VII. *The Sensitiveness of the Retina to Light and Colour.*

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Received May 10,—Read June 3, 1897.

1. *New Form of Apparatus for Reducing the Intensity of Light.*

IN "Colour Photometry," Part III. ('Phil. Trans.,' A, 1892), a description was given of the apparatus employed for estimating the intensity of light of any colours which just failed to cause any sensation on the retina. In the following research a modified form of apparatus has been employed, and experience has shown it to be equally as accurate as and more convenient in many ways than that formerly used. When rotating sectors are employed with less than 4° of aperture, small errors in the reading of the graduated arc cause appreciable errors in the result. Hence, the more nearly the zero reading is approached, the less trustworthy are the determinations of the diminution of the total intensity, and this uncertainty affects all observations in which the light is reduced below $\frac{1}{40}$ of its initial amount. The sectors have also the disadvantage of not being noiseless, and of requiring an electro or other motor to work them. With the extinction box, described in Part III., the difficulty of being able to reduce the light to, say $\frac{1}{10000}$ part of its initial intensity, was overcome by using diaphragms of varying aperture in front of the ground glass, which was practically the source of illumination. It is obvious that any instrument which would allow a similar decrease in illumination without the intervention of a diaphragm would be advantageous, more particularly if it were noiseless. In the estimation of star magnitudes by extinction, a wedge has been used from time to time by various investigators, and in 1870 I myself used one for the purpose of measuring the intensities of the electric light. As a rule, these wedges are of dark green glass which have a fairly high exponential coefficient of absorption. The fact that it has a dominant colour at once indicates that for the comparison of spectrum colours by extinction such a wedge should be avoided. Thanks to the kindness of Dr. GROSSMANN, of Liverpool, I had put into my possession a pair of black glass wedges, and with these I hoped to avoid the difficulty caused by the colour of the green glass wedges, but after mounting them and preparing to use them, it was found that the material exhibited bands of absorption in several parts of the spectrum; after graduating them for each spectrum colour, the results were so unsatisfactory that

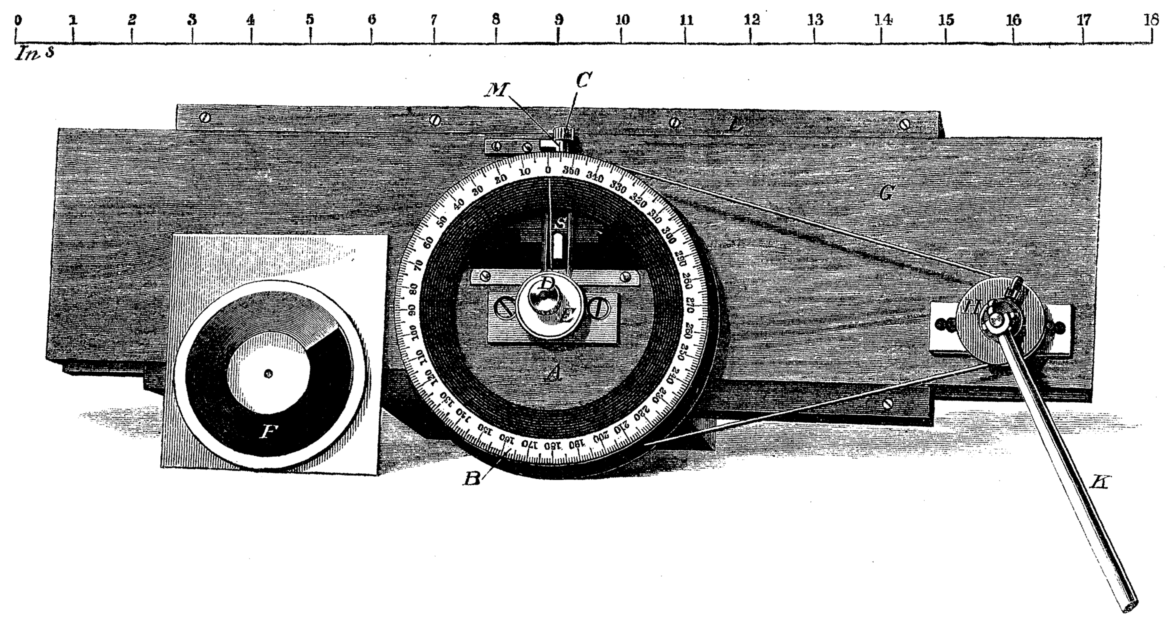
their use had to be abandoned. Reduction of intensity by means of a polarizing apparatus had already been tried and found unsatisfactory, when the beam of light approached the point of absolute visual extinction.

2. *Gelatine Wedge in Annular Form.*

It occurred to me that a few years ago Mr. LEON WARNERKE had brought out a "sensitometer" (an instrument for measuring the sensitiveness of a photographic plate) in which the apparatus for reducing the intensity of light admitted to a sensitive surface consisted of an annulus of gelatine of gradually increasing thickness, coloured either by a dye or by a powder of any colour which might be desired. I applied to Mr. WARNERKE to prepare for me some of these sensitometer screens, and to use as a powder very finely divided lampblack. He kindly gave me several specimens of three varieties, one having but little pigment mixed with the gelatine, another rather more, and the third with strong absorption. This last reduced the light which penetrated the thinnest part to $\frac{1}{70000}$ part when it had to pass through the thickest portion, the second only reduced it to rather less than $\frac{1}{1000}$ part, and for my purpose I selected this last with which to work as a rule, though in some cases the more opaque annulus was used. I am informed that the mode of the preparation of the annulus is as follows:—In a perfectly flat and thick steel disc a groove of gradually increasing depth is cut by a proper machine into an annulus about 1 inch broad. When the depth of the groove has been tested and found to increase proportionally to the arc of the circle, replicas of the disc and groove are made in non-oxidizable metal. The finest pigment is then mixed with semi-liquid gelatine, and when thoroughly incorporated the viscous liquid is poured into the groove, the top surface of the disc being very carefully levelled. A sheet of worked glass is then laid on the surface of the disc, and any excess squeezed out except a very minute film which appears colourless, and for which there is no means of escape. When the gelatine has properly set, the glass plate is removed with the relief of the groove attached to it. The gelatine annulus is allowed to dry, and is then ready for use. It struck me that such an annulus might be substituted for glass wedges, and after selecting one which was suitable as to colour absorption and regularity of absorption coefficient (if one may so call it), I finally determined to adopt it. It may be said here that not every specimen gave equally good results. It is only when the glass plate is perfectly flat that regularity in the increase in thickness, and consequent uniformity of coefficient per unit angle can be secured. The diminution in light in its passage through the annulus of pigmented gelatine is evidently due to a different cause to that of coloured glass. In the latter case it is due to true absorption, in the former to the obstruction by fine opaque particles. If the opaque particles possessed colour some of the light passing through the gelatine would be tinged with the light reflected from their surfaces, and if they were semi-transparent there would be not

only obstruction but also absorption. As the particles were black and very opaque the light penetrating, and which was reflected from the surfaces of the particles, would be colourless, or rather uncoloured. A photographic plate sensitive to all visible rays was exposed to the spectrum, and on the same plate, and just below it, a more prolonged exposure was given after its passage through a portion of the annulus, and on development the two images appeared identical from B to, at all events, near G, but beyond the image in the extreme violet was rather less opaque in the latter than in the former, indicating a slightly increased absorption for those rays. The use of this annulus was therefore possible and easy between B and G, and between these limits only has it been employed. It seems probable that this falling off in the extreme violet may be due to scattering by fine particles. The following is the method adopted to mount the annulus :—A hole was pierced in the glass exactly at the centre of the two circles and the glass was cut into a disc concentric with the circles.

Fig. 1.



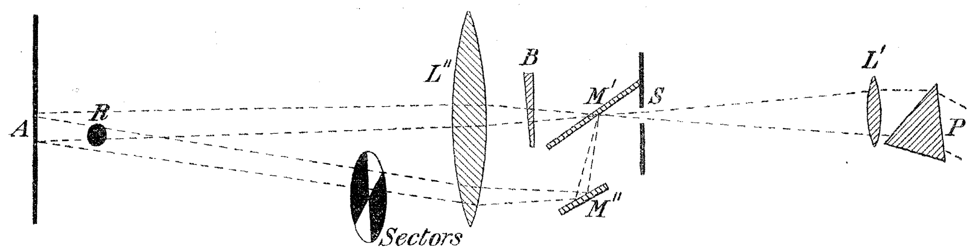
The disc of glass, A, is pierced in its centre with an aperture of just sufficient size to allow a pin with a screw-thread springing from a brass plate attached to the wooden slide, G, to penetrate. The disc of glass, F, with the annulus on it, being also pierced at its centre with an aperture, can be passed over the same pin. The two discs are clamped together with a milled-headed nut, D, a washer of paper, E, being placed between the two. The disc, A, is cemented into a circular ring, B, graduated into degrees. On A is ruled a line joining centre and the zero of the graduation. The junction of the most and least opaque parts of the annulus is caused to lie along that line. The disc, A, is mounted so that the marked line on it, when the zero point is at the index, M, passes across the centre of the slit, S, the width of which can be

adjusted by a screw arrangement worked by the milled head, C. The brass ring is grooved on its outer edge, and round it and a brass pulley, H, passes a thread, and the ring, B, can be rotated by means of an universal joint and the handle, K. The pulley, H, by an obvious arrangement, can be moved towards or away from the annulus, thus allowing the thread to be slackened or tightened as may be desired. When F is in position the annulus covers the slit, S. By turning the handle, K, which is of such a length that it can be used 5 feet off from G, different parts of the annulus are caused to pass across S. When in use a small glow-lamp, carefully shaded, is attached to L, the frame of the camera, and after an extinction the readings are made by passing a current through it temporarily. It might be thought that an easier arrangement would be to place the mounted annulus in front of the eye, but the difficulty of reading without illuminating the retina prevented its adoption, and the uncertainty that would exist as to the precise part of the annulus which came between the spot of light and the eye, owing to the large eye-hole, also prevented its use in that position. Perfectly unfettered vision is essential.

3. *Graduation of Annulus.*

The annulus, when thus mounted, was ready for graduation, and as the method adopted is, it is believed, new, a description of it is given. The colour-patch apparatus described in Part II., "Colour Photometry" ('Phil. Trans.'), was utilized, but to the front of the slit in the spectrum a piece of plain worked glass, M′, was attached as shown (fig. 2). The beam of light coming from the prism, P, after

Fig. 2.



passage through the lens, L′, and the slit, S, was partly reflected from a plain mirror M′ on to M″, a silvered mirror, and partly transmitted through M′, the ratio of the amount of reflected to transmitted light varying according to the angle which M′ made with the direction of the beam. The direct beam after passing through M′ also passed through the annulus, B, and through the lens, L″, forming an image of the face of the prism, P, on A. The annulus, B, could be rotated so that the intensity of illumination of the patch of light on A could be increased or diminished at will. The reflected part of the beam also passed through the margin of the lens, L″, and formed a patch of light of the same colour and very

closely of the same size on A, and by adjusting the mirror, M″, the two patches could be superposed. Rotating sectors with adjustable apertures were placed in the path of the reflected beam as shown. A rod, R, cast two shadows, which were arranged to touch one another. When the undiminished reflected beam fell on A the two shadows were made equally luminous by rotating B. The number of degrees from the zero point was then noted. The sectors then were set so that half the light of the reflected beam was cut off, and equality of illumination of the shadows again secured by rotating B. The number of degrees was again noted. When the sectors were set at 45° the same procedure was adopted. If the coefficient of absorption (obstruction) did not vary, the intervals between first and second readings and between the second and third should be the same. By again setting the angle of the sectors to give one-eighth part of the light, another reading could be obtained, and so on. By altering the angle of M′ a new set of readings could be obtained, till every part of the annulus had been tested. By altering the position of the slit, S, in the spectrum, the obstruction coefficient for any colour could be arrived at. It will be seen that by this method one beam of light alone is utilized in a very simple method, and is in fact a modification of the method adopted when graduating wedges in white light, as described in the monthly notices of the Royal Astronomical Society four years ago. From the extreme red to beyond G no difference was found in the "obstruction" coefficients above that which would arise from pure error in observation. The following is the adopted coefficient for the annulus mostly employed :—

TABLE I.—Scale of Wedge, the coefficient being ·0086 for each degree.

Degrees.	Log.	Value of the light penetrating.	Degrees.	Log.	Value of the light penetrating.
0	4·000	10,000	190	2·366	232
10	3·914	8,200	200	2·280	190
20	3·828	6,870	210	2·194	156
30	3·742	5,500	220	2·108	128
40	3·656	4,520	230	2·022	105
50	3·570	3,710	240	1·936	86·1
60	3·484	3,040	250	1·850	71·5
70	3·398	2,500	260	1·764	58·0
80	3·312	2,050	270	1·678	47·8
90	3·226	1,680	280	1·592	39·0
100	3·140	1,380	290	1·506	32·0
110	3·054	1,130	300	1·420	26·2
120	2·968	925	310	1·334	21·6
130	2·882	760	320	1·248	17·8
140	2·796	625	330	1·162	14·5
150	2·710	512	340	1·076	11·9
160	2·624	420	350	0·990	9·7
170	2·538	345	360	0·904	8·0
180	2·452	283			

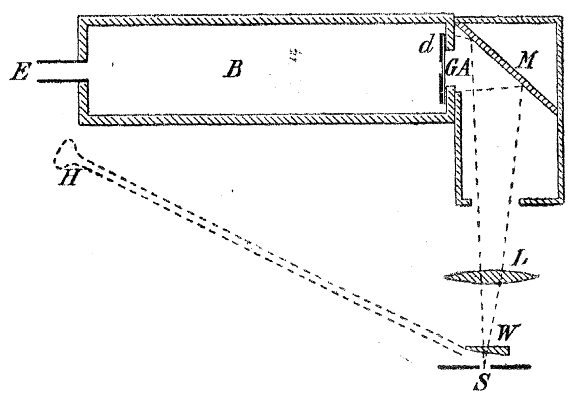
It may be noted that the annulus was graduated at the same distance from the screen as that at which it was employed in the subsequent experiments. This is, perhaps, an unnecessary refinement in the case of a medium presenting such fine particles, though it would not have been so had they been as coarse as the grains of silver in a photographic negative, for in the last case a certain amount of light is lost through scattering. The annulus having been graduated, it became necessary to ascertain what *breadth* of annulus might be used so that no appreciable error might be incurred by reading the centre of the slit as the mean reading of the light passing through it. If the slit occupied 10° of the annulus, the light passing through the margins would be as 2051 to 1683, and the mean of these two would be 1867. The light passing through the centre of the slit would be in reality 1858 on the same scale. There would be, therefore, a difference between the mean of the marginal rays and that of the mean absorption of ·9 per cent.

