III. *The Threshold of Vision for Different Coloured Lights.*

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1. The question as to the sensitiveness of the different regions of the retina to light of various wave-lengths is one which has received a considerable amount of attention. The results obtained by previous observers, while being in agreement in certain particulars, yet differ materially in others. For instance, the question as to whether dark adaptation takes place at the fovea and the controversy as to whether there is a failure of the secondary image at the fovea may be cited. In the course of some other experiments we were led to investigate certain differences which existed between our own eyes. The results obtained seem to throw a very considerable amount of light on the differences obtained by previous workers as well as to give interesting information as to the action of the retina.

Our results support the idea that we have to do with two distinct processes when considering the variation in the sensations produced by light, a view which was first put forward by Parinaud and has been elaborated by von Kries. The latter further identifies the rods and cones respectively as the two receptive elements of the retina. He supposes that the cones are responsible for all sensations of colour and are chiefly operative at medium and high illuminations. The rods he supposes are chiefly operative at low illuminations and only to come into action when the illumination is so low that all perception of colour is wanting, so that whatever the wave-length of the light stimulus the sensation produced is one corresponding to white or grey. Although our experiments do not provide any evidence as to the identification of the rods and cones with these two forms of vision, yet it saves so much circumlocution to speak of the sensation due to the cones or rods as the case may be that we shall use the terminology of von Kries. Thus when we speak of the sensation due to the rods we must be understood to mean the sensation due to that mechanism, whatever it is, which is alone operative at low illuminations in the central part of the retina, and similarly for the sensation due to the cones.

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2. *Threshold of Light. Extinction Curves.*

A series of experiments have been made to determine the minimum intensity of light of the various colours which can be perceived when received on the fovea and at different distances from its centre up to 10 degrees. The chief difficulty in obtaining these measurements was to ensure correct fixation and to avoid retinal fatigue. Experiment showed that both these difficulties were very much reduced if the stimulus light in place of being continuously in action was only applied for a short time, say about a second, with a comparatively long interval between flashes.

With a Nernst light the arrangement employed is a slight modification of the arc colour-patch apparatus. It is shown diagrammatically in fig. 1. The source of light, a Nernst glower, A, is enclosed in a blackened metal box which has a small rectangular opening, the width of this opening being such that the glower is not screened from the collimator lens, C, and the height of the opening being such as to give a convenient width of spectrum. No collimator slit was employed, the glower itself acting as the slit and being placed at the principal focus of the lens, C. The dispersion train consists of two 60 prisms, D. A lens, E, forms a pure spectrum in the plane, FG, of a slide which carries a slit by means of which any required colour can be isolated. The position of this slit is read by means of a transparent scale attached to the slide,

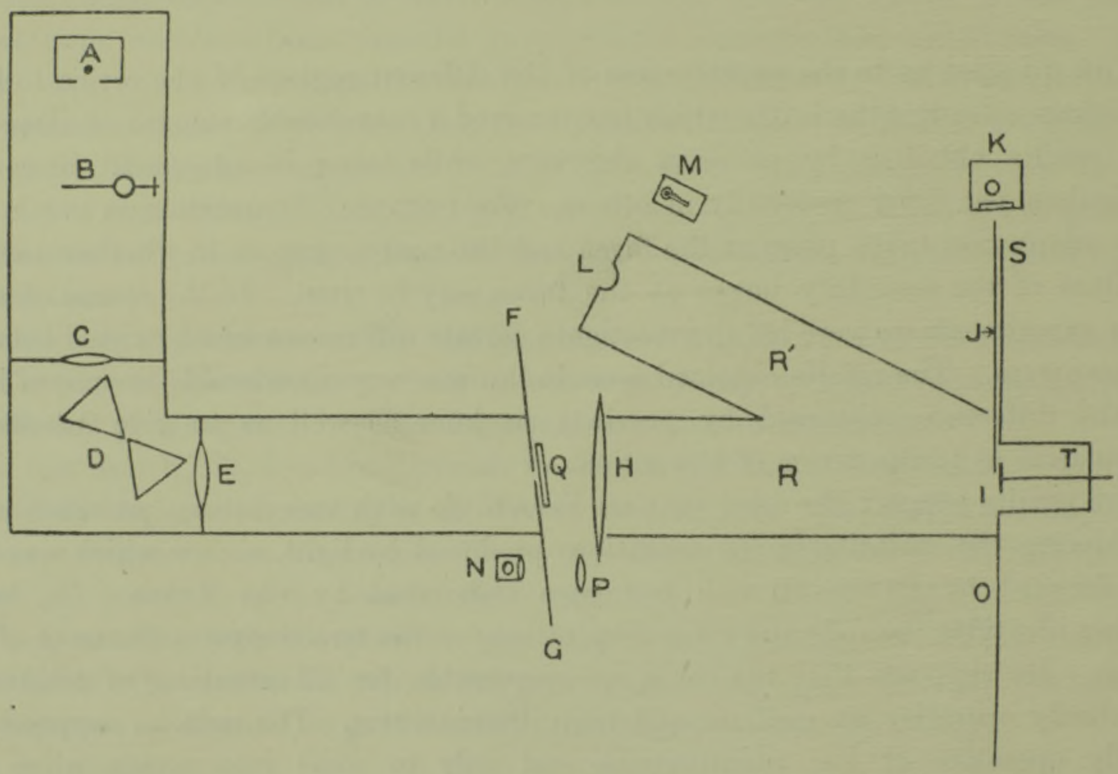

Fig. 1.

an image of this scale being projected by means of a lamp, M, and lens, P, on to a card fixed at O to a screen, OS, covered with black velvet. Attached to the slide, FG, is an annulus, Q, which has been described by one of us in a previous paper ('Phil. Trans.,' A, 190, 156, 1897). This annulus consists of a uniformly increasing wedge of gelatine impregnated with finely divided lamp black. The annulus can be rotated by means of a milled head attached to a pinion which engages with a circular rack attached to the glass carrying the annulus. A graduated circle is also attached so that the part of the annulus opposite the slit can be identified. The light after passing through the annulus is received by a large lens, H, which forms an image of the front face of the prism train in the plane of the screen, OS. This image is received on a metal disc, I, which is covered with magnesium oxide.* The velvet-lined recess, T, is of such a depth that the light which misses the disc, I, and strikes the back of the recess and might be reflected from it, cannot reach the eye of the observer who is at L. Tunnels, R and R′, lined with black velvet are used to screen off any stray light. Further, the Nernst light, prisms, &c., are all enclosed in boxes which are painted dead black inside. The instrument is placed in a room which can be rendered entirely dark. Small 3-candle power electric lamps, which are themselves screened and only switched on when required, are used to make the necessary readings of the annulus. These readings are made by an assistant who also keeps the current passing through the Nernst lamp constant.

Between the Nernst glower and the collimator lens is placed a pivoted screen, B, which normally cuts off the light from the collimator lens. By pressing a key, M, placed near the observer's hand, the screen, B, is raised by an electro-magnet. Thus the light only reaches the disc, I, when the observer presses the key, while by turning the milled head attached to the annulus he can alter the intensity of the light which falls on the disc, I. To give a fixation spot a rod of glass, J, is drawn down at the end to a diameter of about a millimetre and ground off at about 45 degrees. A small electric lamp, K, enclosed in a box with a small window covered with red glass, is placed opposite the end of this rod. The light from the lamp passes down the glass rod and owing to internal reflections does not escape from the sides till it reaches the ground end. At this end the light is scattered and thus gives a small source of red light. (By means of a resistance in the circuit of the lamp the intensity of this fixation light can be adjusted.) When fixation is desired for the central part of the retina, the circuits are so arranged that on depressing the key, M, the lamp, K, is extinguished. Thus the depression of the key by the observer causes the fixation light to disappear, and at the same instant causes the coloured light to illuminate the disc, I. When working away from the fovea the fixation light is disconnected from the key, M, so that the fixation spot does not vanish when the stimulus light is turned on. The reason for using a deep red fixation light is that such a light has little or no stimulus value for the rods.

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* Obtained by holding the disc over a piece of burning magnesium wire.

The amount by which the light coming through the slit in the spectrum is reduced owing to its passage through the annulus depends for any given position of the annulus not only on the colour of the light but also on the distance of the receiving surface, I, from the annulus. The reason is that in the first place the coefficient of absorption of the annulus is a function of the wave-length. Secondly, there is a certain small amount of light scattered by the annulus, and the amount of this scattered light which falls on the disc depends on the distance. Hence it was necessary to measure the absorption of the annulus throughout the spectrum in exactly the same relative position as that in which it is used. This calibration involved a very considerable amount of work but need not be described.

It enabled us to calculate for any wave-length and for any annulus reading what fraction of the light passing through the slit fell on the disc. The intensity of the light falling on the disc, when the slit was placed at the sodium line, was determined by comparison with a standard Hefner lamp. This lamp is very suitable for the purpose, as the colour of its light does not differ greatly from that of the D line.

The procedure adopted was for the observer, who had been in complete darkness for more than half-an-hour, to look steadily with both eyes at the fixation spot and then to press the key, M, for about a second, thus allowing the light to fall on the disc, I, for this time. If the light was visible, he then turned the annulus so as to reduce the light, and again pressed the key. This process was continued till the light was just imperceptible when the key was pressed. The circle attached to the annulus having been read, the annulus was turned so as to make the light brighter, when the setting was repeated. In general, three settings were taken at each selected wave-length.

