination, bluish with strong. Always inconspicuous.
5	Green-yellow	Violet	Pink, or pale purple	Mixed red and green light gave images similar to those of Nos. 4 and 5.
6	Green	Purple	Purple	Inferior only to No. 1 in intensity. Easier to produce than any other.
7	Blue-green ..	Red	Purple	Nearly the same as No. 6.
8	Blue........	Orange-yellow	(1.) Dull pink (2.) Orange	(1.) For ordinary illumination and on screen. (2.) For intense illumination with direct vision.
9	Blue-violet and violet	Yellow	(1.) Bluish-pink (2.) Yellow	Remark as for No. 8. Violet gave no visible image upon screen.
10	Purple......	Green	Blue-green	Same as No. 2. The addition of blue to red made no perceptible difference.
11	White	Neutral grey..	(1.) Purple or purplish-grey (2.) Neutral	(1.) With all ordinary illumination, for recombined spectrum and for combinations of red and green and of yellow and blue. (2.) With strong direct sunlight.
12	Spectrum....	—	—	Blue-green and purple very conspicuous; all other colours comparatively feeble.

The weakness of the pulsative image of yellow is remarkable, and cannot be readily explained. If a yellow colour-patch is formed by combining red and green rays, and the image is then put slightly out

of focus by moving the screen 3 or 4 cm. nearer to the lens, there appear two patches, one red the other green, which overlap one another, the part common to both being yellow. In the pulsative image the red and green become respectively blue-green and purple, while the overlapping portion is almost colourless. Possibly both the pulsative colours are less blue than they should be, with the result that their combination produces white or grey.

The difficulty of forming a satisfactory pulsative image from blue and violet is no doubt to be accounted for by the superior persistence of those colours. With stronger luminosity than can be obtained by the method of projection or by the use of pigments this difficulty is diminished, for then the greater part of the luminous impression vanishes more quickly.

Though the work of which an account is given in the present paper has occupied a large amount of time, it is obvious that the subject is far from being exhausted. Several doubtful points remain to be cleared up and apparent discrepancies reconciled, while of a number of remarkable phenomena which presented themselves no mention at all has been made. With more refined apparatus than that at present at my disposal, similar methods of experiment might be expected to yield important contributions to the theory of colour-vision.

"The Solar Activity 1833–1900." By WILLIAM J. S. LOCKYER, M.A., Ph.D., F.R.A.S., Assistant Director, Solar Physics Observatory, Kensington. Communicated by Sir NORMAN LOCKYER, K.C.B., F.R.S. Received April 29,—Read May 23, 1901.

Introduction.

A close examination of the curves representing the varying amount of spotted area on the Sun's surface, shows that no two successive cycles are alike either in form or area. The individuality of the cycles seems, on further inspection, to be repeated after a certain period of time, and this peculiarity, coupled with a like variation in the curves representing the variations of the magnetic elements, and with suspected cycles of change in various terrestrial phenomena, suggested a new investigation of the whole subject.

The object of this communication is to place before the Royal Society the first results which an examination of the various records has furnished.

Dr. Rudolf Wolf,* of Zürich, from a study of the sunspot observations made up to the end of 1875, drew attention to the facts, to use

* 'Mem. R. Astron. Soc.,' vol. 43, p. 200.

Fig. 9.