If the breadth of slit occupied 5° of the annulus, the difference between the mean of the marginal intensities and that of the actual central intensity would be ·2 per cent. The true mean of all the rays would be less than these figures. A slit of 5° width would, therefore, be admissible to use as giving an error much less than that found in observations—as a matter of fact, the slit was always considerably narrower than this, so that no appreciable error can be found on this account.

4. *New Extinction Box.*

In Part III. of "Colour Photometry" a diagram is given of an "extinction box," and also of the curves of extinction of the visible spectrum for various classes of colour vision. For the greater part of the experiments the box was slightly altered, so far as regards the method of admitting the light.

Fig. 3.



At the end of the box, B, an aperture was cut, which was closed by a piece of glass, G, finely ground on each side, or by an opal glass. Provision was made for

the insertion of diaphragms, *d*, in front of the glass. The eye-piece, E, was at the opposite end of the box, as shown. Outside the box was a mirror, M, enclosed in a frame, as shown. The slit, S, in the spectrum and the collecting lens, L, together with the wedge, W, are shown in the figure. H is the handle used to move the annulus round its axis. This form of box only admits light through the end ; there is no reflected light in the inside. The one thing necessary is to secure a good scattering of light by the ground glass, so that the direct light is inappreciable compared with that scattered, a desideratum which is obtained by using glass ground on each surface. The box in which M is fixed is blackened, or lined with black velvet, and M itself can be either a silvered or plain glass. In the old arrangement the light entered from the side and by reflection, and after passage through ground glass illuminated a white disc at the end of the box. When the disc was of fair size any reflections from the black interior were extinguished long before the light from the disc itself vanished, and hence no inconvenience was felt from the presence of the light from the black interior, which may be taken as about $\frac{1}{30}$ of that reflected from the disc. If, however, the area of the white disc is very much diminished, the illumination, as will be seen presently, may be as much as 100 times greater than on the larger disc and yet be invisible, and then the reflection from the interior of the box would be visible after the extinction of light from the small disc was completed. For this reason the new form of extinction box was designed.

5. *Sensitiveness of the Retina to the Spectrum Colours with Varying Sizes of Image.*

The first series of experiments to be described, though not first in order of making, was to ascertain the sensitiveness of the eye to different sizes of image at the point of extinction. It has long been known that equally illuminated images on the retina, but of varying size, produced different sensations of brightness, but I am unaware of any exact measures of the difference. These I propose to give, and trust that they will be of use in studying the physiology of the eye. It was, of course, impracticable to use many eyes in this research, and I have been content with the observations made by myself and by my assistant, Mr. BRADFIELD, more especially as they were made quite separately, at different times, and are quite confirmatory of each other. The size of the image on the retina is best expressed in the angular measure which the object subtends outside the eye, and this plan I have adopted throughout. In Part III., "Colour Photometry," the extinction curves showed the absolute values of the light of the various parts of the spectrum, when just failing to impress the retina, in terms of a candle, and a change in the scale of ordinates several times in the same figure was necessitated. When the results of my first set of experiments were plotted with the angles of the annulus at which extinction occurred

as the ordinates, a much more convenient form of curve was obtained. As the angles are proportional to the logarithms of the extinction these latter were employed instead of the angles themselves, to enable the results obtained with any other wedge to be made comparable with those obtained with the new apparatus. For the sake of comparing the results of the extinction of the spectrum obtained in the former experiments, given in Part III., "Colour Photometry," the curve of the extinction for the normal eye was converted to a logarithmic curve, and the conversion will be found in Table II.

TABLE II.—Extinction by the Centre of the Eye, from Part III., "Colour Photometry."

Scale Number.	λ.	Reduction.	Log.	Scale Number.	λ.	Reduction.	Log.
64	7217	55,000	4·740	33	4963	10·2	1·009
63	7082	30,000	4·477	32	4924	11·6	1·064
62	6957	15,000	4·176	31	4885	13·6	1·130
61	6839	7,500	3·875	30	4848	16·3	1·212
60	6728	3,750	3·574	29	4812	20·5	1·312
59	6621	1,900	3·278	28	4776	26·0	1·415
58	6520	1,410	3·070	27	4742	31·0	1·491
57	6423	650	2·812	26	4707	38·5	1·585
56	6333	380	2·579	25	4674	46	1·663
55	6242	272	2·434	24	4639	56	1·748
54	6152	196	2·292	23	4608	67	1·826
53	6074	112	2·046	22	4578	80	1·903
52	5996	79	1·900	21	4548	95	1·978
51	5919	53	1·752	20	4517	107	2·029
50	5850	35	1·544	19	4488	124	2·093
49	5783	24	1·380	18	4459	140	2·146
48	5720	17	1·230	17	4437	160	2·204
47	5658	12·6	1·100	16	4404	180	2·255
46	5596	10·2	1·050	15	4377	200	2·301
45	5538	8·6	0·934	14	4349	220	2·342
44	5481	7·4	0·869	13	4323	240	2·380
43	5427	6·7	0·826	12	4296	270	2·431
42	5373	6·55	0·816	11	4271	300	2·477
41	5321	6·5	0·813	10	4245	335	2·525
40	5270	6·55	0·816	9	4221	375	2·574
39	5221	6·65	0·822	8	4197	430	2·633
38	5172	6·85	0·835	7	4174	490	2·690
37	5128	7·2	0·857	6	4151	560	2·748
36	5085	7·6	0·881	5	4131	640	2·806
35	5043	8·15	0·911	4	4106	750	2·875
34	5002	8·8	0·944				

When the ordinates of the curves are the logarithms of the actual values, the reduction in intensity of the same ray required to make it invisible under different conditions is readily seen. Thus, if two such curves are parallel to one another, we at once see that the intensities for all colours are proportionally reduced.

The first experiments were made with three illuminated circular discs, 2 inches, $\frac{1}{2}$ inch, and $\frac{1}{4}$ inch in diameter, and reduction necessary to cause invisibility (which in future will be called, as it was in "Colour Photometry," Part III., the "extinction") for different parts of the spectrum was noted for both. The angular measure of these discs was 4° 11′, 1° 3′, and 31′ respectively.

The following were the readings obtained. The scale of the spectrum has been reduced to the standard scale used in Part III., "Colour Photometry."

TABLE III.

Standard scale numbers.	2-inch disc readings.		$\frac{1}{2}$-inch disc readings.		$\frac{1}{4}$-inch disc readings.	
	Degrees.	Logs.	Degrees.	Logs.	Degrees.	Logs.
56·93	110	3·05	40	3·65		
55·82	125	2·83	71	3·38	20	3·83
53·60	198	2·30	139	2·81	80	3·31
51·38	235	1·93	180	2·45	128	2·90
49·16	277	1·62	220	2·11	160	2·69
46·94	310	1·34	250	1·85	187	2·36
44·72	331	1·15	275	1·63	215	2·15
42·50	345	1·05	290	1·51	230	2·02
40·28	345	1·05	285	1·55	225	2·07
38·06	340	1·07	281	1·57	221	2·09
35·84	335	1·12	275	1·62	218	2·12
33·62	320	1·24	255	1·81	195	2·22
31·40	300	1·42	240	1·93	180	2·45
29·18	280	1·59	230	2·02	165	2·58
26·96	265	1·74	207	2·22	150	2·71
24·74	240	1·94	180	2·45	130	2·88
22·52	215	2·15	154	2·68	110	3·05
20·30	205	2·24	145	2·75	92	3·24
18·08	193	2·30	137	2·81	80	3·31
15·86	180	2·45	115	3·00	60	3·48
13·64	162	2·61	96	3·17	45	3·61

All these readings were taken with the same intensity of light, and are, therefore, comparable with one another. These log readings were plotted, and freehand curves drawn through the points, and the following table constructed from them, the standard curve of extinction being added for comparison.

TABLE IV.—Obtained from the Freehand Curves drawn from Table III.

	λ.	Standard curve.	2-inch disc.	$\frac{1}{2}$-inch disc.	$\frac{1}{4}$-inch disc.		λ.	Standard curve.	2-inch disc.	$\frac{1}{2}$-inch disc.	$\frac{1}{4}$-inch disc.
60	6728	3·60				31	4885	1·15	1·43	1·90	2·42
59	6621	3·32				30	4848	1·22	1·55	1·97	2·50
58	6520	3·07				29	4812	1·31	1·58	2·06	2·57
57	6423	2·81	3·10	3·65		28	4776	1·41	1·62	2·12	2·62
56	6330	2·60	2·85	3·42	3·90	27	4742	1·50	1·75	2·18	2·72
55	6242	2·40	2·62	3·18	3·63	26	4707	1·58	1·82	2·35	2·82
54	6152	2·20	2·40	2·95	3·40	25	4675	1·66	1·90	2·43	2·92
53	6074	2 04	2·20	2·73	3·20	24	4634	1·75	2·02	2·52	2 97
52	5996	1·87	2·05	2·55	3·03	23	4608	1·83	2·07	2·60	3·02
51	5919	1·70	1·87	2·40	2·85	22	4578	1·91	2·15	2·65	3·07
50	5850	1·54	1·75	2·20	2·72	21	4548	2·00	2·20	2·70	3·15
49	5783	1·37	1·57	2·07	2·57	20	4517	2·05	2·28	2·77	3·20
48	5720	1·25	1·45	1·95	2·42	19	4488	2·09	2·30	2·82	3·27
47	5658	1·12	1·35	1·85	2·37	18	4459	2·14	2·35	2·90	3·32
46	5596	1·02	1·25	1·75	2·25	17	4437	2·20	2·40	2·95	3·40
45	5538	0·93	1·17	1·65	2·17	16	4404	2·25	2·50	3·00	3·47
44	5481	0·87	1·10	1·57	2·09	15	4377	2·30	2·54	3·06	3 53
43	5427	0·83	1·07	1·53	2·05	14	4349	2·34	2·57	3·15	3·58
42	5373	0·82	1·05	1·52	2·02	13	4323	2·38			
41	5321	0·815	1·045	1·52	2·02	12	4296	2·43			
40	5270	0·82	1·05	1·52	2·03	11	4271	2·48			
39	5221	0·825	1·05	1·53	2·05	10	4245	2·52			
38	5172	0·84	1·07	1·57	2·07	9	4221	2·57			
37	5120	0·86	1·09	1·58	2·08	8	4197	2·63			
36	5085	0·88	1·10	1·60	2·10	7	4174	2·69			
35	5043	0·91	1·15	1·65	2·14	6	4151	2·75			
34	5002	0·95	1·20	1·70	2·20	5	4131	2·80			
33	4963	1·00	1·25	1·77	2·27	4	4106	2·87			
32	4924	1·07	1·35	1·83	2·35						

These curves are shown on the diagram, fig. 4, and it will be evident that within the limits of error of observation they are parallel to one another. Had the same intensity of original light been used in these experiments as with the standard curve (viz., had the intensity of the light at D been equal to 1 amyl acetate lamp), Curve I. would have been superposed on Curve V., which is the curve of the standard extinction. The intensity of the D light actually employed was very closely $\frac{1}{17}$ of an amyl acetate lamp. The curves being very nearly parallel to one another show that the light has to be proportionally reduced throughout to cause extinction, and further that the smaller the angular aperture of the disc the less the reduction in the original intensity has to be. A reference to the results of further experiments, to be shortly given, will show that their distance apart has been correctly derived. As it might happen that the extinction of a point of light differed from one of very sensible size, a disc ·012 inch and subtending an angle of only 1′ 29″ was observed. The intensity of the spectrum had to be much

increased, and therefore the results given in Table V. can only be regarded as showing that even in this case parallelism to the other curves is obtained. The curve (IV.) is also shown in fig. 4.

Fig. 4.