When observing away from the fovea the fixation spot was always placed vertically above the disc on which the stimulus light was received. Unless otherwise mentioned, the disc, on which the light was received, had a diameter of 6·3 mm., and was at a distance of 72 cm. from the observer's eye, so that the angle subtended at the eye was 34 minutes.

With the fixation spot at 1·5 mm. or more away from the centre of the disc, all the observers found it quite easy to obtain consistent results. With foveal fixation, some observers required a little practice before they were able to overcome the tendency for the eye to wander. The reason for this tendency is that for most people the sensitiveness of the retina increases (except in the red), that is the threshold value decreases, rapidly as we go out from the fovea, and hence, when striving to see the last glimmer of light they instinctively shift the axis of the eye so as to bring the image on the more sensitive area surrounding the fovea. The curves shown in fig. 2 illustrate the successive readings of the annulus obtained by one untrained observer with central fixation.* At the first attempt the numbers obtained correspond

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* The numbers plotted in this figure are the annulus readings. The greater the annulus reading the greater the reduction in the light.

to those obtained with the fixation spot at 2·5 degrees from the fovea. At the second attempt the fixation was better but still not central. At the third attempt, the start in each case being made at the red end of the spectrum, the fixation was central down to SSN 40, after which the eye wandered slightly. During the fourth, fifth, and sixth sets of readings, the fixation was kept central throughout, and all the points obtained are in good agreement.

On the supposition that we start with a spectrum of such an intensity that the illumination on the disc when the slit is at the D line is one lux (metre-candle), we have calculated from the annulus readings by how much the light has to be reduced to reach the threshold for the different parts of the spectrum. This reduction, in conformity with the nomenclature used by one of us in previous papers, we shall call the *extinction*. The actual numbers obtained for the extinction, except of course at the D line, will depend on the distribution of light in the spectrum employed, that is on the source of light and on the dispersion curve of the prisms. In order to obtain numbers which do not involve these quantities we have determined the distribution of energy in the spectrum we have used, so that we can calculate what is the energy of the radiation falling on unit area of the disc, I, at the threshold. Since our measures of the energy are relative they give the comparative distribution of energy throughout the spectrum, but do not give the absolute values, as we have to fix an arbitrary unit. Since it is convenient to tabulate and plot the figures in the logarithms of the energy, it is advisable to avoid the use of negative characteristics,

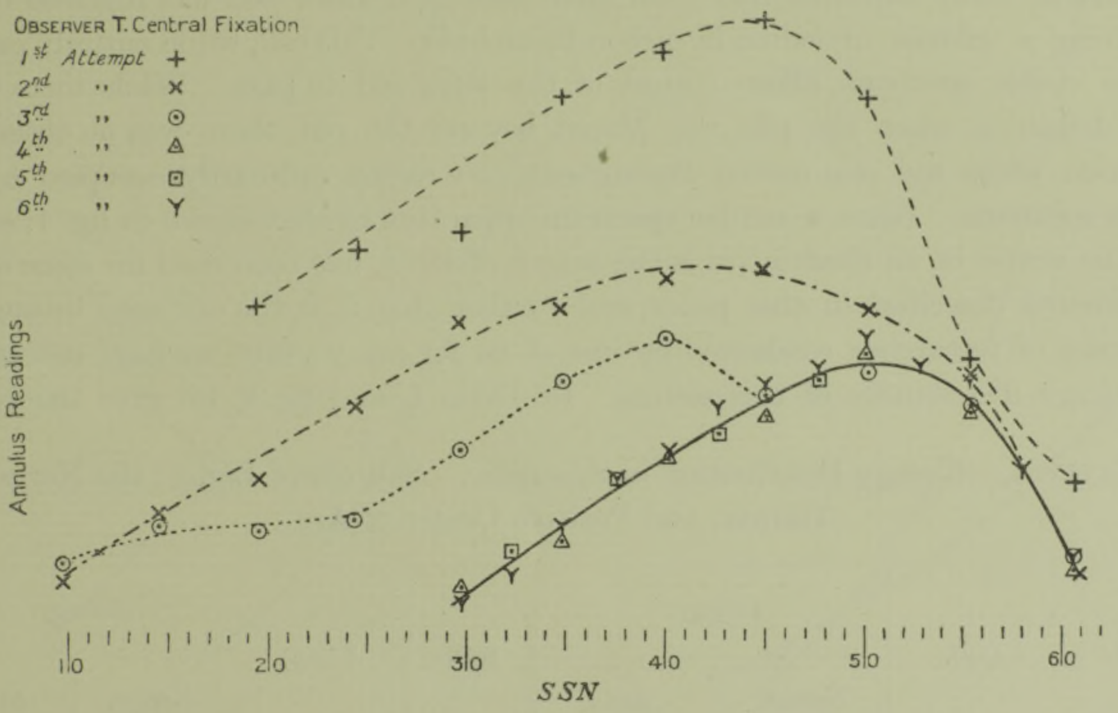

Fig. 2.

our unit is such that when the intensity of illumination by the D light on the disc, I, is one lux the energy per square centimetre is equal to 100,000 such units.

A measurement of the light diffused from the magnesium oxide surface showed that when the illumination of this surface was one lux the radiation it sends out normally per square centimetre is equal to 0·000026 candles, so that if the cosine law be assumed to hold the coefficient of reflection is 0·83.

In order to obtain the energy distribution in the spectrum, a linear thermopile was attached to the slide, FG, fig. 1, and the deflections of a sensitive galvanometer were read as the pile moved through the spectrum. In order to reduce the effect of stray heat a pair of slits were placed one in front of the other before the pile and a water cell was interposed between the Nernst glower and the collimator lens. As a test to see whether stray radiation had been eliminated, the water cell was replaced by one containing a solution of iodine in carbon bisulphide. This cell, while entirely cutting off the visible spectrum, allowed most of the infra red to pass. While there was a large deflection when the pile was placed beyond the red, there was no observable deflection while the pile moved throughout the region ordinarily occupied by the visible spectrum. Since a similar spectrum apparatus to that shown in fig. 1, except that the crater of an electric arc is the source of light, has been used for some of the experiments described in this paper, and further that it is the one used throughout the series of researches conducted by one of us for many years, we have determined the energy distribution of this source. In Table I. and fig. 3 we give the results

TABLE I.—Energy Distribution in Spectrum. Sources of Light: the Nernst Glower, and Positive Crater of Arc.

SSN.	λ ($\mu\mu$).	Energy.		SSN.	λ ($\mu\mu$).	Energy.	
		Nernst.	Arc.			Nernst.	Arc.
64	721·7	396	182	35	504·3	27·0	42·3
62	695·7	325	166	34	500·2	25·2	40·0
60	672·8	261	151	32	492·4	21·2	35·2
58	652·1	205	137	30	484·8	17·9	30·7
56	633·0	165	126	28	477·6	15·3	26·9
55	624·2	151	121	26	470·7	12·9	23·8
54	615·2	137	116	25	467·0	12·0	22·3
52	599·6	114	106	24	463·9	11·2	20·8
50	585·0	96	97	22	457·8	9·7	18·2
48	572·0	80	89	20	451·7	8·4	16·0
46	559·6	68	81	18	445·9	7·2	13·8
45	553·8	62·5	77	16	440·4	6·1	11·9
44	548·1	57	73	15	438·1	5·7	11·1
42	537·3	46·5	65·5	14	434·9	5·2	10·4
40	527·0	39·6	58	12	429·6	4·2	9·0
38	517·2	34·3	51·5	10	424·5	3·3	8·2
36	508·5	29·6	45·5				

obtained with the two instruments. In Table I. will also be found the wave-lengths corresponding to the dispersion scale, the readings of which are indicated by the letters SSN, and which are used throughout this paper to indicate the different colours.

In Table II. are given the results obtained by eight observers. Of these A. and W. are the authors, and B. is Mr. W. Bradfield, the assistant in the Colour Vision Laboratory, to whom we are very much indebted for great assistance throughout the work. Observers T., Bk., Ar. and R. were students in the advanced Physics Class, and N. is one of our colleagues. Of these observers A., W., B., T. and Bk. have normal colour vision, Ar. and N. are dichromates, Ar. being green blind (deuteranope) and N. red blind (protanope), while R. is a case of a displaced green sensation curve whose case has already been described in a previous paper ('Roy. Soc. Proc.,' A, vol. 89, 232, 1913). Observations were in each case made throughout the spectrum using central fixation, and also with the fixation spot 1·25, 2·5, 5, and 10 degrees shown above the centre of the disc on which the stimulus light was received.