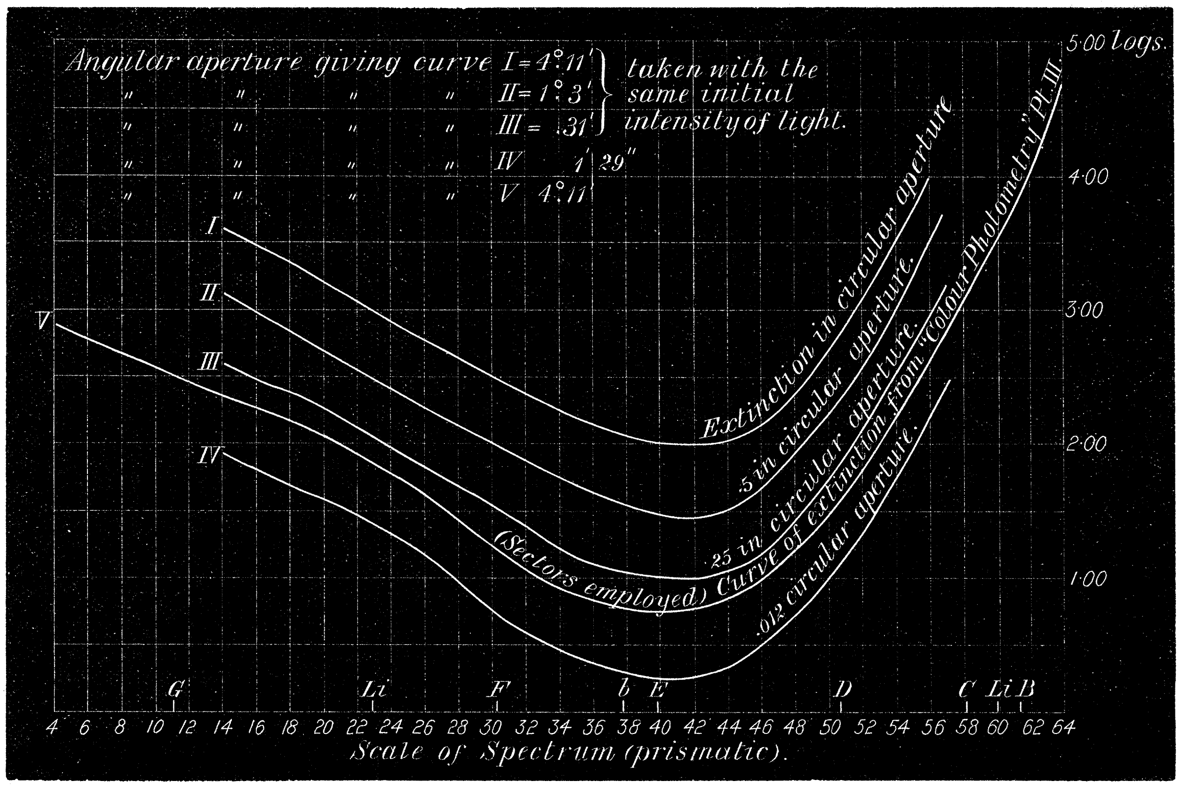


TABLE V.—Readings and logs with ·012 inch (1′ 30″) aperture.

Standard scale number.	·012-inch (1′ 30″) aperture readings.		Standard scale number.	·012-inch (1′ 30″) aperture readings.	
	Degrees.	Logs.		Degrees.	Logs.
58·57	60	3·50	34·15	295	1·46
56·35	90	3·23	31·93	280	1·59
54·13	140	2·80	29·71	260	1·76
51·91	190	2·37	27·49	240	1·94
49·69	250	1·85	25·27	210	2·19
47·47	275	1·64	23·05	185	2·41
45·25	298	1·40	20·83	175	2·50
43·03	310	1·33	18·61	155	2·68
40·81	320	1·25	16·39	135	2·84
38·59	320	1·25	14·17	127	2·94
36·37	314	1·30			

Some twenty-four series of observations with the spectrum were made with discs of different sizes, and all gave similar results to those tabulated, and hence we may fairly take it as proved that whatever the size of illuminated disc may be, all rays follow the standard curve of extinction, that is to say, that if with a disc of one size a green ray has to be reduced to $\frac{1}{1000000}$ of its original intensity to fail to stimulate the retina to cause a sensation of light, and with another smaller disc observed at the same distance to only $\frac{1}{500000}$, then every ray in the spectrum, when illuminating the same size of discs, will have to be reduced in the same proportion.

6. *The most Sensitive Condition of the Retina.*

In all observations of extinction, the greatest care must be taken to obtain the most sensitive condition of the eye, and I have found that it is useless to attempt any readings until the eye has been placed in darkness for at least twelve minutes. It is well to vary the plan of reading by first reducing the light till it disappears, and then to note the exact point when it reappears. The latter would be the best plan to use entirely, since the eye is in darkness till the very last part of the observation, were it not for the fact that, in noting the reappearance of the light, we are noting something less defined than when we are noting its disappearance. The combination of the two methods has been found to be the most satisfactory plan. A very great difficulty also often arises in keeping the axis of the eye employed in a line with the object observed, particularly when it is of very small angular aperture. It has been found advantageous to have a feeble light which can be flashed momentarily on the aperture to guide the eye just previous to the disappearance of the light. This is more particularly the case when it is desired to extinguish with the centre of the retina, as is the case in these observations. The intrinsic light in the eye is also sometimes difficult to deal with, but by judiciously recognizing the fact that it exists, and by giving proper intervals between each observation, one is enabled to surmount this difficulty. Again, a healthy state of mind and body is most essential when making observations, as the sensitiveness of the eye largely depends on it.

7. *Law Connecting the Angular Aperture with the Extinction.*

The next investigation carried out, was to ascertain if any law connected the angular aperture of the object observed with the diminution of the intensity of the light which was required to cause invisibility. For the purpose, a large number of diaphragms of very differing apertures were inserted in front of the ground glass (fig. 3). For the sake of plotting, in the first instance, and as they give the most rational scale, the diameters of the discs were expressed in powers of 2, thus $\frac{1}{2}$ inch, which is 2^{-1}, is used on the scale of abscissæ as -1; $\frac{1}{4}$ as -2, and so on—all diameters not being expressed in exact powers of 2 being calculated out in the ordinary way.

The following are the values, in inches, of the apertures used, and in powers of 2, and the angles they subtended at the distance from which they were observed :—

Diameter in inches.	Angles subtended.	Value in powers of 2.
2·0	4° 11′ 0″	+1·0
1·50	3 8 0	+0·6
0·94	1 57 0	−0·09
0·725	1 30 0	−0·48
0·525	1 5 0	−0·93
0·42	0 52 35	−1·25
0·35	0 43 43	−1·52
0·30	0 37 33	−1·74
0·17	0 21 17	−2·56
0·086	0 10 46	−3·56
0·036	0 4 30	−4·81
0·012	0 1 30	−6·40

These diaphragms were placed in front of the ground glass, and the light from the discs thus formed, extinguished. In the first set of experiments, the pure colours of the spectrum were employed; whilst in the others, ordinary lamp light and lamp light screened with different colour glasses or solutions were used, and identical results were found in all cases. The following tables are made from the mean readings, and the diagram shows them plotted :—

Fig. 5.

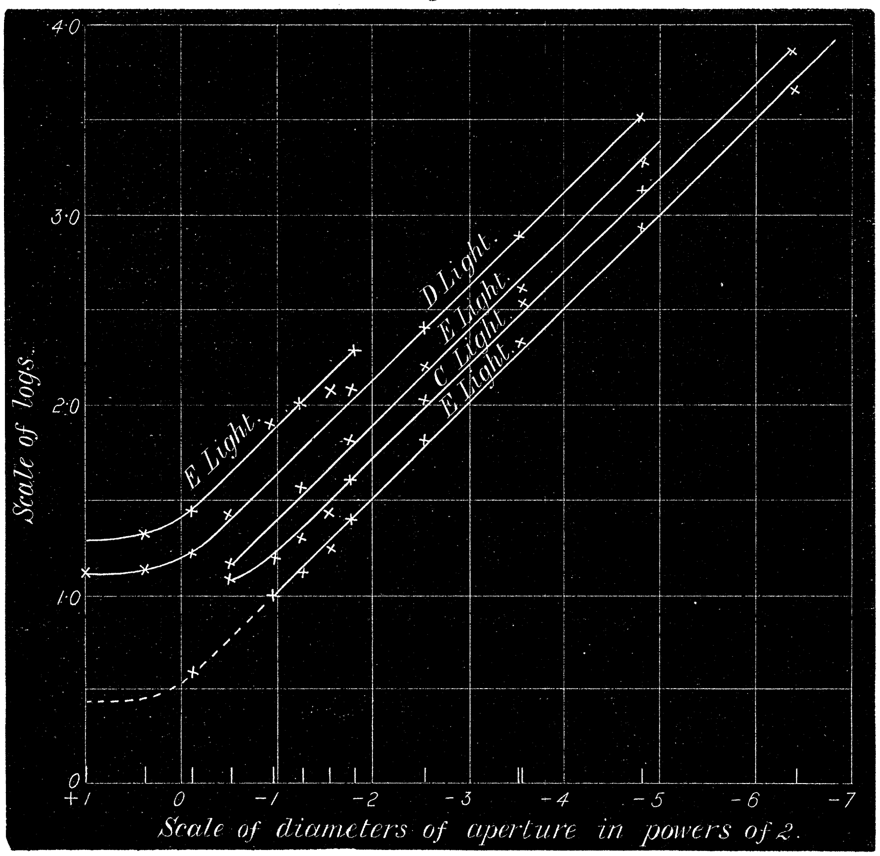


TABLE VI.—Extinctions with Apertures of Different Sizes.

E light.			
Diameter.	Diameter in powers of 2.	Reading.	Log.
inches.			
0·725	−0·48	331	1·17
0·42	−1·25	285	1·55
0·30	−1·74	255	1·81
0·17	−2·56	209	2·20
0·086	−3·56	163	2·60
0·036	−4·81	85	3·27

C light.			
Diameter.	Diameter in powers of 2.	Reading.	Log.
0·725	−0·48	340	1·076
0·525	−0·93	325	1·20
0·42	−1·25	312	1·30
0·35	−1·52	300	1·42
0·30	−1·74	275	1·63
0·170	−2·56	230	2·02
0·086	−3·56	178	2·57
0·036	−4·81	100	3·14
0·012	−6·40	15	3·85

E light.			
Diameter.	Diameter in powers of 2.	Reading.	Log.
2·00	+1·0	315	1·29
1·50	+0·6	315	1·29
0·94	−0·09	303	1·39
0·525	−0·93	245	1·89
0·42	−1·25	234	1·98
0·35	−1·52	220	2·11
0·30	−1·74	200	2·28

E light.			
Diameter.	Diameter in powers of 2.	Reading.	Log.
inches.			
0·94	−0·09	above 360	
0·725	−0·48	,,	
0·525	−0·93	352	1·00
0·42	−1·25	335	1·12
0·35	−1·52	323	1·22
0·30	−1·74	303	1·39
0·170	−2·56	255	1·81
0·086	−3·56	195	2·32
0·036	−4·81	123	2·94
0·012	−6·40	39	3·67

D light.			
Diameter.	Diameter in powers of 2.	Reading.	Log.
2·00	+1·0	335	1·12
1·50	+0·6	332	1·13
0·94	−0·09	325	1·20
0·725	−0·48	300	1·42
0·30	−1·74	223	2·08
0·170	−2·56	185	2·40
0·086	−3·56	132	2·87
0·036	−4·81	55	3·51

The indications here given are that (fig. 5) the curves with apertures less than $1\frac{1}{2}$ inch diameter become straight lines, all of which are parallel, and it is somewhat remarkable that from that point the intensity of a light which will be just extinguished with a certain diameter of aperture may be increased 10 times, and yet be invisible when an aperture with $\frac{1}{4}$ of that diameter is employed; if the intensity of the light be increased 100 times, we have only to diminish the diameter of the aperture to $\frac{1}{16}$, and it will again disappear. (It may be noted that in the lowest curve the dotted portion is taken from the two top curves.) The equation connecting the two has the form of $I = x^m$, where m is determined by the slope of the line and the log 2.

We shall see further on that connection between the intensity of the light

just necessary to fail to produce the sensation of colour takes the same form, the exponential coefficient being changed. The connection between star magnitudes and the intrinsic brightness of a measurable disc of the same brightness and colour will have the same form.

8. *The Extinction Dependent on the Least Diameter of the Aperture.*

There is a peculiarity in the result, in that it looks as if the diameter of the aperture and not its area, determined the intensity of the light required to be extinguished. A very ready way of ascertaining this was to use an adjustable slit, and to take the extinctions with varying apertures. In such a case the length of the slit would remain constant, whilst the width alone would vary. If it were the latter that determined the extinction there can be but little doubt that the area of the object played at all events a secondary part; for in the case of the circular apertures the areas would be as the squares of the diameters, whilst in the latter they would be as the width of the aperture. A slit from a spectroscope was employed which increased in aperture $\frac{1}{50}$ inch for each complete revolution of the screw. The head of the screw was divided into twenty-five divisions, so that five divisions on the screwhead opened the aperture ·004 inch, the smallest aperture employed was ·00155 inch and the largest ·06555. Intermediate apertures were also used, and extinction of white light and red light noted.

The following table gives the results of the measures, the apertures being put in powers of 2 :—

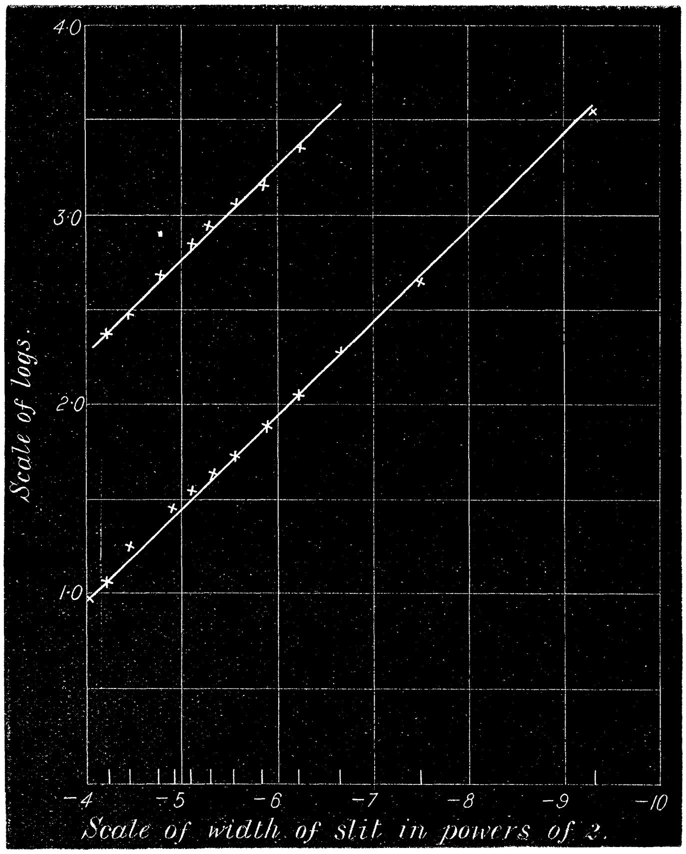
TABLE VII.

White light.				Red light.			
Absolute width in inches.	Width in powers of 2.	Readings.		Absolute width in inches.	Width in powers of 2.	Readings.	
		Degrees.	Logs.			Degrees.	Logs.
0·06155	−4·02	350	0·99	0·05355	−4·22	192	2·35
0·05355	−4·22	342	1·06	0·04555	−4·46	176	2·45
0·04555	−4·46	323	1·23	0·03755	−4·73	154	2·68
0·03355	−4·90	298	1·44	0·02955	−5·08	135	2·84
0·02955	−5·08	285	1·55	0·02555	−5·29	124	2·94
0·02555	−5·29	275	1·63	0·02155	−5·53	110	3·05
0·02155	−5·53	267	1·72	0·01755	−5·83	98	3·16
0·01755	−5·83	250	1·85	0·01355	−6·20	76	3·35
0·01355	−6·20	228	2·04	0·00955	−6·67	50	3·57
0·00955	−6·67	202	2·26				
0·00555	−7·49	156	2·67				
0·00155	−9·33	54	3·53				

The results are plotted diagrammatically in fig. 6, from which it will be gathered that again the curve is a straight line in each case, and that the ordinates bear the

same relation to the abscissæ that they did in case of circular apertures. We may therefore presume, with a considerable degree of certainty, that it is the width of the aperture, horizontal or vertical (for the experiments were repeated in both directions), that governs the extinction. These results, it will at once be seen, have an important bearing on spectroscopic work, and the invisibility of lines when the light is feeble.

Fig. 6.



Taking into consideration the extinction curve of the spectrum, and these results, we can see how the green lines of a feeble spectrum will be the first to be seen (perhaps colourless), whilst others, though present, will fail to be seen except with a very wide slit.

A further experiment was made which confirmed the previous measures. The extinction of the light from a circular, a square, and a rectangular aperture of the same area was made. The circular aperture had a diameter ·94 inch, the sides of the square were ·84 inch, and of the oblong 1·68 × ·42 inch. In addition, an oblong aperture ·84 × ·42, exactly half the latter, was also used.

The following are the results of the extinction, and in the last column are given the results that would have been obtained from the curves already described:—

TABLE VIII.

Aperture.	Width of powers of 2.	Readings.		Logs from diagram.
		Degrees.	Logs.	
Circular disc, ·94 inch diam.	— ·09	234	1·98	1·98
Square, ·84 inch side	— ·25	216	2·14	2·15
Rectangle, 1·68 × ·42 inch	— 1·25	152	2·69	2·65
Rectangle, ·84 × ·42 inch	— 1·25	154	2·68	2·65

Remarks on this table seem unnecessary, as they so plainly indicate the guiding factor in the extinction.

This, perhaps, is one of the most curious results that have been obtained, for it is hard to conceive that the area of the retina impressed should not be a factor. The experiments clearly show that the estimate of small intensities of light by their effect on the light-perceiving apparatus is not a simple matter. The extinction of comparatively larger areas of light is most instructive. The light from a square, or a disc, or an oblong, just before extinction, is a fuzzy patch of grey, and appears finally to depart almost as a point. This can scarcely account for the smallest width of an illuminated surface determining the intensity of the light just not visible; but it tells us that the light is still exercising some kind of stimulus on the apparatus, even when all sensation of light is gone from the outer portions. The fact that the disappearance of the image takes place in the same manner, whether viewed centrally or excentrically, tells us that this has nothing to do with the yellow spot or fovea, but is probably due to a radiation of sensation (if it may be so called) in every direction on the retinal surface. Supposing some part of the stimulus impressed on one retinal element did radiate in all directions over the surface of the retina, the effect would be greatest in the immediate neighbourhood, and would be inappreciable at a small distance, but the influence exerted upon an adjacent element might depend not only on its distance, but also upon whether it was or was not itself exerted independently. Following the matter out further, we should eventually arrive at the centre of an area, being the part which was the recipient of the greatest amount of the radiated stimuli, and consequently that would be the last to disappear. With a slit aperture, the slit is visible till extinction is very nearly executed, but it finally merges into a fuzzy spot at the moment before it finally fails to make any impression of light.

9. *Extinction of Light Excentrically.*

A further investigation into the extinction of light at different angular distances from the centre of the eye was attempted. The experiments are of a very difficult nature, and it requires long practice to enable a satisfactory series to be made.

The method adopted was to place pins with heads painted with Balmain paint at every 5° from the central line joining the illuminated aperture and the position occupied by the eye. The paint was very feebly phosphorescent, and only just sufficient to fix the centre of the eye at the required angle from the object. The results of two experiments, red and white light (paraffin), at 10° are given. It appears from these that at this angular distance the extinction of all light from the red takes place when the light is about one-third brighter than is required for the centre of the eye. With the paraffin light it is somewhat less. With green light about E, and with blue at the lithium line, the necessary reduction of the light is greater than for the centre of the eye, a result already shown in "Colour Photometry," Part III.

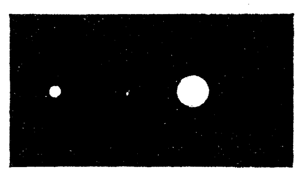
TABLE IX.

Aperture.	Angle.	2^{-x}.	Red light.		White light.	
			Direct.	10° from axis.	Direct.	10° from axis.
0·940	1° 57′ 0″	0·09	275	255	305	290
0·724	1 30 0	0·48	252	230	270	265
0·525	1 5 0	0·93	225	204	265	240
0·420	0 52 35	1·25	217	195	252	230
0·350	0 43 43	1·52	195	174	235	220
0·300	0 37 33	1·74	185	162	215	200
0·170	0 21 17	2·56	152	125	174	157
0·086	0 10 46	3·56	93	75	118	105

There is a further falling-off of sensitiveness at greater angles than those shown in the tables, but the extinction is very difficult to make with certainty.

10. *Luminosity of the Light coming through different Apertures.*

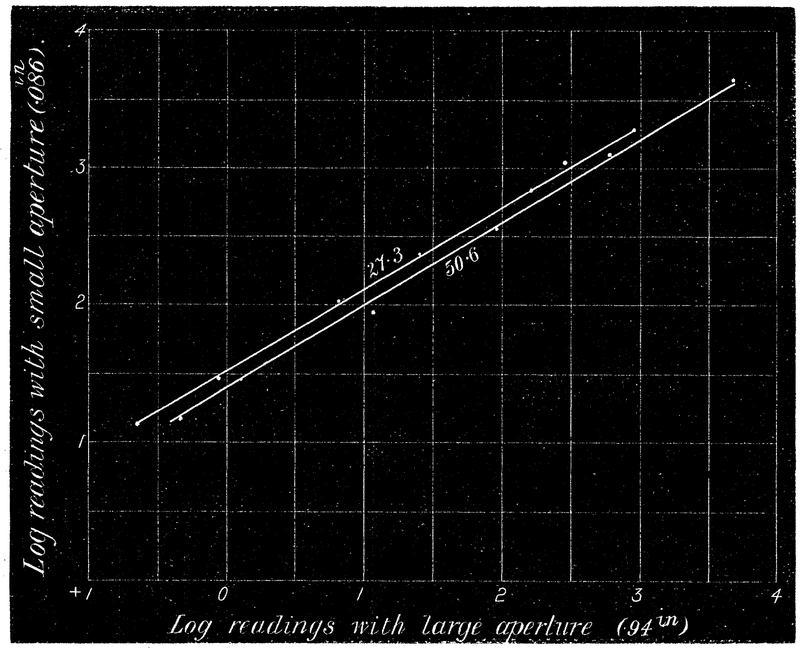
The next point investigated, but without any great degree of detail, was the comparative luminosities of the same light coming through two apertures of different diameters. The method adopted was as follows:—The ground glass was illuminated uniformly with the light to be tested, and two apertures cut in a black mask were placed in contact with it, as shown. Sectors were placed close behind the larger aperture, and rotated with angular apertures of any desired amount. In front of the slit of the spectrum the annulus was placed so that a regular diminution of the light could be effected. The sectors having been set at 90°, the light coming through the bigger aperture was diminished to half. As the light coming through the small aperture is extinguished long before that coming through the larger one, there must be some intensity of light when the two apertures will appear equally bright to the eye in the extinction box. The light



coming through the slit is, therefore, diminished till the two appear equally bright. The diminution of light is noted, that coming through the larger aperture being diminished twice as much as that coming through the smaller. The sectors are again set at 45°, and the same procedure adopted as before.

Table X. gives the measurements thus made, and fig. 7 shows them diagrammatically. The ordinates are the intensities of light of the large aperture. These are derived from the value of diminution of the light falling on the ground glass, together with the reduction due to the sectors. The latter is converted into the degrees of the annulus and added to that by which the light has been diminished before falling on the plate. The abscissæ show the values of the reduction of the light on the smaller aperture. Both the annular values are shown as logarithms. Again, the resulting curve is for a large part of its length a straight line. Each aperture has its own

Fig. 7.



inclination and is determined by the extinction values of the two apertures. In making these determinations the eye has to judge the brightness of very dissimilar sizes of area, and it might be thought that this fact would present an almost insuperable difficulty in making very accurate measures. As a matter of fact, it was not so; the greatest difficulty was encountered in those cases when the light of the large aperture was so diminished that it became colourless, whilst the other had very nearly its original tint. The red was perhaps the hardest to judge on that account; the other colours did not present any great difficulty. One of the curious phenomena encountered in these measures at times was a distinct scintillation of the light emitted by the small aperture. Sometimes this was perplexing, but never to the extent to render the comparisons uncertain.

TABLE X.

Sector in degrees.	Equivalent values of annulus.	Scale number, 27·3.				Scale number, 52·8.			
		Readings of apertures.				Readings of apertures.			
		S.	L.	Logs.		S.	L.	Logs.	
				S.	L.			S.	L.
180	0	..	..	..	..	..	..	..	..
90	35	90	125	3·23	2·92	100	135	3·14	2·84
45	70	140	210	2·80	2·19	185	255	3·42	1·80
22·5	105	200	305	2·28	1·38	270	380	1·68	·73
11·25	140	230	370	2·02	·82	305	445	1·38	·17
5·6	175	295	470	1·46	— ·04	310	520	1·33	— ·47
Extinction	200	325	525	1·21	— ·51	340	540	1·08	— ·64

Sector in degrees.	Equivalent values of annulus.	Scale number, 44.				Scale number, 50·6.			
		Readings of apertures.				Readings of apertures.			
		S.	L.	Logs.		S.	L.	Logs.	
				S.	L.			S.	L.
180	0	0	0	4	4	40	40	3·66	3·66
90	35	40	75	3·66	3·35	110	145	3·05	2·75
45	70	110	180	3·05	2·45	170	240	2·54	1·94
22·5	105	200	305	2·28	1·38	240	345	1·94	1·03
11·25	140	260	400	1·76	·56	300	440	1·42	·22
5·6	175	310	485	1·33	— ·17	330	505	1·16	— ·34
Extinction	200	350	550	·99	— ·73	340	540	1·08	— ·64

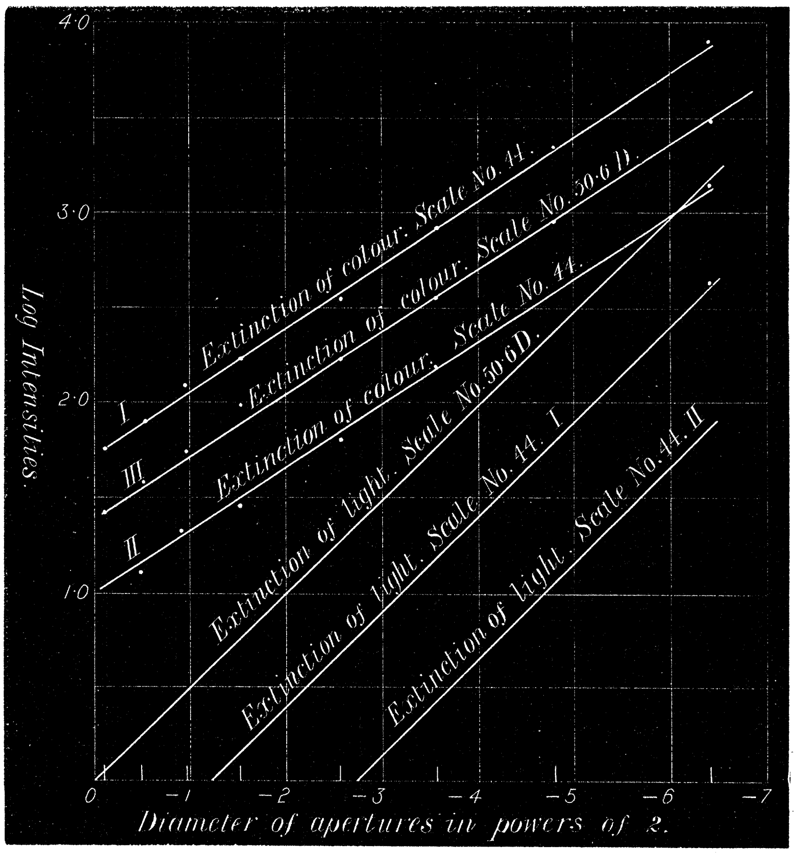
N.B.—S. and L. refer to the small and large aperture respectively. From fig. 5 it is found that the extinction value of the larger aperture, ·94 diameter, requires 200° more of the annulus to extinguish it than the smaller aperture ·086 diameter. This accounts for the last line in the table.

Fig. 7 shows the logarithm of the readings of S. N. 27·3 in the blue and S. N. 50·6 in the orange (D.). The other series of readings are so close to the above that they are omitted.