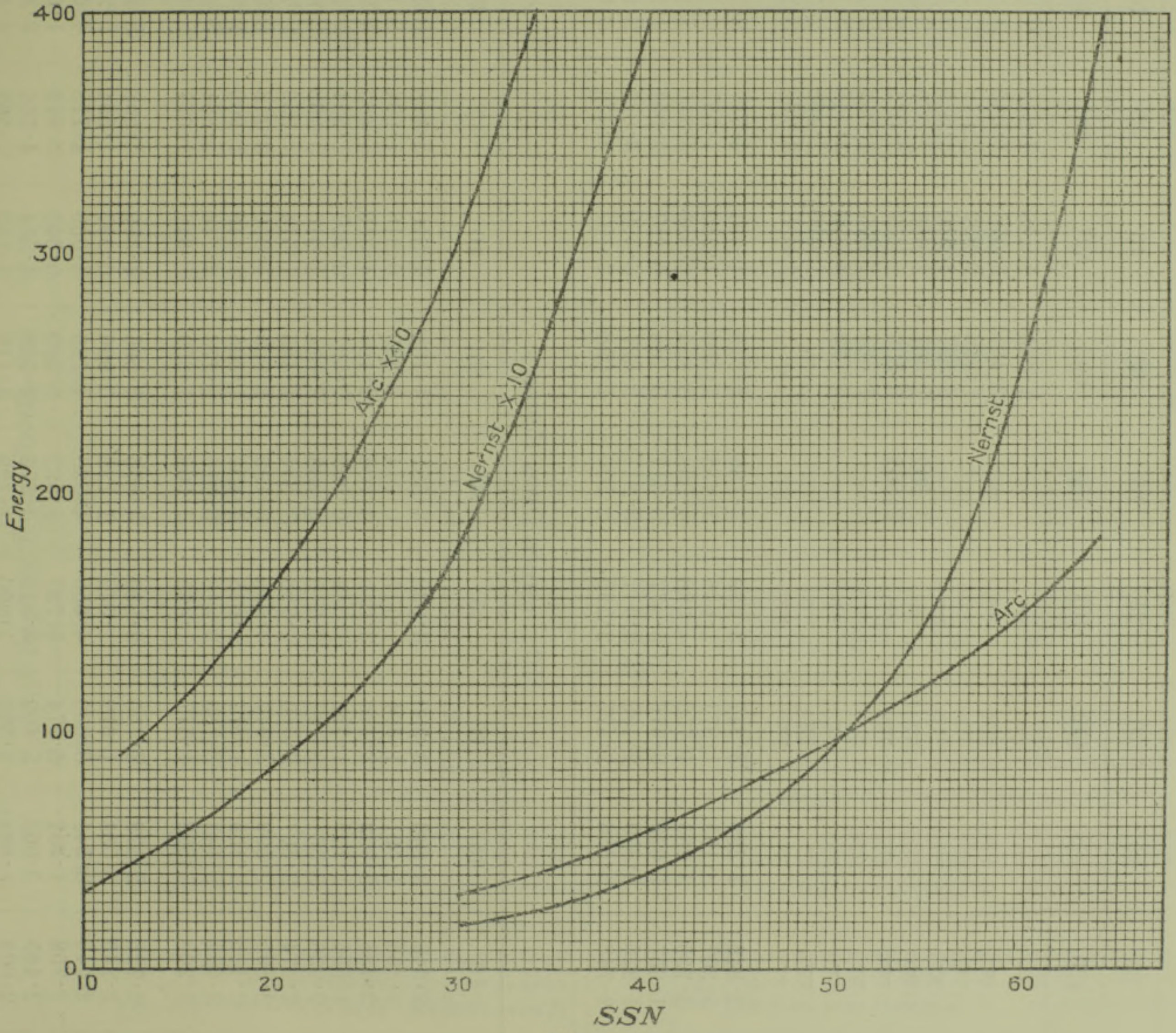

Fig. 3.

Table II.—Central Fixation.

Observer.	SSN . . .	10	15	20	25	30	35	40	45	50	55	60
	λ (μμ) . . .	425	438	452	467	485	505	527	554	585	625	673
W.	log reduction .	—	—	—	—	—	$\bar{1}$·056	$\bar{2}$·498	$\bar{2}$·249	$\bar{2}$·241	$\bar{2}$·429	$\bar{1}$·152
	log energy . . .	—	—	—	—	—	3·487	3·096	3·045	3·223	3·608	4·569
Bk.	log reduction .	—	—	—	—	—	$\bar{1}$·396	$\bar{2}$·932	$\bar{2}$·519	$\bar{2}$·280	$\bar{2}$·490	$\bar{1}$·269
	log energy . . .	—	—	—	—	—	3·827	3·530	3·315	3·262	3·669	4·686
T.	log reduction .	—	—	—	—	$\bar{1}$·609	$\bar{1}$·097	$\bar{2}$·669	$\bar{2}$·279	$\bar{2}$·267	$\bar{2}$·429	$\bar{1}$·292
	log energy . . .	—	—	—	—	3·862	3·528	3·267	3·075	3·249	3·608	4·709
R.	log reduction .	—	—	—	—	—	$\bar{1}$·328	$\bar{2}$·801	$\bar{2}$·352	$\bar{2}$·180	$\bar{2}$·478	$\bar{1}$·210
	log energy . . .	—	—	—	—	—	3·759	3·399	3·148	3·162	3·657	4·627
N.	log reduction .	—	—	—	—	—	—	$\bar{1}$·090	$\bar{2}$·468	2·259	$\bar{2}$·441	
	log energy . . .	—	—	—	—	—	—	3·688	3·264	3·241	3·620	
A.	log reduction .	$\bar{2}$·849	$\bar{2}$·399	$\bar{3}$·947	$\bar{3}$·529	$\bar{3}$·185	$\bar{4}$·919	$\bar{4}$·691	$\bar{4}$·727	$\bar{3}$·135	$\bar{3}$·813	$\bar{1}$·094
	log energy . . .	2·367	2·155	1·871	1·608	1·438	1·350	1·289	1·523	2·117	2·992	4·511
B.	log reduction .	$\bar{3}$·739	$\bar{3}$·263	$\bar{4}$·752	$\bar{4}$·398	$\bar{4}$·058	$\bar{5}$·815	$\bar{5}$·689	$\bar{5}$·755	$\bar{4}$·290	$\bar{3}$·305	$\bar{2}$·625
	log energy . . .	1·257	1·019	0·676	0·477	0·311	0·246	0·287	0·551	1·272	2·484	4·042
Ar.	log reduction .	$\bar{1}$·230	$\bar{2}$·870	$\bar{2}$·499	$\bar{2}$·111	$\bar{3}$·847	$\bar{3}$·627	$\bar{3}$·509	$\bar{3}$·675	$\bar{2}$·068	$\bar{2}$·574	$\bar{1}$·303
	log energy . . .	2·748	2·626	2·423	2·190	2·100	2·058	2·107	2·471	3·050	3·753	4·720

10 degrees from Fovea.

Observer.	SSN . . .	10	15	20	25	30	35	40	45	50	55	60
W.	log reduction .	$\bar{2}$·348	$\bar{3}$·840	3·380	$\bar{3}$·038	$\bar{4}$·691	$\bar{4}$·458	$\bar{4}$·320	$\bar{4}$·498	$\bar{3}$·160	$\bar{2}$·271	$\bar{1}$·444
	log energy . . .	1·866	1·591	1·304	1·117	0·944	0·889	0·918	1·294	2·142	3·450	4·861
Bk.	log reduction .	$\bar{2}$·438	$\bar{3}$·959	$\bar{3}$·468	$\bar{3}$·065	$\bar{4}$·706	$\bar{4}$·486	$\bar{4}$·359	$\bar{4}$·485	$\bar{4}$·973	$\bar{2}$·042	$\bar{1}$·187
	log energy . . .	1·956	1·715	1·392	1·144	0·959	0·887	0·957	1·281	1·955	3·221	4·604
T.	log reduction .	$\bar{2}$·956	$\bar{2}$·551	$\bar{2}$·141	$\bar{3}$·719	$\bar{3}$·283	$\bar{3}$·014	$\bar{4}$·916	$\bar{3}$·163	$\bar{3}$·807	$\bar{2}$·634	$\bar{1}$·444
	log energy . . .	2·474	2·307	2·065	1·798	1·536	1·445	1·514	1·959	2·789	3·813	4·861
R.	log reduction .	$\bar{2}$·895	$\bar{2}$·399	$\bar{3}$·947	$\bar{3}$·539	$\bar{3}$·199	$\bar{4}$·905	$\bar{4}$·850	$\bar{3}$·113	$\bar{3}$·595	$\bar{2}$·331	$\bar{1}$·503
	log energy . . .	2·413	2·155	1·871	1·618	1·452	1·336	1·448	1·909	2·577	3·510	4·920
N.	log reduction .	$\bar{2}$·682	$\bar{2}$·142	$\bar{3}$·753	$\bar{3}$·416	$\bar{3}$·115	$\bar{4}$·878	$\bar{4}$·744	$\bar{4}$·881	$\bar{3}$·458	$\bar{2}$·550	
	log energy . . .	2·200	1·898	1·677	1·495	1·368	1·309	1·342	1·677	2·440	3·729	
A.	log reduction .	$\bar{2}$·728	$\bar{2}$·278	$\bar{3}$·755	$\bar{3}$·283	$\bar{4}$·875	$\bar{4}$·565	$\bar{4}$·399	$\bar{4}$·558	$\bar{3}$·222	$\bar{2}$·416	$\bar{1}$·444
	log energy . . .	2·246	2·034	1·679	1·362	1·128	0·996	0·997	1·354	2·204	3·595	4·861
B.	log reduction .	$\bar{2}$·240	$\bar{3}$·641	$\bar{3}$·050	$\bar{4}$·658	$\bar{4}$·339	$\bar{4}$·129	$\bar{4}$·069	$\bar{4}$·178	$\bar{4}$·662	$\bar{3}$·813	$\bar{1}$·093
	log energy . . .	1·758	1·397	0·974	0·737	0·592	0·560	0·667	0·974	1·644	2·992	4·510
Ar.	log reduction .	$\bar{2}$·485	$\bar{2}$·068	$\bar{3}$·602	$\bar{3}$·211	$\bar{4}$·875	$\bar{4}$·688	$\bar{4}$·584	$\bar{4}$·766	$\bar{3}$·458	$\bar{2}$·598	$\bar{1}$·526
	log energy . . .	2·003	1·824	1·526	1·290	1·128	1·119	1·182	1·562	2·440	3·777	4·943

Table II. (continued).