11. *Extinction of Colour from Spots of different Diameters.*

Following on the extinction of light came the investigation of the loss of colour from areas of varying angular aperture. In Part III. of "Colour Photometry," a method was described of estimating the point where all colour disappeared. In that paper no reference was made to the size of the area under examination, it being greater than the 4° diameter, and all apertures greater than this, as we have seen, behave alike. In this investigation a somewhat different method was adopted. Two apertures were placed side by side and a very feeble white light from the arc light

Fig. 8.



was caused to illuminate one aperture, while the colour under examination filled the other. The two were darkened together and the point of diminution where they perfectly matched in tint was taken as the point at which the colour of the latter vanished. It was very necessary to make the apertures of equal area and equally bright, as, if not, the measurements became more difficult. A large number of different rays were examined, with the centre of the retina, for colour persistency in this way, but the following will suffice to show that the colour extinction does not follow that of the light extinction when regard is had to the sizes of the apertures

employed. In this case the intensity of the light to cause a loss of colour has to be increased tenfold, whilst the aperture is diminished to $\frac{1}{8}$ in diameter. In the extinction of light the same increase in intensity only requires a diminution to $\frac{1}{4}$ the diameter.

This seems to show that the stimulus required to produce colour is of a different order from that required to produce light. These experiments apply equally to all colours, and therefore to the sensations producing them, and if, as in the HERING theory, there is a black-and-white sensation co-ordinate with the red-green and yellow-blue sensations of light, the extinction of the white sensation ought to follow the same curve as that of the other sensations.

The following table gives examples of the extinction of colour. (See fig. 8.)

TABLE XI.

Diameter of aperture.	Diameter in powers of 2.	I.		II.		III.		Remarks.
		Reading.	Log.	Reading.	Log.	Reading.	Log.	
0·94	− ·09	260	1·76	350	0·99	300	1·42	Extinction of ·012 aperture in I., II., III. were in Logs. 2·62, 1·85, and 1·25 respectively; this would make the extinction of ·94 aperture $\frac{1}{200}$, that of the colour extinction ·2 for I., II., and for III., $\frac{1}{28}$. In Colour Photometry, Part III., they were $\frac{1}{130}$ and $\frac{1}{26}$ respectively.
0·724	− ·48	245	1·89	335	1·12	280	1·59	
0·525	− ·93	220	2·11	310	1·33	260	1·76	
0·35	−1·52	210	2·19	295	1·46	235	1·98	
0·17	−2·56	170	2·54	255	1·80	205	2·235	
0·086	−3·56	125	2·925	210	2·19	170	2·54	
0·036	−4·81	75	3·355	155	2·66	120	2·97	
0·012	−6·4	10	3·91	100	3·14	60	3·48	

Nos. I. and II. are the same ray (44 on the scale), but with different intensities. No. I. was measured by myself, and No. II. by Corporal ATTEWELL. No. III. was read by myself, and was D in the spectrum or scale No. 50·6. It may be remarked that with the small apertures the extinction of colour in the red was impracticable, as the extinction of light and colour took place together, as it should do according to other experiments.

12. *Colour Fields and Perimeters.*

An enquiry was next undertaken as to the variation in the extent of colour fields under different conditions of light. The question of colour fields is one regarding which much has been written, and experiments on the subject have been numerous, but with one or two exceptions it is believed that these latter have been carried out

with pigment colours, which, from their nature, are impure. In the ordinary methods pursued the knowledge that is gained is slight compared with the trouble involved, and the colours selected have been based on the assumption that HERING's theory of colour vision is one that has been thoroughly established; experiments from which a great deal more may be learnt have been neglected or overlooked. I refer especially to the measurements of colour fields, where the colours used are pure spectrum colours. In these the colour may be isolated and viewed against a black background, as for instance, by throwing a spot of light of any desired colour on a white surface in a dark room. This is a very different condition to that which obtains in the ordinary procedure, when the retina receives not only the colour of the pigment but also is illuminated by extraneous light. In the experiments to be described, two kinds of perimeters were employed. One was the ordinary form but modified for use in a dark room. The arc, which subtended a semicircle, was internally coated with white, on which degrees were marked at the boundaries, and just below the eye was a small mirror on a ball and socket joint, which, by means of an arm, would cause a beam of light falling on it to be cast in any direction desired. Thus it could be caused to travel along the arc, which might be placed at any angle with the vertical. The light employed was that coming from the spectrum of an electric arc light, the crater of the positive pole being the source from which the spectrum was formed. The colour patch apparatus was employed to get a surface of monochromatic light, as described in Part II. of "Colour Photometry." A spot of light of any desired form or size was obtained by the plan described in my recent paper in the 'Proceedings of the Royal Society' "On the Formation of Monochromatic Images." The light issuing from the slit in the spectrum could be altered in intensity (1) by closing or opening that slit, (2) by placing the annulus already described in front of it, (3) by closing the slit of the collimator, (4) by using rotating sectors in front of either slit.

In the second form of perimeter a hollow white hemisphere made of "papier mâché" was employed. The centre of the surface was pierced with a circular aperture some $1\frac{1}{2}$ inches in diameter. This aperture was closed by a doubly-ground glass, and outside the shell apertures of any desired shape or dimensions could be placed in contact with the ground glass. The colour patch apparatus was caused to throw the patch of colour on to the ground glass, and when the last was removed the patch of white that the combining lens cast when the whole spectrum was uncovered fell upon the eye when placed at the centre of the hemisphere, thus insuring that every ray was equally received on the pupil when the ground glass was again interposed. It may be stated here, once for all, that when light falling on the ground glass was measured, by placing a white card in its place and balancing it with an amyl-acetate lamp, it was found that the brightness of the ground glass as seen from the centre of the hemisphere was within a very small fraction, twelve times that which was reflected from the white card.

The hemisphere was furnished with a chin and cheek rest, which would move round a vertical axis. It was divided internally into degrees. The eye was directed to any part of the surface by means of a small phosphorescent bead at the end of a stick; and a small electric lamp, which could be switched on by a simple movement of the hand, gave light sufficient to read the position occupied by the bead at any desired instant. The intensity of the light illuminating the ground glass was altered by any of the four methods mentioned above. The annulus was usually employed to effect the alteration, and it could be rotated at the will of the observer by a long handle attached to the rack and pinion motion of the rotating gear.

13. *Similarity of Fields for Different Colours.*

The order in which the experiments were made will not be followed, for, as a matter of fact, amongst those to be first described some were among the latest, and others among the earliest made. It was essential to know whether the fields for each colour were of the same form when the illumination was so adjusted that one point in a field of one colour coincided with one point in the field of a different colour. The following two sets of observations made by myself, and the succeeding ones made by one of my assistants (W. B.), will give the answer to the inquiry.

An aperture of ·525 inch subtending an angle of 2° 30′ was inserted behind the ground glass, and the light falling on the eye when D was the ray selected, was 4·5 amyl-acetate lamps at 1 foot. (In future this light will be designated as AL, and this particular illumination would be 4·5 AL.)

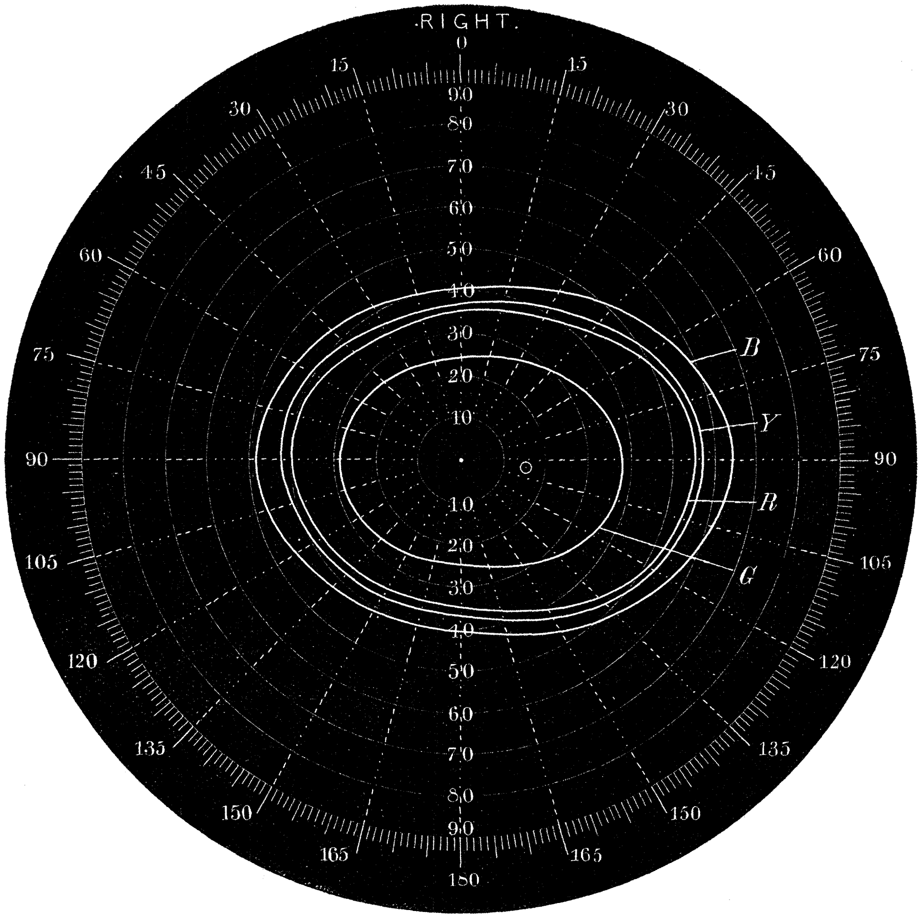
The following rays were used to illuminate the aperture: red lithium (λ 6705) D (λ 5892), a ray having the standard scale number ·36 (λ 5085), and the blue lithium ray (λ 4603). These had respectively the luminosities of ·3, 4·5, 2·1, and ·4 AL.

The measures were made with the right eye (see fig. 9).

TABLE XII.

Angle of field in degrees.	Extent of fields in degrees.			
	Red Li.	D.	SN 36.	Blue Li.
0	35	36	24	40
30 T.	37	40	27	47
60 T.	47	50	33	57
90 T.	55	57	38	65
120 T.	51	53	36	60
150 T.	41	43	29	50
180	34	36	25	40
150 N.	35	36	26	40
120 N.	37	38	27	45
90 N.	40	42	28	49
60 N.	38	40	27	45
30 N.	34	36	25	42

Fig. 9.



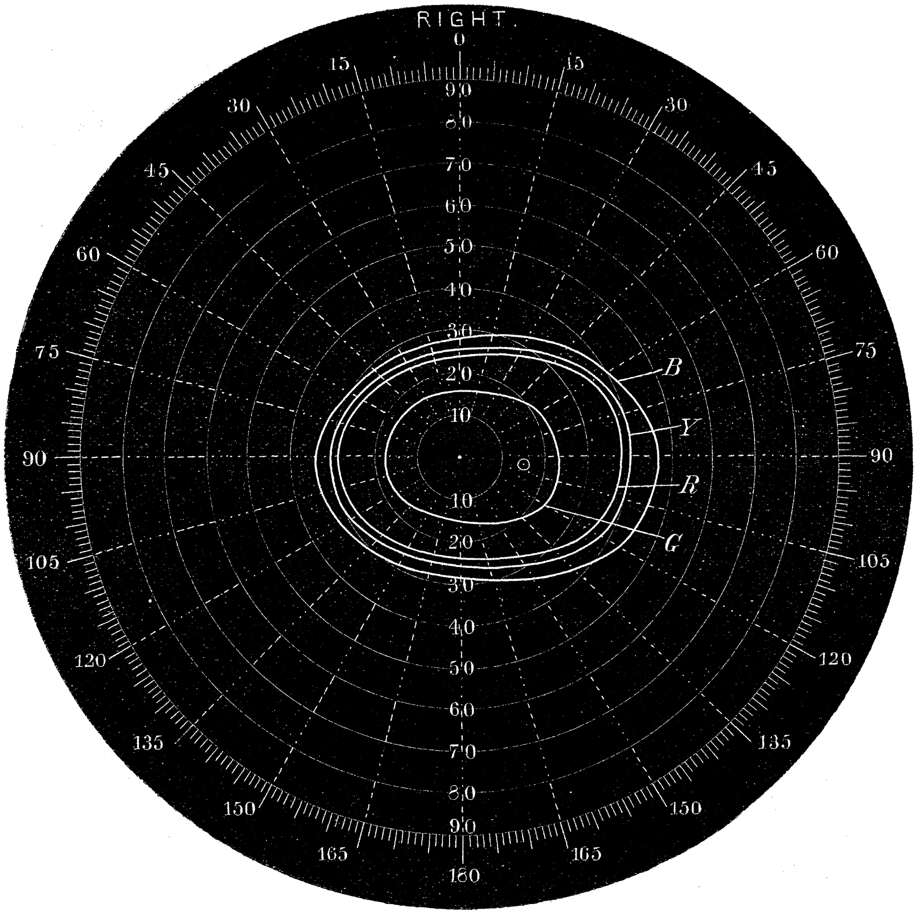
In the following observations the illumination by the D light was much reduced, being only ·23 AL, and for certain reasons, which will be apparent, the ray at scale number 41·7 was substituted for that at scale number 36. The other three rays were the same as before (fig. 10).

TABLE XIII.

Angle of field in degrees.		Extent of fields in degrees.			
		Red Li.	D.	SN 41·7	Blue Li.
0		23	25	15	28
30	T	28	27	16	32
60	T	35	37	21	40
90	T	38	40	23	47
120	T	35	37	22	42
150	T	27	30	18	35
180		23	25	16	28
150	N	25	26	16	29
120	N	28	30	18	32
90	N	29	30	18	34
60	N	26	27	17	30
30	N	23	25	16	28

Taking these sets of observations separately, the diagrams show that the fields for properly selected luminosities are evidently the same, the D and red lithium being very close to one another. If we compare the fields for the D and red lithium rays in the second table with that of the field for the green (S.N. 36) in the first table, we shall see that they are practically identical.

Fig. 10.



The next measurements were made by my assistant, and, since, as before stated, his colour fields differ considerably from my own, the confirmation obtained by his measurements appears very conclusive. They were made for illustrating a different part of the research, but they will be given here and referred to subsequently. Two places in the spectrum were selected, such that the two rays when combined would give white light, the white being that of the electric light, which is indistinguishable from the sensation produced by the coloured rays when falling on the peripheral portions of the retina. The first positions selected were in the red and green, at λ 6500 and λ 5002, corresponding to the scale of the spectrum with the numbers 57·8 and 34. The relative luminosities of the rays reaching the eye were 225 and 270 respectively.

Two other positions were chosen in the yellow-green at (λ 5614), and in the blue (λ 4603), corresponding to the scale numbers of the spectrum 46·3 and 22·8. The relative luminosities of the rays transmitted to the eye were 96·5 and 21·5 respectively.

The colour field for each of these four colours was taken with the left eye, and the following table shows the results (fig. 11) :—

TABLE XIV.

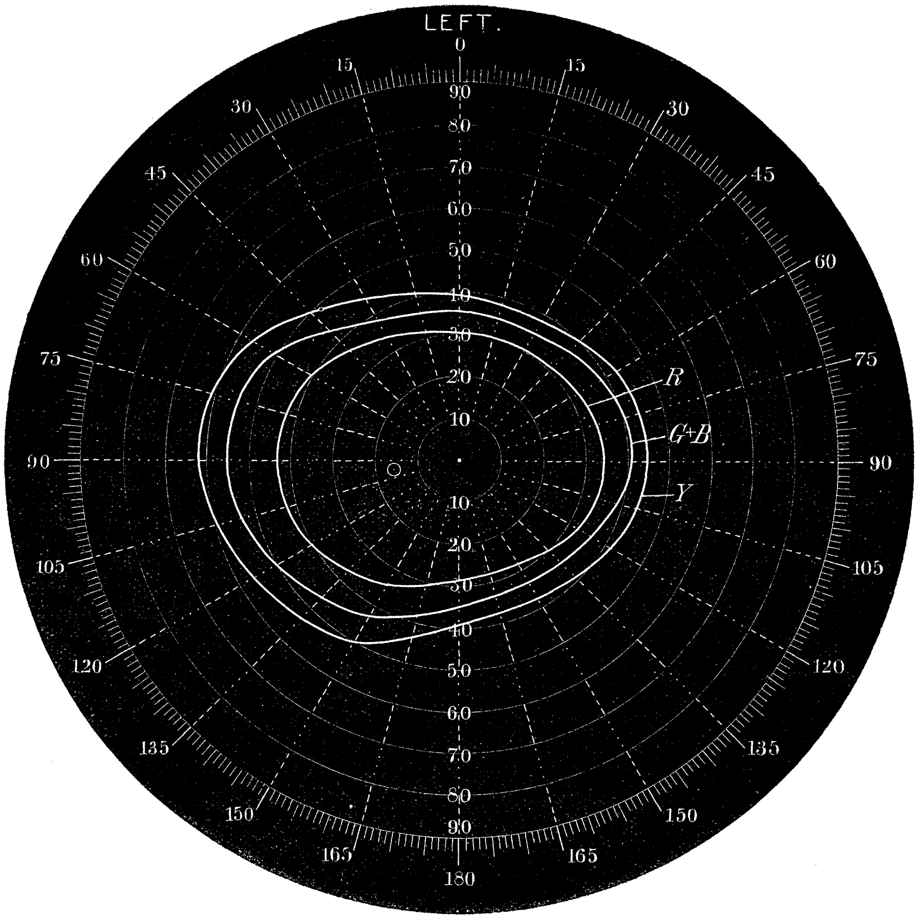
Angle of field in degrees.	Extent of fields in degrees.			
	Red.	Green.	Yellow-green.	Blue.
0	30	35	39	36
30 N	28	34	37	35
60 N	31	37	42	38
90 N	33	40	44	41
120 N	32	36	42	37
150 N	28	34	38	34
180	29	35	39	36
150 T	34	43	50	44
120 T	40	50	57	50
90 T	43	55	62	55
60 T	41	51	56	50
30 T	33	38	43	39

Here we have two fields, the green and the blue, which are practically identical, showing that the limits of the boundaries are not affected by the hue, though, of course, the illumination is very different in the two cases. Attention must here be drawn to the fact that, though, according to HERING's theory, the fields of the dissimilation colours ought to be both external, or else both internal, to the fields of the assimilation colours, they differ in each pair, and the frequency of similar want of accordance has been very generally met with.

14. *Fields of Impure or Mixed Colours.*

When considering the question of the fields of mixed colours, such as those produced by pigments, it became apparent that a crucial test as to their efficiency might be made by mixing colours of the spectrum together to imitate some single spectrum colour, and, after making the mixture of the same luminosity, to compare the fields. With this in view, a red and green, near E, were mixed together to match the D light in hue and in intensity. The fields for each colour, including D, were taken, as also was that of the mixed colours.

Fig. 11.



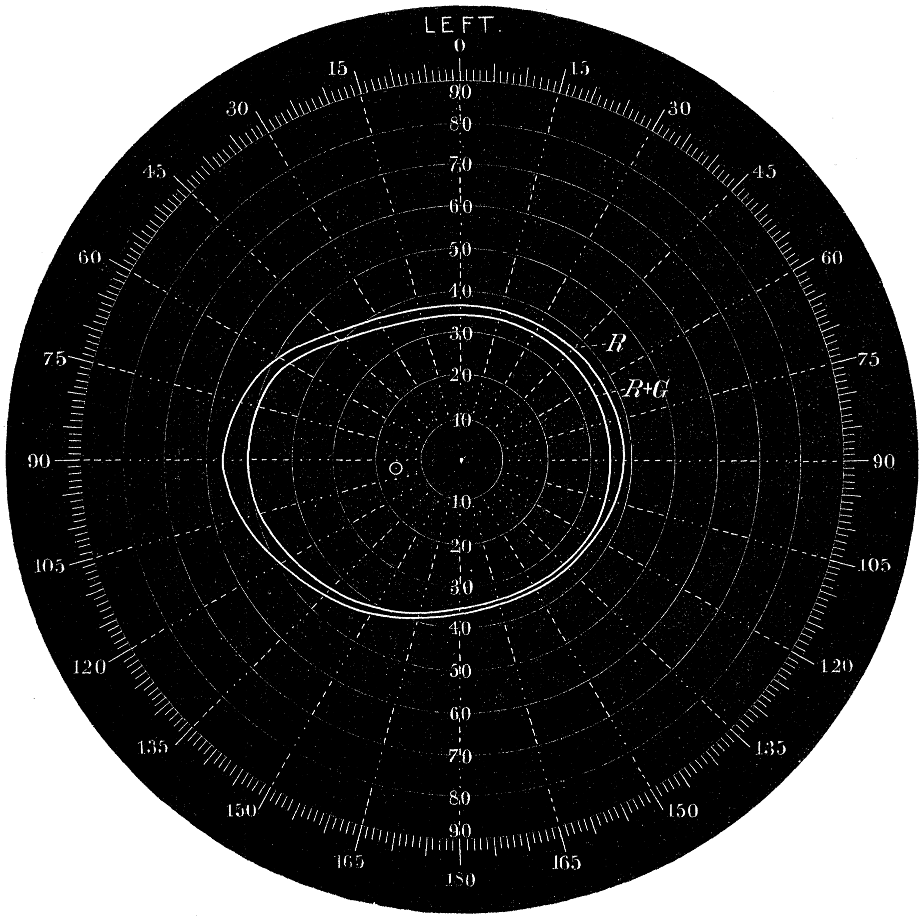
The following table gives the results :—

TABLE XV.

Angle of field in degrees.	Extent of field in degrees.			
	Red.	Green.	G + R.	D.
0 N	35	36	33	38
30 N	35	35	33	36
60 N	36	36	35	39
90 N	39	41	37	43
120 N	37	38	37	42
150 N	35	35	34	37
180	37	38	35	38
150 T	43	46	40	47
120 T	49	51	45	50
90 T	56	58	50	61
60 T	50	52	46	53
30 T	39	40	35	42

These colour fields all have the same shape (see fig. 12). They do not cut one another, and if we compare the fields of the red and the green with those of the green and the blue in the previous table, we shall see that they practically coincide. Thus the fields of a red, two greens and a blue, are the same when proper luminosities are taken for each. Before leaving this table, it is well to point out that the field for D

Fig. 12



is considerably more extended than that of the mixed colours, as are also the fields for green and red separately. We may conclude that the intrinsic white light in each colour, when added together, is greater than the intrinsic white light in the D ray. This points to the fact that the colours of pigments should not give the same fields as the spectrum colours with which they approximately match.

15. *Connection between Change of Intensity of Colour and Extent of Field.*

The difference in extent of field, caused by difference in illumination, was next determined in the horizontal directions. The four rays, red lithium, D, scale No. 41·7 in the green, and the blue lithium, were experimented with as fairly representative of

the whole spectrum. The different rays were first allowed to pass through the annulus at 0°; and, subsequently, measures were made after passing through it, when its readings were 35, 70 . . . 280°, as every added 35° halved the previous intensity. The D light coming through the slit with the annulus at 0°, measured 4·5 AL. The following were the luminosities of the other rays coming through the same slit: red lithium, ·5 AL; SN 41·7, 3·2 AL; and blue lithium, ·3 AL (fig. 13).

Table XVI.

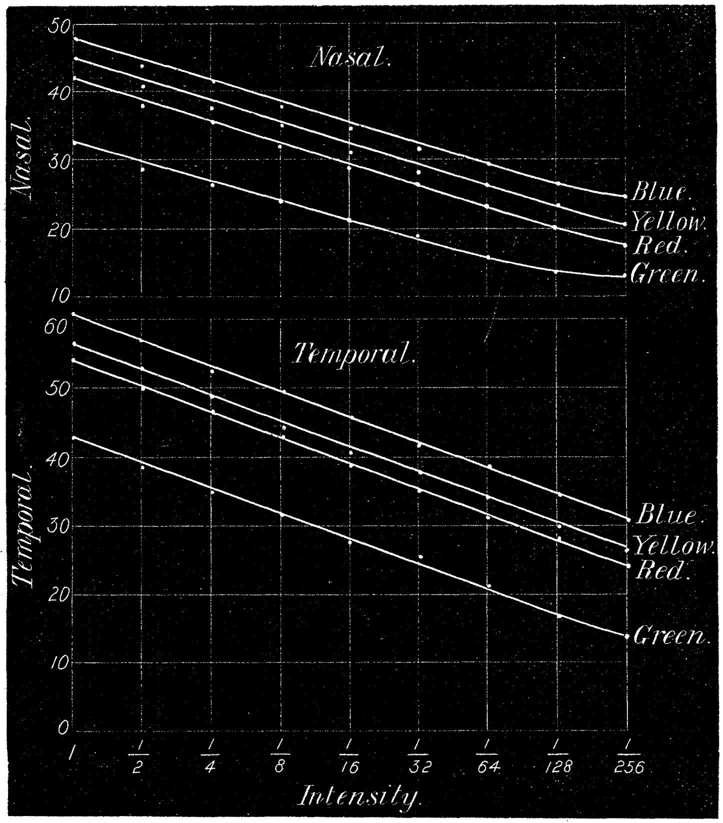
Degrees annulus.	Intensity of ray.	Reading of horizontal field in degrees.							
		Red Lithium.		D.		Scale No. 41·7.		Blue Lithium.	
		Temporal.	Nasal.	Temporal.	Nasal.	Temporal.	Nasal.	Temporal.	Nasal.
0	1	54	42	57	45	43	33	61	48
35	$\frac{1}{2}$	50	38	53	41	39	29	57	44
70	$\frac{1}{4}$	47	36	49	37	35	27	53	42
105	$\frac{1}{8}$	43	32	45	34	32	24	50	38
140	$\frac{1}{16}$	39	29	41	31	28	22	46	34
175	$\frac{1}{32}$	35	26	37	28	25	19	42	31
210	$\frac{1}{64}$	32	24	33	26	21	16	39	29
245	$\frac{1}{128}$	28	20	30	23	17	14	35	26
280	$\frac{1}{256}$	24	18	26	20	14	13	31	25

We find from the above that the average diminution in field for each reduction of half intensity on the temporal side is 3·75°, and on the nasal side close upon 3°. Using these figures, the above table would be as follows:—

Table XVII.

Degrees annulus.	Intensity of ray.	Reading of horizontal field in degrees.							
		Red Lithium.		D.		Scale No. 41·7.		Blue Lithium.	
		Temporal.	Nasal.	Temporal.	Nasal.	Temporal.	Nasal.	Temporal.	Nasal.
0	1	54	42	57	45	43	33	61	48
35	$\frac{1}{2}$	51	39	53	42	39	30	57	45
70	$\frac{1}{4}$	46·5	36	49·5	39	35·5	27	53·5	42
105	$\frac{1}{8}$	43·75	33	46	36	32	24	50	39
140	$\frac{1}{16}$	39	30	42	33	28	21	46	36
175	$\frac{1}{32}$	35	27	38	30	24	18	42	33
210	$\frac{1}{64}$	31·5	24	34·5	27	20·5	15	38·5	30
245	$\frac{1}{128}$	28	21	31	24	17	12	35	27
280	$\frac{1}{256}$	24	18	27·00	21	13	9	31	24

Fig. 13.



With my assistant (W. B.), these numbers appear to be 4 and 2·5 respectively, showing a consistent variation from my own measures. That there is a diminution in the angle of field in an arithmetical progression, as the intensity diminishes in geometrical progression, is somewhat strange, and appears to be unaccountable. It will be noticed that the region of the macula lutea has been avoided in these observations, as it seemed to be useless to attempt any observations on parts of the retina which were evidently unsuited for them.