5 degrees from Fovea.

Observer.	SSN . . .	10	15	20	25	30	35	40	45	50	55	60
W.	log reduction .	$\bar{2}$·256	$\bar{3}$·748	$\bar{3}$·275	$\bar{4}$·918	$\bar{4}$·593	$\bar{4}$·374	$\bar{4}$·253	$\bar{4}$·330	$\bar{3}$·073	$\bar{2}$·184	$\bar{1}$·374
	log energy . . .	1·774	1·505	1·199	0·997	0·846	0·805	0·851	1·176	2·055	3·363	4·791
Bk.	log reduction .	$\bar{2}$·240	$\bar{3}$·760	$\bar{3}$·305	$\bar{4}$·891	$\bar{4}$·537	$\bar{4}$·239	$\bar{4}$·151	$\bar{4}$·331	$\bar{4}$·813	$\bar{3}$·909	$\bar{1}$·093
	log energy . . .	1·758	1·516	1·229	0·970	0·790	0·670	0·749	1·127	1·795	3·088	4·510
T.	log reduction .	$\bar{2}$·469	$\bar{3}$·899	$\bar{3}$·453	$\bar{4}$·978	$\bar{4}$·593	$\bar{4}$·402	$\bar{4}$·257	$\bar{4}$·331	$\bar{4}$·912	$\bar{3}$·994	$\bar{1}$·151
	log energy . . .	1·987	1·655	1·377	1·057	0·846	0·833	0·855	1·127	1·894	3·173	4·568
R.	log reduction. .	$\bar{2}$·803	$\bar{2}$·324	$\bar{3}$·902	$\bar{3}$·500	$\bar{3}$·143	$\bar{4}$·824	$\bar{4}$·639	$\bar{4}$·740	$\bar{3}$·471	$\bar{2}$·453	$\bar{1}$·327
	log energy . . .	2·321	2·080	1·826	1·579	1·396	1·255	1·237	1·536	2·453	3·632	4·744
N.	log reduction	$\bar{2}$·697	$\bar{2}$·172	$\bar{3}$·723	$\bar{3}$·309	$\bar{4}$·974	$\bar{4}$·728	$\bar{4}$·491	$\bar{4}$·580	$\bar{3}$·196	$\bar{2}$·271	
	log energy . . .	2·215	1·928	1·647	1·388	1·227	1·159	1·089	1·376	2·178	3·450	
A.	log reduction .	$\bar{2}$·895	$\bar{2}$·369	$\bar{3}$·872	$\bar{3}$·428	$\bar{3}$·016	$\bar{4}$·742	$\bar{4}$·519	$\bar{4}$·561	$\bar{3}$·322	$\bar{2}$·393	$\bar{1}$·655
	log energy . . .	2·413	2·125	1·796	1·507	1·269	1·173	1·117	1·357	2·304	3·572	5·072
B.	log reduction .	$\bar{2}$·145	$\bar{3}$·643	$\bar{3}$·155	$\bar{4}$·731	$\bar{4}$·368	$\bar{4}$·129	$\bar{5}$·980	$\bar{4}$·113	$\bar{4}$·675	$\bar{3}$·788	$\bar{1}$·035
	log energy . . .	1·713	1·399	1·079	0·810	0·621	0·560	0·578	0·909	1·657	2·967	4·452
Ar.	log reduction .	$\bar{2}$·756	$\bar{2}$·340	$\bar{3}$·901	$\bar{3}$·502	$\bar{3}$·156	$\bar{4}$·920	$\bar{4}$·756	$\bar{4}$·933	$\bar{3}$·482	$\bar{2}$·671	$\bar{1}$·503
	log energy . . .	2·274	2·096	1·825	1·581	1·409	1·351	1·354	1·729	2·464	3·850	4·920

$2\frac{1}{2}$ degrees from Fovea.

Observer.	SSN . . .	10	15	20	25	30	35	40	45	50	55	60
W.	log reduction .	$\bar{2}$·693	$\bar{2}$·172	$\bar{3}$·751	$\bar{3}$·341	$\bar{3}$·017	$\bar{4}$·728	$\bar{4}$·599	$\bar{4}$·715	$\bar{3}$·347	$\bar{2}$·272	$\bar{1}$·304
	log energy . . .	2·211	1·928	1·675	1·420	1·270	1·159	1·197	1·511	2·329	3·451	4·721
Bk.	log reduction .	$\bar{2}$·622	$\bar{2}$·111	$\bar{3}$·648	$\bar{3}$·167	$\bar{4}$·834	$\bar{4}$·474	$\bar{4}$·244	$\bar{4}$·484	$\bar{4}$·998	$\bar{2}$·042	$\bar{1}$·234
	log energy . . .	2·140	1·867	1·572	1·246	1·087	0·905	0·842	1·280	1·980	3·221	4·651
T.	log reduction .	$\bar{2}$·545	$\bar{2}$·036	$\bar{3}$·514	$\bar{3}$·094	$\bar{4}$·762	$\bar{4}$·470	$\bar{4}$·343	$\bar{4}$·485	$\bar{3}$·036	$\bar{2}$·163	$\bar{1}$·128
	log energy . . .	2·063	1·792	1·438	1·173	1·015	0·901	1·041	1·281	2·018	3·342	4·545
R.	log reduction .	$\bar{2}$·805	$\bar{2}$·293	$\bar{3}$·841	$\bar{3}$·414	$\bar{3}$·016	$\bar{4}$·716	$\bar{4}$·454	$\bar{4}$·631	$\bar{3}$·284	$\bar{2}$·272	$\bar{1}$·427
	log energy . . .	2·323	2·049	1·765	1·493	1·269	1·147	1·052	1·427	2·266	3·451	4·844
N.	log reduction .	$\bar{1}$·139	$\bar{2}$·658	$\bar{2}$·126	$\bar{3}$·719	$\bar{3}$·381	$\bar{3}$·096	$\bar{4}$·942	$\bar{3}$·073	$\bar{3}$·533	$\bar{2}$·332	
	log energy . . .	2·657	2·414	2·050	1·798	1·634	1·527	1·540	1·869	2·515	3·511	
A.	log reduction .	$\bar{2}$·849	$\bar{2}$·409	$\bar{3}$·971	$\bar{3}$·530	$\bar{3}$·157	$\bar{4}$·769	$\bar{4}$·523	$\bar{4}$·689	$\bar{3}$·284	$\bar{2}$·188	
	log energy . . .	2·367	2·165	1·895	1·609	1·410	1·200	1·121	1·485	2·266	3·367	
B.	log reduction .	$\bar{2}$·211	$\bar{3}$·641	$\bar{3}$·183	$\bar{4}$·731	$\bar{4}$·421	$\bar{4}$·129	$\bar{5}$·980	$\bar{4}$·013	$\bar{4}$·662	$\bar{3}$·607	$\bar{1}$·035
	log energy . . .	1·729	1·397	1·107	0·810	0·674	0·550	0·578	0·809	1·644	2·786	4·552
Ar.	log reduction .	$\bar{1}$·080	$\bar{2}$·658	$\bar{2}$·141	$\bar{3}$·648	$\bar{3}$·297	$\bar{3}$·055	$\bar{4}$·964	$\bar{3}$·200	$\bar{3}$·745	$\bar{2}$·731	$\bar{1}$·239
	log energy . . .	2·598	2·414	$\bar{2}$·065	1·727	1·550	1·486	1·562	1·996	2·727	3·910	4·656

Table II. (continued).

1¼ degrees from Fovea.