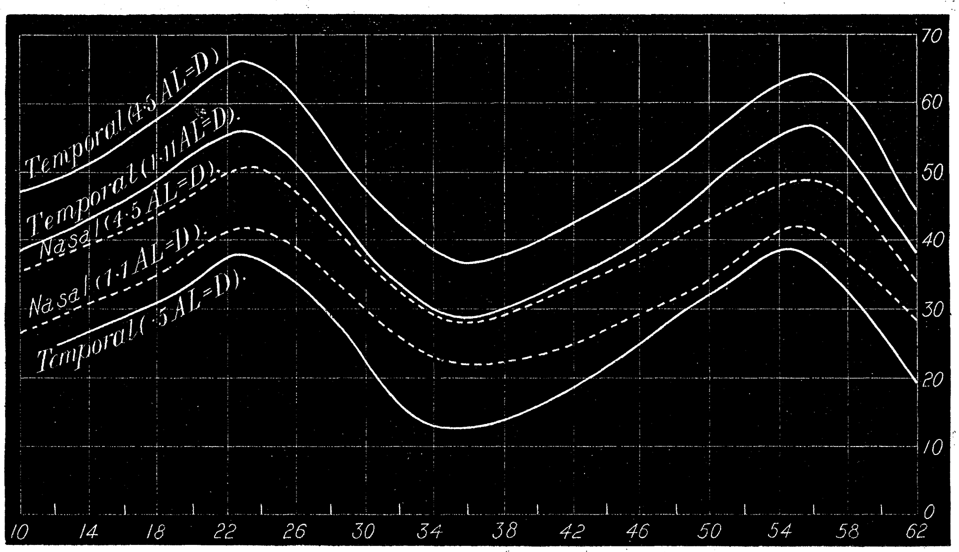
16. *Extent of Field for the Different Rays of the Spectrum.*

It now became of interest to ascertain the extent of the fields to my own eyes when a slit was passed unaltered through the spectrum, for it then became a matter of calculation to find the intensity (luminosity) of each colour required to give equal horizontal fields at any given angular distance from the centre of the retina, and as all fields are similar, when one has been measured for any colour, all the others may be constructed. The following is a table of three sets of observations. The two first were taken with an aperture of ·525 inch, with an angular value of 2° 30′. The third was taken with an aperture of ·086 inch, embracing an angle of 25′ only, the temporal extent being only observed with it.

TABLE XVIII.

Scale No.	λ.	No. 1.		No. 2.		No. 3.	Remarks.
		Temporal.	Nasal.	Temporal.	Nasal.	Temporal.	
62	6957	44	34	37	28	18	The luminosity of the D light in No. 1 = 4·5 A L; an aperture of ·525 inch was used at 1 foot distance.
60	6728	53	41	45	33	27	
58	6520	61	47	53	37	33	
56	6330	64	49	56	41	38	
54	6152	63	48	55	41	39	
52	5996	60	46	52	38	36	The luminosity of the D light in No. 2 = 1·1 A L, with an aperture of ·525 inch.
50	5850	56	43	48	35	33	
48	5720	52	40	44	32	29	
46	5596	49	38	40	30	25	
44	5481	46	35	37	28	22	The luminosity of the D light in No. 3 was ·5 A L, an aperture of ·086 inch being used at 1 foot.
42	5373	43	33	34	26	18†	
40	5270	40	31	32	24	16†	
38	5172	38	29	30	23	14†	
36	5085	37	28	29	22	13†	
34	5002	39	29	30	23	13†	The readings marked † were doubtful, as they fell on or close to the blind spot. They were obtained by reading at a small angle to the horizontal line.
32	4929	42	32	33	25	16†	
30	4848	47	36	39	30	21	
28	4776	54	42	45	35	28	
26	4707	61	47	52	39	34	
24	4639	65	50	56	42	37	
22	4578	65	50	55	42	38	
20	4517	61	47	53	39	34	
18	4459	58	44	49	35	31	
16	4404	54	41	46	33	29	
14	4393	51	39	43	31	27	
12	4296	49	38	41	29	25	
10	4245	47	36	39	27		

Fig. 14.



If we plot the curves from the above table, and take the distance apart of the nasal from the temporal ordinates, we shall find that when the latter reads 40° the

former reads 30°, no matter what the colour may be; and that, as the field increases about $7\frac{1}{2}$ degrees on the temporal side, the field on the nasal side increases nearly 6° —a variation which is in accordance with the table showing the field with variation of intensities of the beam (fig. 14).

17. *Luminosities of Colours for Equal Fields.*

From this curve we can calculate, within certain limits, the intensity (*i.e.*, luminosity) of any colour to give any required extension of field. Suppose, for instance, we required to know the luminosity of the whole of the colours of the spectrum at, say, 30° from the axis on the temporal side, which would give equal fields, we should proceed as follows:—Take the height of the ordinate of any colour above (or below) the ordinate of 30°, and divide it by 3·75; that would give a factor in powers of $\frac{1}{2}$ by which the intensity (luminosity) should be diminished, in order to cause the field of that particular ray to fall at 30°. Thus, at 48·4 of the spectrum scale, the height of the ordinate is 45° (that is, 15° above the ordinate of 30°). Hence, since $15/3{\cdot}75 = 4$, the intensity of the ray would have to be diminished to $(\frac{1}{2})^4$ to cause its field on the temporal side to fall at 30°. The luminosity of this ray is at the maximum spectrum luminosity, or 100, and would thus have to be reduced to 100/16, or 6·25; whilst the luminosity at scale numbers 38 and 34 would remain the same, viz., 49 and 31 respectively. On this plan fig. 15 was calculated, which gives the comparative luminosities for equal fields, the maximum being made 100.

TABLE XIX.

Scale No.	Original Luminosity.	Luminosity for equal fields.	Scale No.	Original Luminosity.	Luminosity for equal fields.
60	3·5	·58	36	40	77·6
58	15	·56	34	32	53·5
56	34	1·00	32	25	29·0
54	55	1·6	30	19	9·5
52	70	2·5	28	15	2·5
50	94	8·1	26	13	·7
48	100	16·5	24	9·5	·24
46	96	32·6	22	7·5	·21
44	85	49·4	20	6	·20
42	74	86·2	18	5	·35
40	60	100·0	16	4	·42
38	50	98·0			

This calculation is made on the assumption that the comparative luminosities of the colours of the spectrum are the same at 30° on the temporal side as they are at 10°.

Fig. 15.

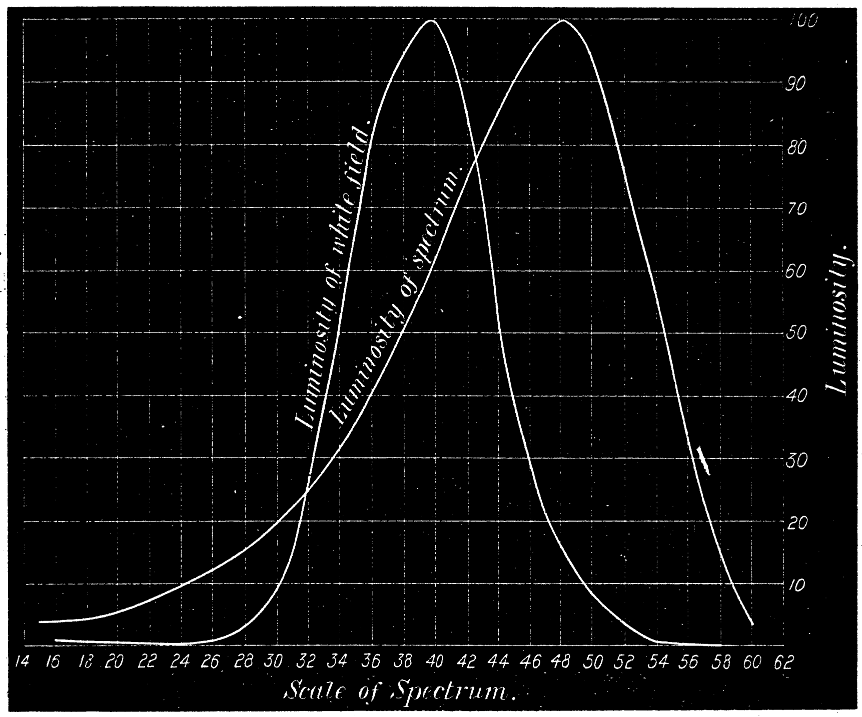
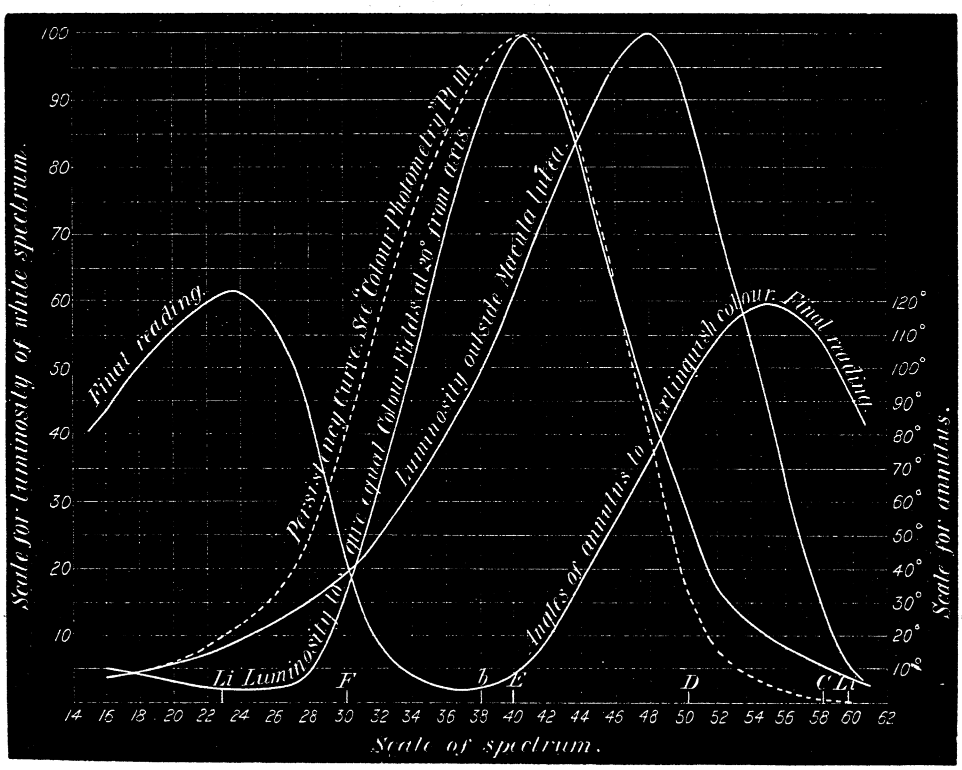

Luminosity of white field.
Luminosity of spectrum.
Luminosity.
100 90 80 70 60 50 40 30 20 10
14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62
Scale of Spectrum.

Fig. 16.


Scale for luminosity of white spectrum.
100 90 80 70 60 50 40 30 20 10
Final reading.
Luminosity to give equal Colour Fields at 20° from axis.
Luminosity outside Macula Lutea
Angles of annulus to extinguish colour. Final reading.
Li Luminosity
F b E D C Li
120° 110° 100° 90° 80° 70° 60° 50° 40° 30° 20° 10°
Scale for annulus.
14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62
Scale of spectrum.

In connection with this it may be well to quote another observation made direct for the purpose of ascertaining the luminosities of different colours required to give equal colour fields. The different parts of the spectrum were observed on the retina at 25° from the axis on the temporal side, and the luminosities reduced by the annulus till the colour disappeared. The readings were somewhat difficult to make, but the mean gives the table following. (See fig. 16.)

TABLE XX.

I. Scale No.	II. λ	III. Mean value of reading of annulus.	IV. Value of light when 0° = 100.	V. Luminosity of spectrum.	VI. Col. V. × Col. IV. ÷ 100.	VII. Col. VI. Max. = 100.
60	6728	90	16·2	3·5	·6	1·3
58	6520	112	10·9	12 5	1·4	3·1
56	6330	120	9·2	27·5	2·5	5·5
54	6152	118	9·0	43·0	3·8	8·4
52	5996	108	11·8	61·0	7·2	15·2
50	5850	93	16·0	79 0	12·6	28·5
48	5720	72	19·6	85·0	16·7	37·5
46	5596	55	33·7	81·0	27·3	62·0
44	5481	37	48	72·5	34·8	79·0
42	5373	19	70	62·5	43·7	98·0
40	5270	8	85	52·0	43·2	97·0
38	5172	5	90	41·5	37·3	84·5
36	5081	4	93	33·5	31·1	70·0
34	5002	8	85	26·5	22·5	51·0
32	4924	17	65	21	13·6	31·0
30	4848	43	43	16·5	7·1	15·8
28	4776	86	18·3	13	2·4	5·4
26	4707	114	10·5	10·5	1·3	2·3
24	4639	124	8·6	8·2	·71	1·6
22	4578	120	9·2	6·3	·58	1·27
20	4517	108	11·8	5·0	·50	1·30
18	4459	97	14·7	4·0	·58	1·27
16	4349	86	18·3	3·1	·57	1·25

At the time when these results were obtained an experiment was also made by the same eye to determine the variations in the fields for four different colours when the intensity was altered. The four colours chosen were the same as used in many of the experiments made with my own eyes. The fields were taken in the horizontal direction, and on the nasal and temporal sides. As the light was varied for each colour, in order that readings up to about 60° might be obtained, the fields for the rays are not comparable with each other. Each field must be considered by itself.

TABLE XXI.