Observer.	SSN . . .	10	15	20	25	30	35	40	45	50	55	60
W.	log reduction .	$\bar{1}$·336	$\bar{2}$·824	$\bar{2}$·350	$\bar{3}$·922	$\bar{3}$·537	$\bar{2}$·245	$\bar{3}$·087	$\bar{3}$·201	$\bar{3}$·707	$\bar{2}$·308	$\bar{1}$·164
	log energy . . .	2·854	2·580	2·274	2·001	1·790	1·676	1·685	1·997	2·689	3·487	4·581
Bk.	log reduction .	$\bar{2}$·926	$\bar{2}$·536	$\bar{2}$·126	$\bar{3}$·762	$\bar{3}$·396	$\bar{3}$·109	$\bar{4}$·887	$\bar{4}$·926	$\bar{3}$·483	$\bar{2}$·272	$\bar{1}$·152
	log energy . . .	2·444	2·392	2·050	1·841	1·649	1·540	1·485	1·722	2·465	3·451	4·569
T.	log reduction .	$\bar{2}$·971	$\bar{2}$·521	$\bar{3}$·992	$\bar{3}$·500	$\bar{3}$·016	4·715	$\bar{4}$·520	$\bar{4}$·664	$\bar{3}$·347	$\bar{2}$·272	$\bar{1}$·210
	log energy . . .	2·489	2·277	1·916	1·579	1·269	1·146	1·118	1·460	2·329	3·451	4·627
R.	log reduction .	—	$\bar{1}$·279	$\bar{2}$·858	$\bar{2}$·401	$\bar{2}$·002	$\bar{3}$·654	$\bar{3}$·440	$\bar{3}$·470	$\bar{3}$·819	$\bar{2}$·344	$\bar{1}$·210
	log energy . . .	—	3·035	2·782	2·480	2·255	2·085	2·038	2·266	2·801	3·523	4·627
N.	log reduction .	$\bar{1}$·123	$\bar{2}$·703	$\bar{2}$·276	$\bar{3}$·864	$\bar{3}$·422	$\bar{3}$·055	$\bar{4}$·758	$\bar{4}$·791	$\bar{3}$·347	$\bar{2}$·212	
	log energy . . .	2·641	2·459	2·200	1·943	1·675	1·486	1·356	1·587	2·329	3·391	
A.	log reduction .	$\bar{2}$·499	$\bar{3}$·991	$\bar{3}$·499	$\bar{3}$·138	$\bar{4}$·734	$\bar{4}$·375	$\bar{4}$·189	$\bar{4}$·542	$\bar{3}$·197	$\bar{3}$·990	$\bar{1}$·096
	log energy . . .	2·017	1·747	1·423	1·217	0·987	0·806	0·787	1·338	2·179	3·169	4·513
B.	log reduction .	$\bar{2}$·439	$\bar{3}$·916	$\bar{3}$·408	$\bar{4}$·876	$\bar{4}$·481	$\bar{4}$·130	$\bar{5}$·980	$\bar{4}$·113	$\bar{4}$·687	$\bar{3}$·788	$\bar{2}$·986
	log energy . . .	1·957	1·672	1·332	0·955	0·734	0·561	0·578	0·909	1·669	2·967	4·403
Ar.	log reduction .	$\bar{1}$·351	$\bar{2}$·976	$\bar{2}$·545	$\bar{2}$·111	$\bar{3}$·650	$\bar{3}$·286	$\bar{3}$·074	$\bar{3}$·291	$\bar{3}$·844	$\bar{2}$·611	$\bar{1}$·362
	log energy . . .	2·869	2·732	2·469	2·190	1·903	1·717	1·672	2·087	2·826	3·790	4·779

In fig. 4 the logarithms of the energy at the threshold are plotted against the deviations (colour) for W., while in fig. 5 the corresponding curves for B. are given. In the case of W. the curve corresponding to the fovea is very much higher, *i.e.*, the threshold is higher that for the peripheral curves, and with the intensity of spectrum used the central curve could not be traced beyond SSN 35 on the blue side. In the case of B., however, the foveal curve is lower than any of the others, showing that for this observer the threshold is lower at the fovea than for any other part of the retina, while all the curves can be traced right down to SSN 10. For W. as we proceed outwards from the fovea the threshold values, except in the red, rapidly decrease, indicating an increasing sensitiveness, up to 5 degrees, there being a slight decrease at

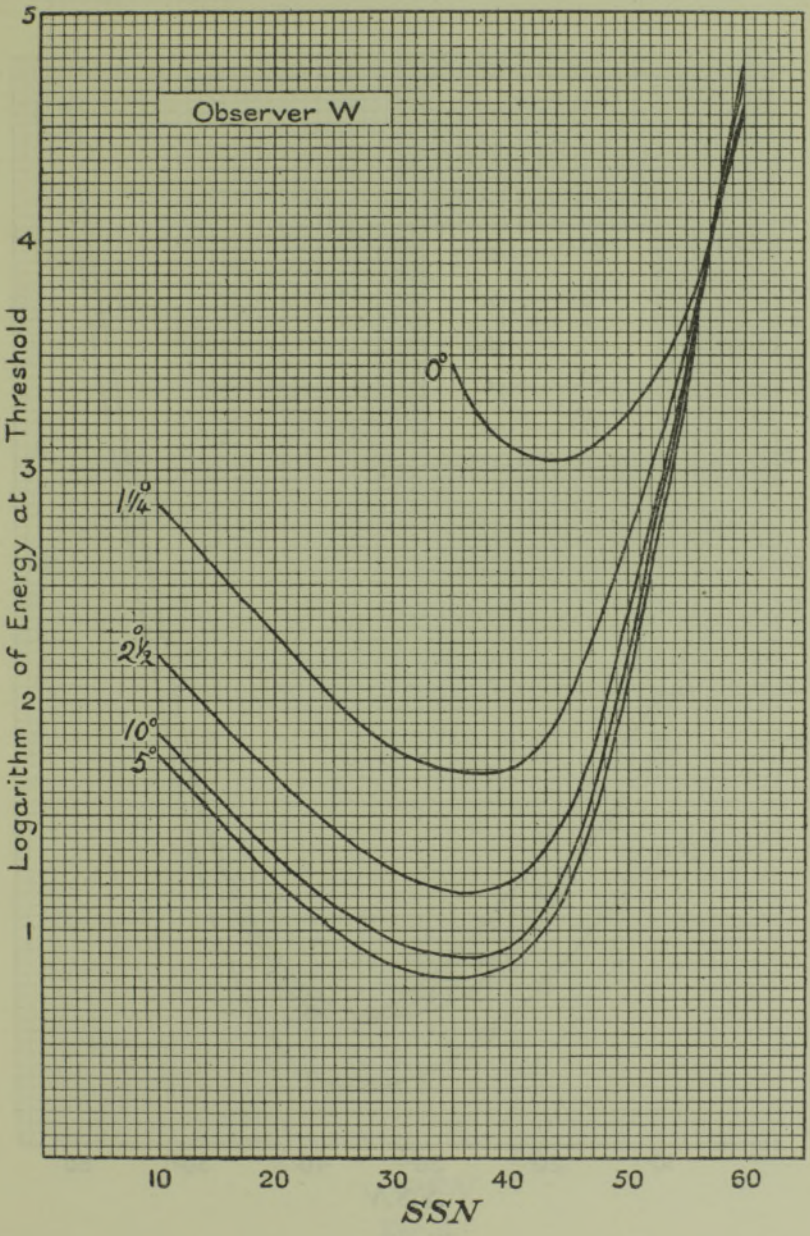

Fig. 4.

10 degrees. For B., while the threshold at the fovea is slightly lower than for the rest of the retina, the values obtained at the other distances are very nearly the same, indicating that over this region of his retina the sensitiveness remains practically constant for light of very low intensities. This peculiarity that the sensitiveness of B.'s retina for feeble lights is a maximum at the fovea has some interesting consequences. Thus he finds no difficulty in obtaining central fixation and he can obtain luminosity measurements even with very feeble intensities which are quite consistent. With W., on the contrary, central fixation with feeble lights is difficult, and when he attempts to make luminosity measurements at low intensities his results are very irregular, owing to the tendency to use the parafoveal regions of the retina, which are more sensitive than the fovea. Adopting as beforesaid for convenience von Kries's

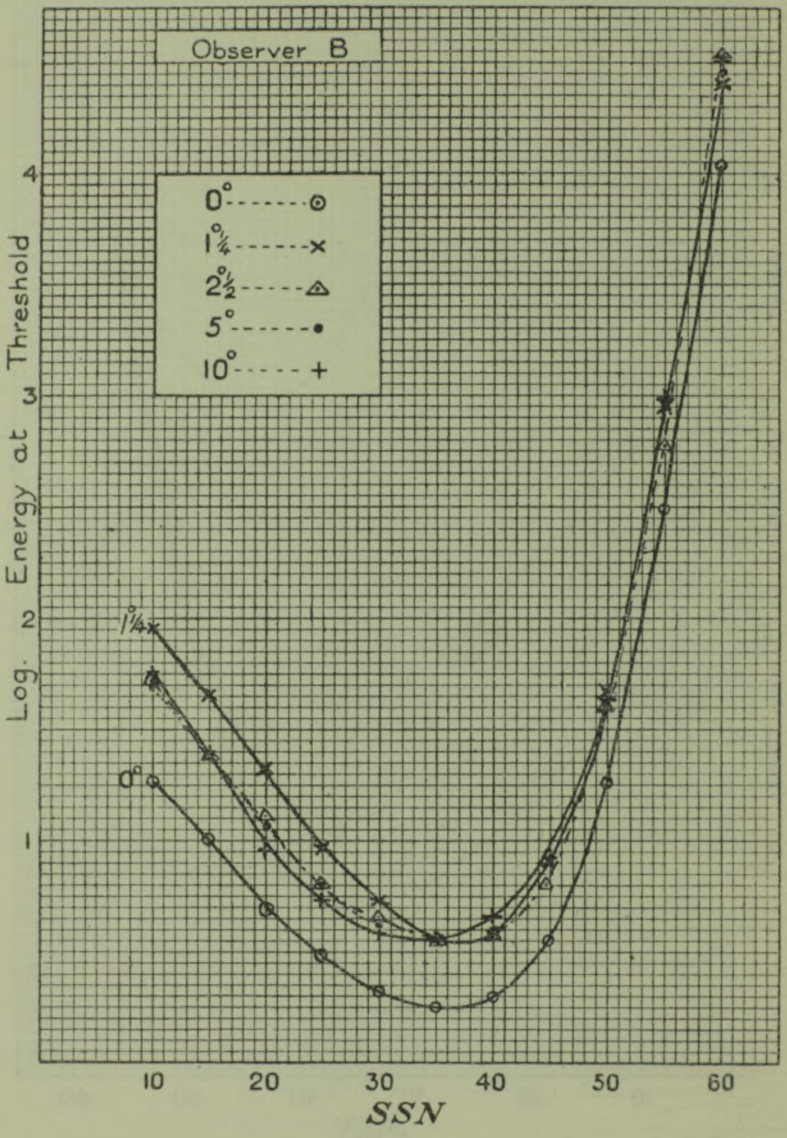

Fig. 5.

theory, the results indicate that in the case of W. the fovea is free from rods while the number of rods increase rapidly as we go from the fovea. In the case of B., however, the distribution of rods, at any rate up to at least 10 degrees, is very nearly uniform, if anything there being an excess at the fovea. It is, however, possible that the lower value for the threshold obtained at the fovea may be due to the better definition of the image formed at the fovea, so that the falling off of the sensitiveness as we go from the fovea may possibly be due to spherical aberration of the eye.

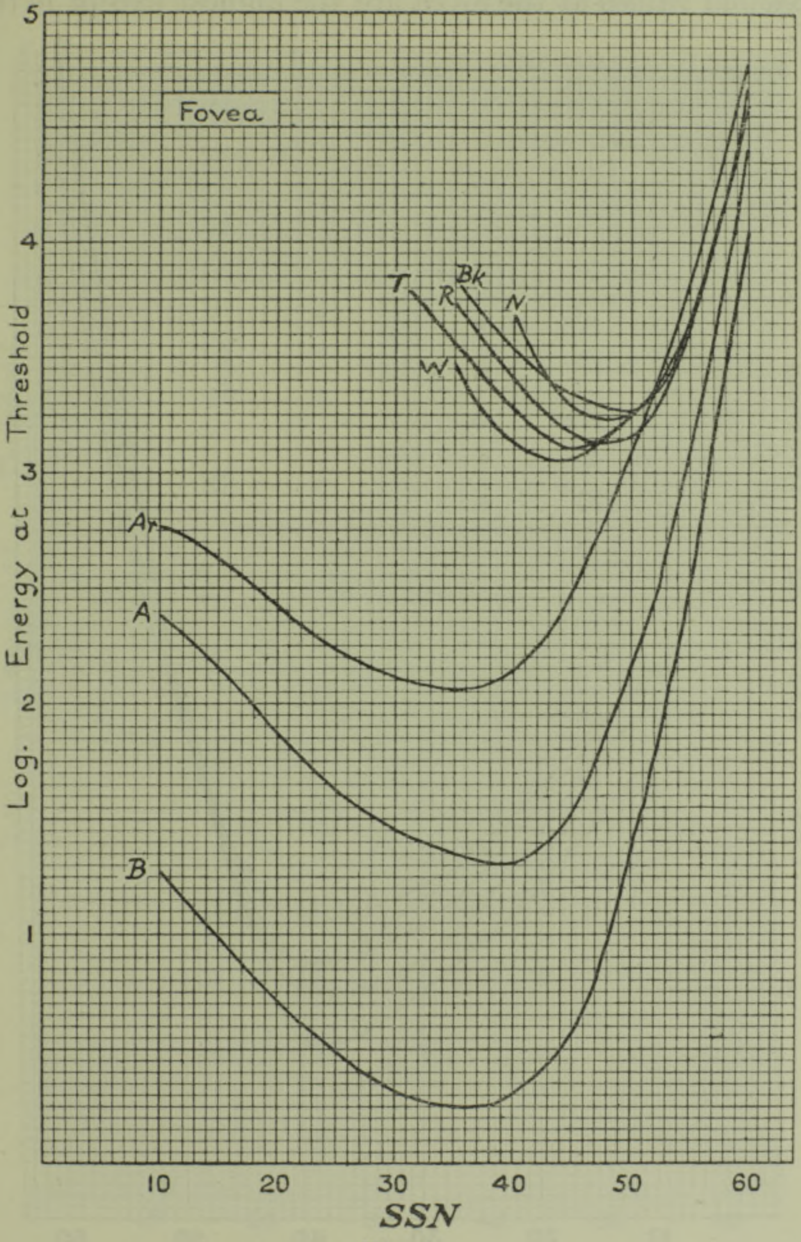

Fig. 6.

In fig. 6 the curves corresponding to the foveal measurements for all the observers are plotted together, and it will be seen that in the case of observers W., T., Bk., R. and N. the curves are in very fair agreement, and we may classify these persons as belonging to a single class, I., who have a fovea practically free from rods. Observers B., A.

and Ar. on the other hand belong to another class, II., who have a more or less plentiful supply of rods at the fovea.

Since persons belonging to class II. so far appear to be less common, and as much greater individual variation occurs in this class than in class I., we give the series of curves for the two other observers of class II. It will be noticed that in the case of A (fig. 7) the threshold values at the fovea are the highest except in the red, while the

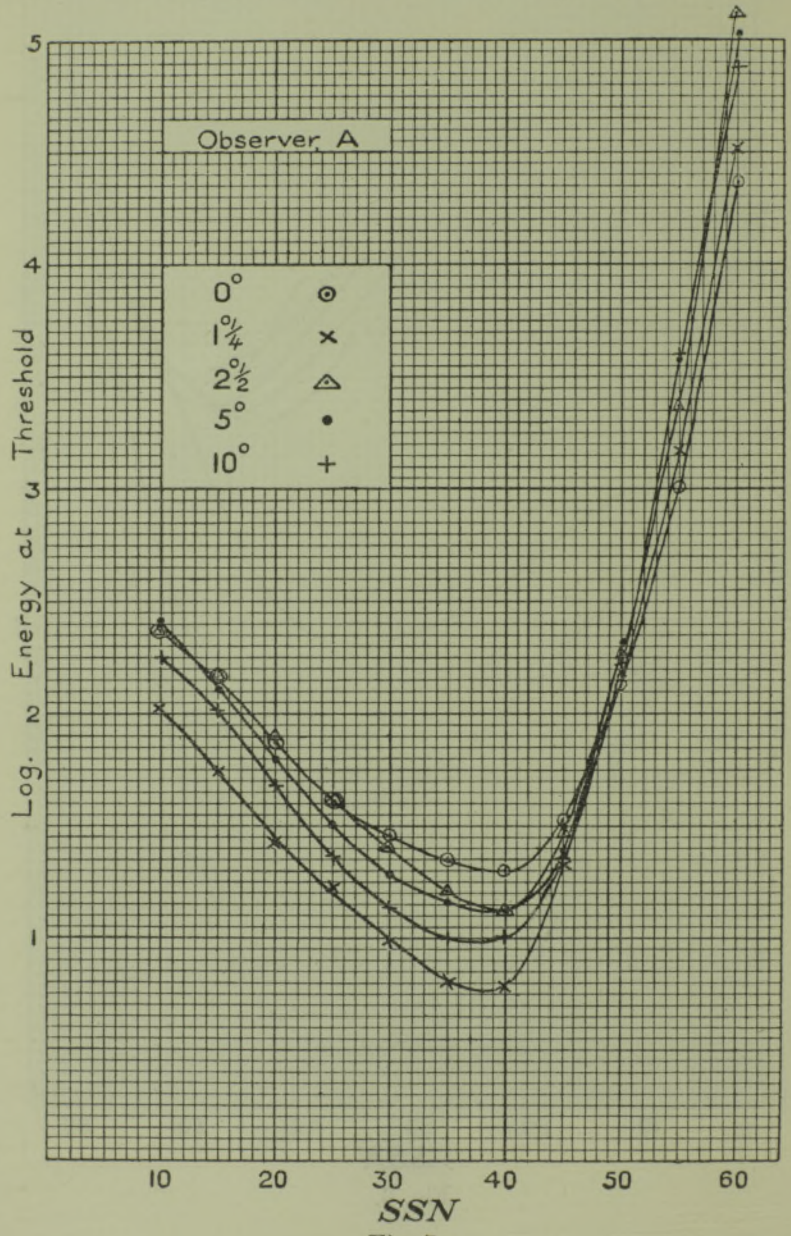

Fig. 7.

values at 1·25 degrees from the fovea are the lowest. The differences for the different parts of the region studied are not however very great, so that up to 10 degrees from the fovea the distribution of rods is fairly uniform. In the case of Ar. (fig. 8) there is a fairly uniform decrease in the threshold values as we go out from the fovea, at any rate up to 10 degrees.

The differences obtained at the fovea between observers belonging to the two classes could be explained without supposing any distinction as to the distribution of rods if we suppose that the observers belonging to class II. did not obtain correct foveal fixation. There is, however, strong evidence that this is not the correct explanation. In the first place observers A. and B. are very expert in making this kind of observation. They can repeat their measures day after day even after many months and obtain constant values. Had there been any faulty fixation the measurements obtained would not remain constant but would be of the same nature as those illustrated in fig. 2. Further evidence that in the case of A. and B. there are rods at the fovea will be given later.