Annulus reading.	Comparative intensity of light.	Red lithium.		D.		41·7 S.N.		Blue lithium.	
		Nasal.	Temporal.	Nasal.	Temporal.	Nasal.	Temporal.	Nasal.	Temporal.
0	1	42	54	47	60	33	43	42	53
35	$\frac{1}{2}$	37	46	42	53	29	35	37	46
70	$\frac{1}{4}$	32	38	36	45	24	28	31	37
105	$\frac{1}{8}$	26	31	31	38	20	21	26	30
140	$\frac{1}{16}$	22	24	26	29	15	8	21	24

All we have to deal with here are the readings on the temporal side. We find that for each diminution of one-half intensity the field contracts 7° 5′, or twice that of the writer's. The figures in the table on the previous page are now explained, and they compare fairly with the results tabulated on p. 186. The variation in sensitiveness in different eyes is here well illustrated.

18. *Dependence of Field on the Size of the Coloured Spot.*

It has been shown that the loss of colour in the centre of the retina depends largely on the size of the spot of light viewed. Such being the case, it was to be presumed that the boundaries of a field would contract if the aperture used in the apparatus was diminished, and it seemed possible that some expression might be found which would connect the two together.

To make measurements of field with dimishing apertures the same kind of perimeter was employed as before, and the spot of light on the ground glass was diminished in size by placing circular apertures of diminishing diameter in contact with it. The fields were measured in a horizontal direction only at first, and the following table gives the mean of the actual measures. The intensity of the D light was 1·1 AL.

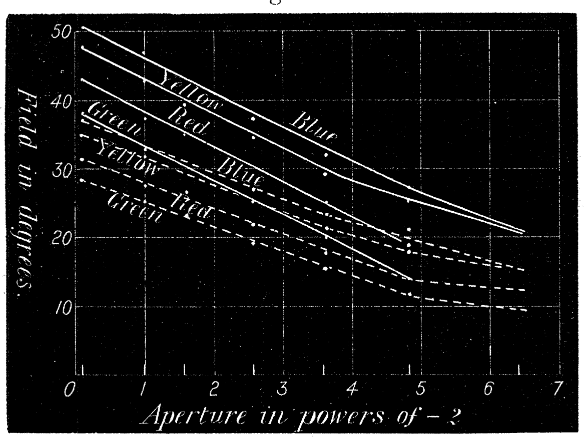
TABLE XXII.

Diameter of aperture in inches.	Angle subtended.	Diameter of aperture in powers of 2.	Red lithium.		D.		41·7.		Blue lithium.	
			Temporal.	Nasal.	Temporal.	Nasal.	Temporal.	Nasal.	Temporal.	Nasal.
0·94	4° 18′ 0″	−0·09	42	32	48	35	38	28	50	37
0·525	2 30 0	−0·93	37	28	43	32	33	25	47	34
0·35	1 34 0	−1·52	35	26	39	29	31	23	42	31
0·17	0 49 0	−2·56	29	22	34	25	25	18·5	37	27
0·086	0 25 0	−3·56	25	17·5	29	21	20	15	32	23
0·036	0 10 0	−4·8	19	14	25	18	*b.s.*	12	27	21
0·012	0 3 30	−6·4	*b.s.*	12·5	20	15	*b.s.*	9	20	15

b.s. is blind spot where measures are impracticable.

This table when plotted gives a diagram, fig. 17, which shows that between apertures subtending 4° 28′ and 10′ (the power of ½ being taken for the scale of abscissa), the fields decrease in extent and are practically straight lines. On the temporal side for each diminution in aperture to ½ diameter the diminution *in field* is 5° and on the nasal side 4°. The diminution in field for a diminution of ½ the intensity *of light*, it will be remembered, is 7·5° on the temporal side and 6° on the nasal side.

Fig. 17.



The diminutions in field thus bear the same ratio to one another, viz., 5 : 4. This might be expected, but the author was by no means prepared to find that it could be measured so closely as it has been. We thus arrive at the result that diminution in aperture is equivalent to diminution in intensity of light. When the apertures used were greater than the largest given in the table scarcely any alteration of the field was obtained. We may take it that any aperture subtending more than 5° will give the same field. With apertures between 5° and 3° the field will only slightly diminish. Referring to the table of extent of field for the whole spectrum, we shall find that the measured field for an aperture of ·086 inch agrees with the above determination very closely, taking into account the illumination.

19. *Relative Sensitiveness of the Different Parts of the Retina.*

One other determination of sensitiveness of the retina required to be made, viz., the general sensitiveness at all parts compared with that at the centre or close to the yellow spot. In "Colour Photometry," Part III., a comparison was made of the sensitiveness of the centre of the eye compared with that of a point 10° towards the periphery. Determinations of this kind are extremely difficult, and it is only by continued observation that an approach to correct measures can be made. In fact the eye requires training. Perhaps the easiest plan of explaining how the following determinations were made will be by describing a preliminary experiment. Procure a large sheet of black paper and lay it horizontally on a table near a window, so that it is equally illuminated. Cut out some small and equal discs of white paper or card and place two of them about 1 foot apart lying on the black paper. Place the eye about 12 inches above one of them, and receive its image on the centre of the retina. At the same time the image of the other will be received on the retina about 45° from the centre. This last white disc will appear to be very decidedly darker than the first.

Cut out a small disc in grey paper, and substitute it for the white disc, the image of which is viewed centrally. The other white disc may now be moved away from it till the two appear equally luminous. The distance from the grey disc to the white will give the field. By measuring the amount of white light reflected from the grey paper, the comparative luminosities of the discs are found, and from them the relative sensitiveness of the two portions of the retina are determined.

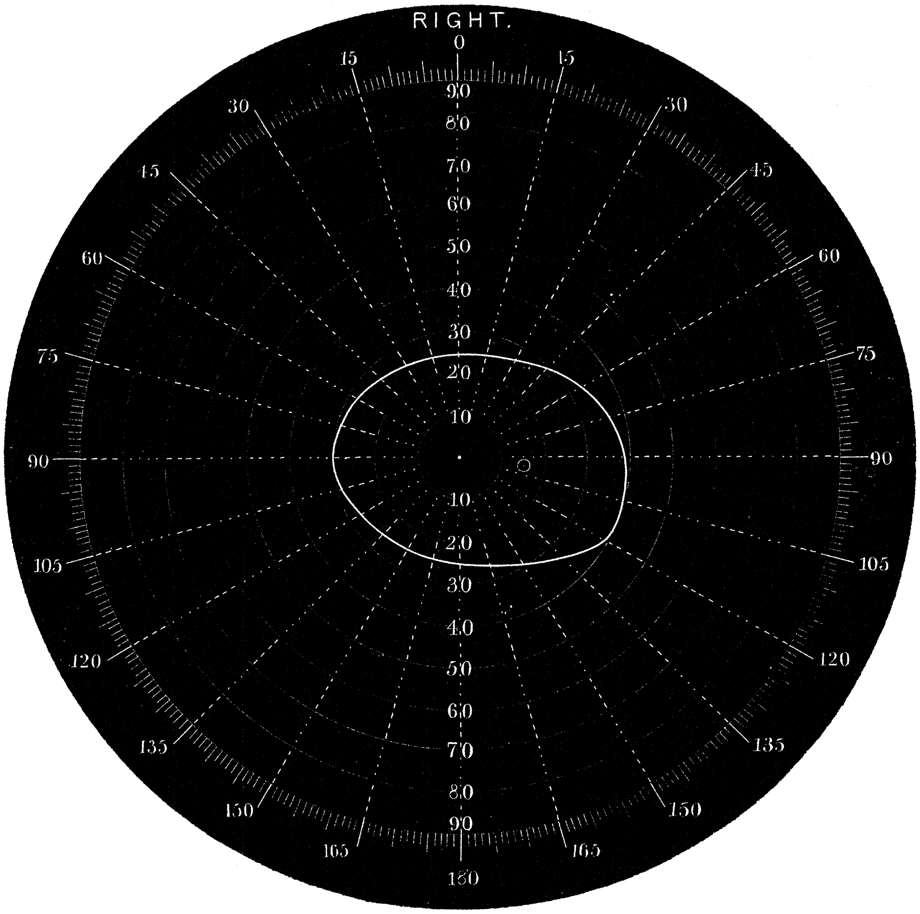
The same procedure can be carried out on an equally illuminated surface, and "iso-lumes" be made for any depth of grey. The following table gives one of the determinations, the grey in this case reflecting $\frac{1}{5 \cdot 4}$ of the white light reflected from the white disc. The diameters of the discs were half an inch, and were viewed with the right eye at a distance of two feet from a vertical screen (see fig. 18).

TABLE XXIII.

Angle with the vertical.		Field, in degrees.	Angle with the vertical.		Field, in degrees.
0		24	180		26
30	N.	27	150	T.	25
60	N.	33	120	T.	27
90	N.	39	90	T.	30
120	N.	40	60	T.	27
150	N.	30	30	T.	25

It will be seen that the "iso-lumes" are of the same character as the colour fields. Some small correction might have to be made for the projection of the white disc on the retina, since it would not be of the same angular dimensions as if viewed in a hemispherical perimeter.

Fig. 18.



An iso-lume.

Other modes of measurement were tried, and the results agreed very fairly *inter se.* The following iso-lumes were taken only in four directions, viz., two in the horizontal and two in the vertical (see fig. 19).

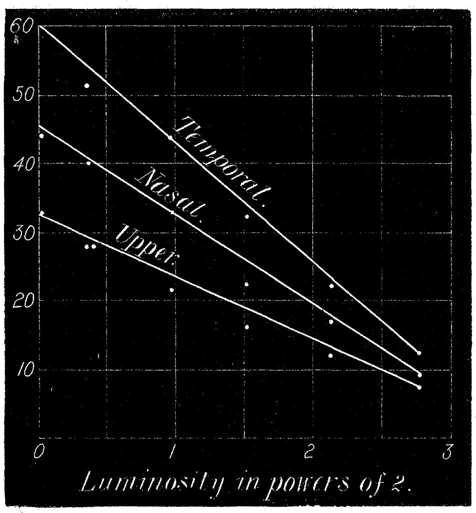
TABLE XXIV.

Light reflected from grey disc when white = 100.	Luminosity in powers of − 2.	Temporal reading.	Nasal reading.	Upper vertical reading.	Lower vertical reading.
60	2·74	12	9	8	9
38·5	2·10	22	17	12	13
25·5	1·51	32	23	16	18
16·8	0·90	43·5	33	22	24
13·5	0·31	51	40	28	28
11·5	0·00	60	44	33	34

Comparing these readings on the temporal and nasal sides, they agree, as well as could be expected from the nature of the observations, with the colour field curves.

They show that with an increase of double the luminosity the field is extended about 17° on the temporal side and about 13° on the nasal. As the increase of dimensions in these two directions of the colour fields for the same increase in luminosity is considerably less, it is evident that there is no exact connection between the luminosity of white light at the different parts of the retina and the luminosity of a colour-ray when colour is extinguished. The sensitiveness of the peripheral portions of the retina to light and colour is therefore different, as it was shown to be when the centre of the retina was under consideration.

Fig. 19.



A good many experiments have been carried out regarding the persistence of coloured images and the rate of perception, but these have indicated that the subject is one which should be treated of in a separate communication.

It may here be reiterated that the sensitiveness of the eye varies considerably at times, which may be due in all probability to the state of health of the observer. Much of the difficulty experienced in these observations has arisen from this variation. As the eye becomes practised to observation, however, the liability to variation very largely disappears, and at the present time readings made by my assistant and myself are very fairly comparable at all times. Whether, when the observations have ceased for some time and are then renewed, there will be a relapse, it is hard to say.

It will be seen that scarcely any reference has been made to the work of other observers. It has not been thought advisable to do so for various reasons, the principal one being that in the experiments described spectrum colours have been employed. The results obtained with these last cannot be comparable with those obtained with the use of impure colours.

20. *General Summary.*

The results of these investigations may be summarized as follows:

1. That where an image is received on the centre of the retina, the reduction in

intensity of the radiation which will just fail to produce the sensation of light depends (within limits) on the size of the image.

2. That the smallest diameter of the image and not its area determines the necessary reduction in intensity.
3. That the reduction in the intensity of the light of an image falling excentrically, which will just fail to produce the sensation of light, follows the same general law as if the image were received centrally.
4. That the visual brightnesses of illumination of a small and a large aperture when illuminated with the same light differ, and that such visual brightnesses are connected by a simple law.
5. That the reduction in the brightness of an image just sufficient to extinguish the sensation of colour, varies with the size of the image and follows a definite law, which, however, differs from that for the extinction of light.
6. That all fields for colours will have the same boundary when the intensity of the coloured ray is properly adjusted.
7. That there is a simple connection between the intensity of a colour and the extent of field.
8. That the colour fields depend on the size of the object viewed, and that the dependence appears to follow a simple empiric law.
9. That the retina is most sensitive to light at its central part and the sensitiveness diminishes towards the periphery.

These results as they stand do not seem to confirm either one of the two main theories of colour vision. The existence of a colour field at all is difficult to explain on the YOUNG theory, and the fact that a colour field for red can be obtained with bright illumination although the disappearance of this colour and light takes place almost together at the centre of the retina, is not easily accounted for on HERING'S theory. It appears as if light were the fundamental sensation caused by the main vibration generally, whilst colour is as it were an overtone to which the receiving nerves are less susceptible than to light, the further away they are situated from the centre, and may be due to the form of vibration.

In closing this paper I should be doing an injustice if I did not place on record the great assistance I have had during the whole of these investigations, which have extended over three years, from my assistant, Mr. WALTER BRADFIELD; with every new step I took he made himself thoroughly acquainted, and every series of measures I made myself he repeated with his own eyes. There is nothing stated as being fairly proved which has not been confirmed by him. Measurements of the kind recorded above are by no means as simple as they look on paper, but those given are the results of hundreds of observations, repetition being an absolute necessity to avoid false deductions.