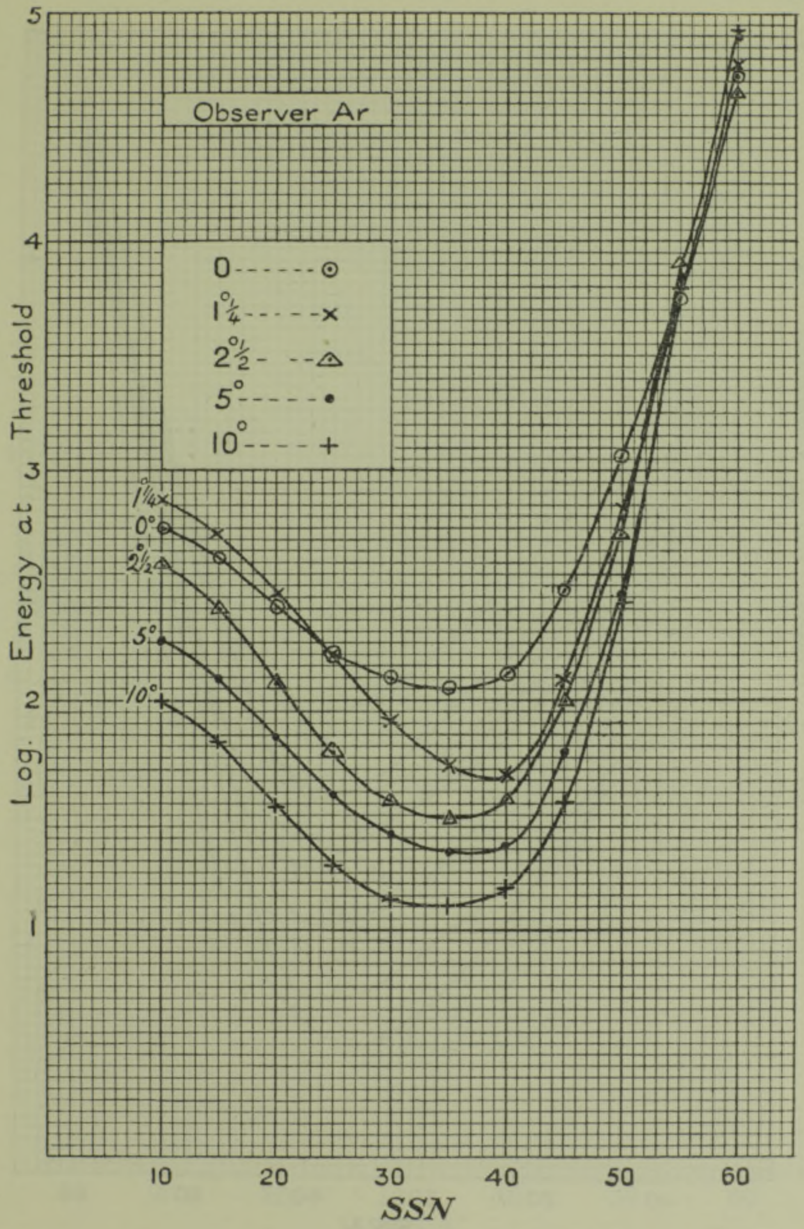

Fig. 8.

In the case of observers of class I., the light just before it is extinguished at the fovea gives the sensation of *colour*. This is particularly well marked in the green, where the faintest light observable with central fixation appears of a dull but very saturated green. In the case of observers of class II., on the other hand, as long as the stimulus light is red they can distinguish the red colour when the light is visible at all, but throughout the rest of the spectrum the light loses colour a considerable time before it is extinguished. These class II. observers have an achromatic interval throughout the whole of the spectrum except perhaps in the red.

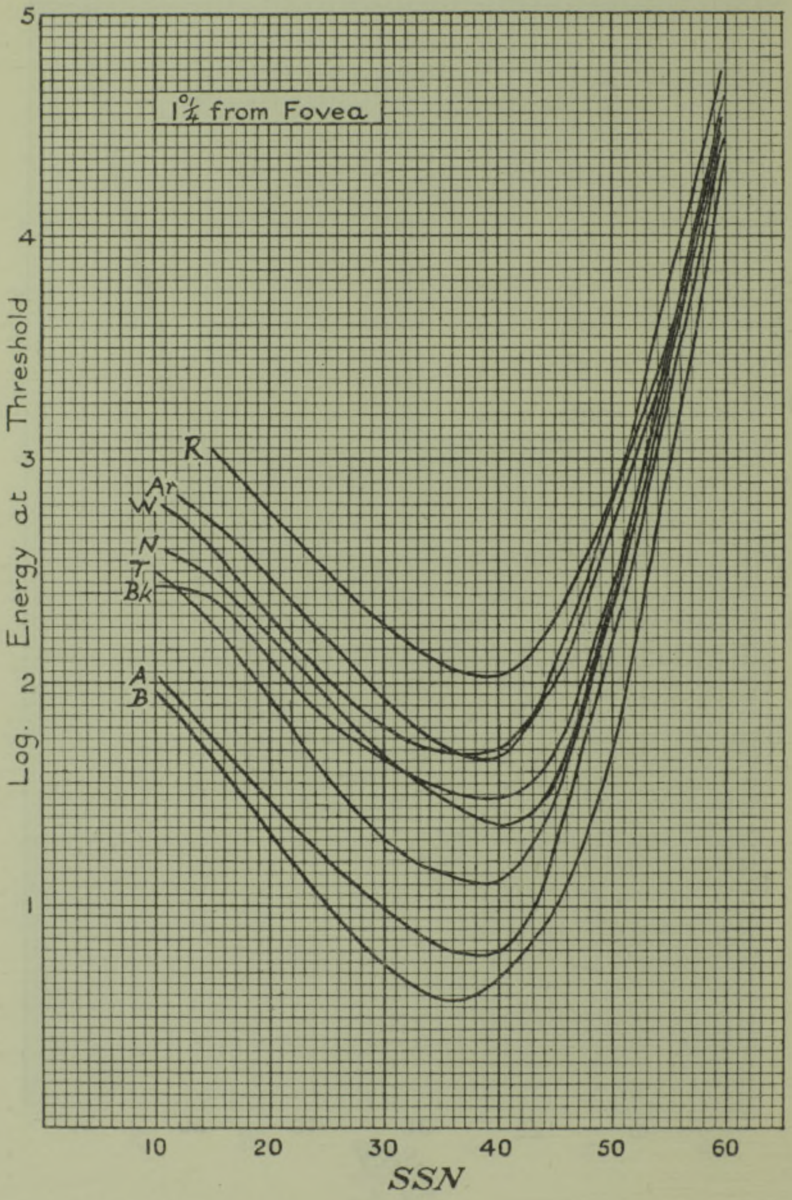

Fig. 9.

It may be remarked, that when W. attempted to determine his foveal threshold values without using the arrangements which have been described above, but employing a continuous illumination which was gradually decreased in intensity, his results were very variable, but corresponded roughly to those obtained at about 2·5 degrees from the fovea though he was under the impression that correct fixation was being secured. During the course of these observations, however, he noticed that the light sometimes appeared to vanish, and he satisfied himself that this occurred whenever he managed to bring the image on the fovea. If, when using the fixation spot and shutter for central fixation the annulus is turned till the light has vanished, say in the green, if the eye is moved a little bit on one side of the fixation spot and the shutter opened, the flash of light seen appears almost blinding.

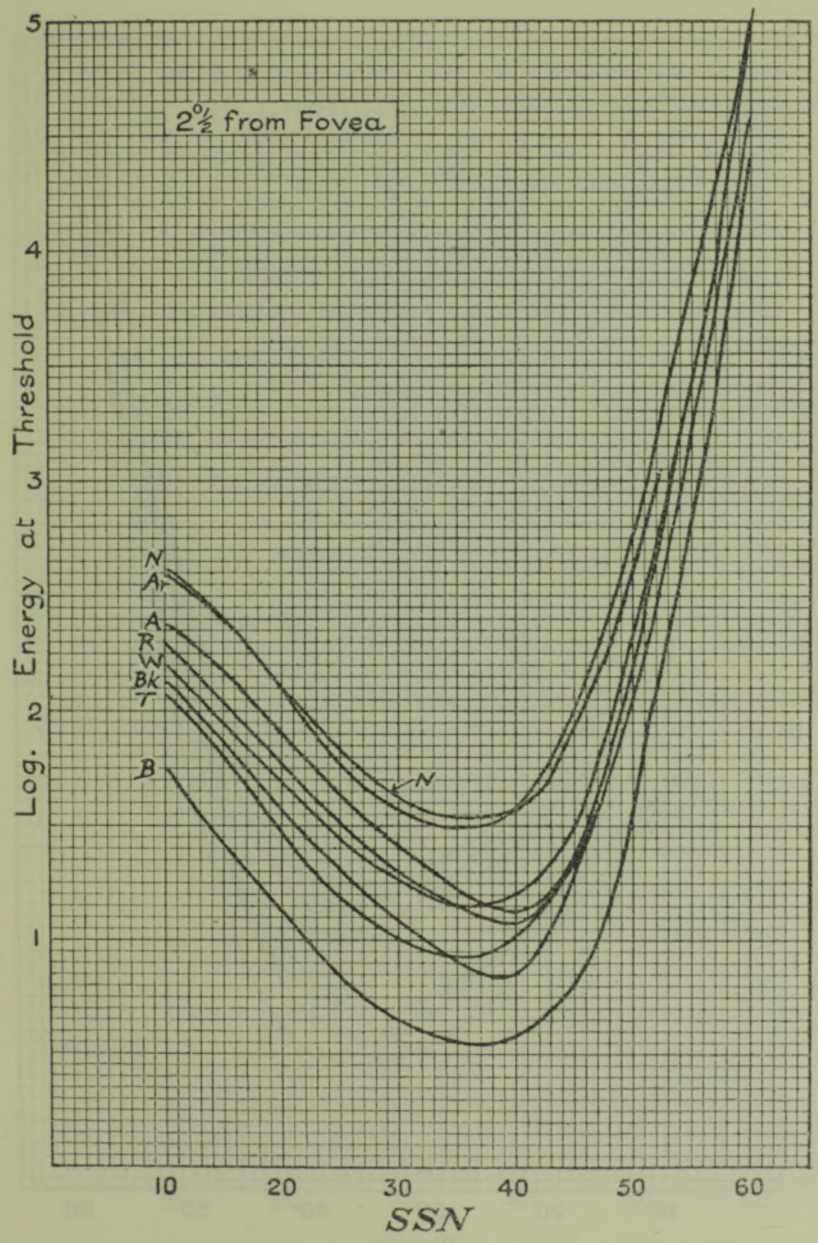

Fig. 10.

In fig. 9 are collected together all the curves for 1·25 degrees from the fovea, and it will be noted how in the case of all observers of class I., there is a marked change from the values at the fovea, but they approximate much more nearly to those obtained by observers of class II. While the threshold values for observers A. and B. are definitely lower than any of the others, observer Ar. has at 1·25 degrees threshold values higher than those of the majority of class I.

In figs. 10, 11, and 12 are collected the threshold curves for 2·5, 5, and 10 degrees, and it will be seen that in each case there is no distinction between the two classes.

With regard to the observers having abnormal colour vision, Ar. and R. have threshold values which do not differ materially from the values obtained by persons with normal colour vision. The red blind observer N. has a markedly higher threshold value at the red end of the spectrum, in fact the spectrum employed in the measurements was not sufficiently bright for him to obtain readings beyond SSN 55 (625 $\mu\mu$). In the green, blue, and violet, his values for the threshold agree with the normal.

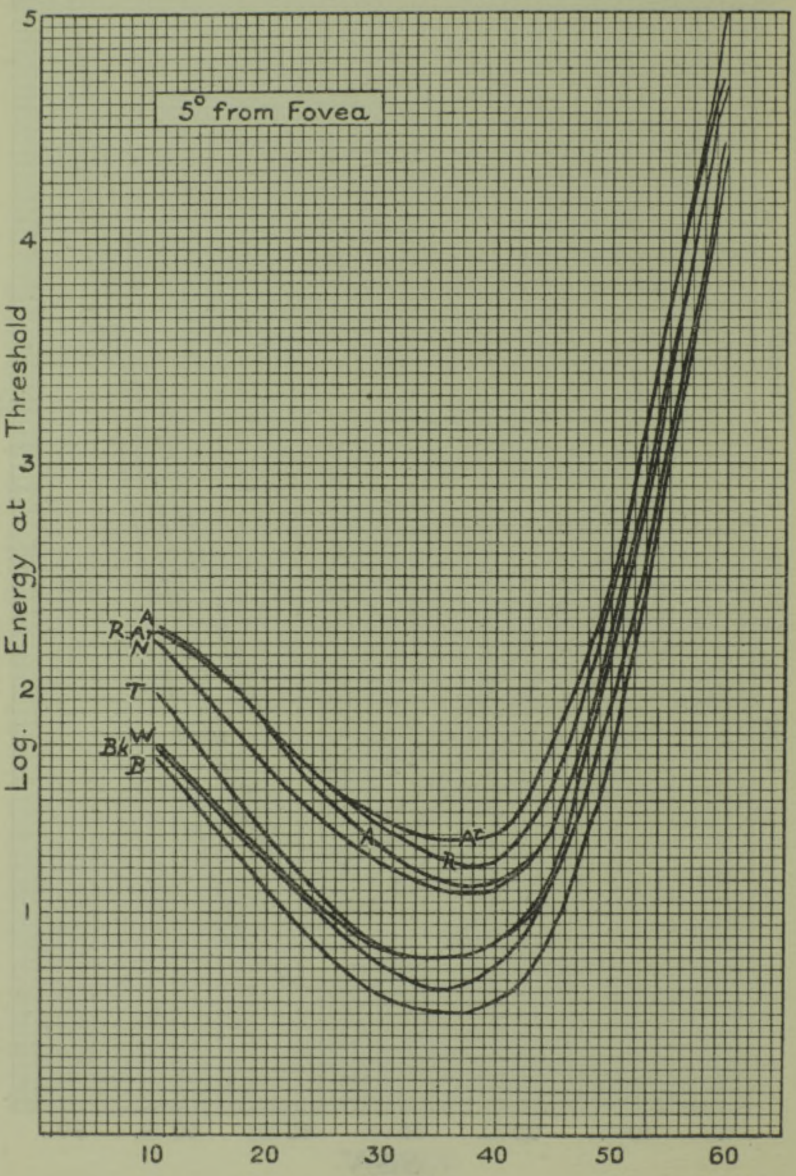

Fig. 11.

The threshold in the red, we are assuming, depends on the cones, and N.'s cone vision is defective since he has a shortened spectrum, hence his high threshold values at the red end.

Piper (' Zeit. f. Psychol. u. Physiol. d. Sinn.,' 32, 161, 1904 ; see also Helmholtz ' Physiol. Optik,' 3rd edition, vol. 2, 286) found that with the dark adapted eye, and with stimuli which approach the threshold, binocular summation occurs, so that when a feebly illuminated surface was examined with both eyes it appeared nearly twice as bright as when one eye only was used. He also found that the threshold values for the two eyes used together were about half the values for either eye used separately. It seemed of interest to examine whether this summation effect would be the same for observers of the two classes, and hence W. (class I.) and B. (class II.) made

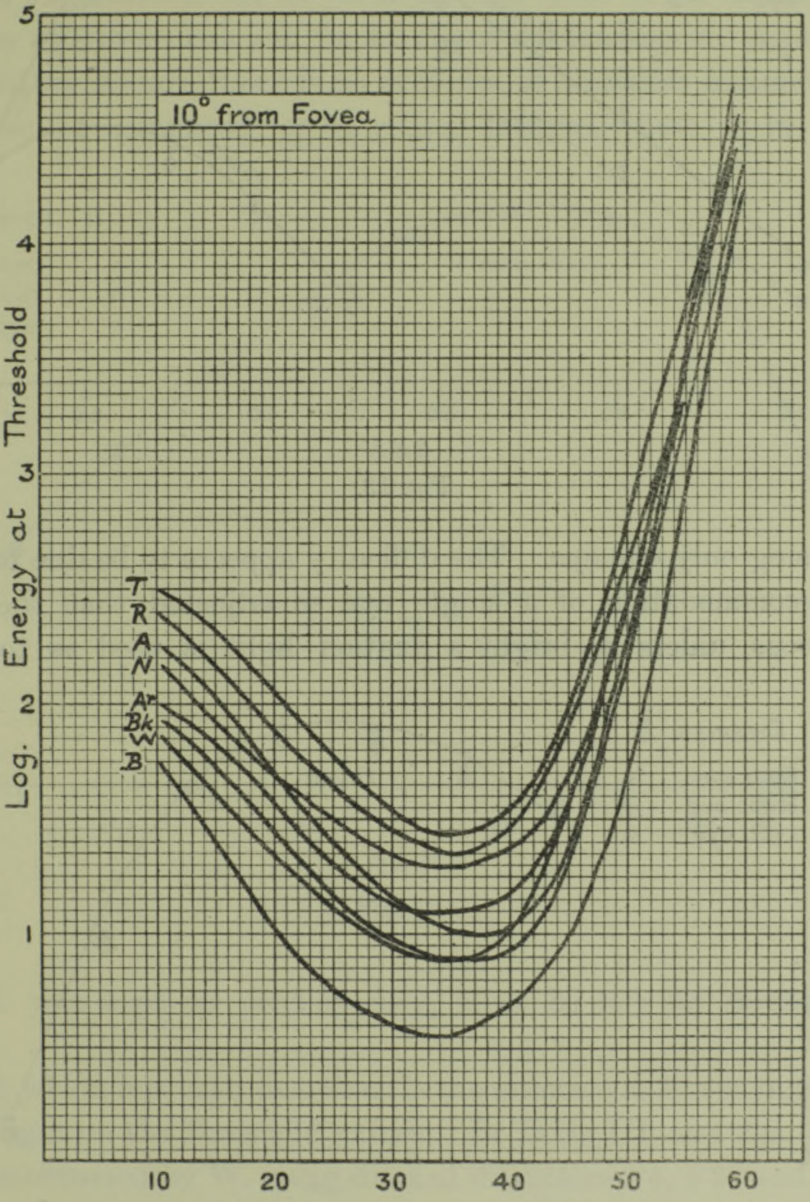

Fig. 12.

threshold observations using (1) both eyes, (2) the right eye only, and (3) the left eye only. Sets of observations were made both at the fovea and at 5 degrees from the fovea. They both found that it was much more difficult to obtain satisfactory settings when using only one eye. The difficulty appears to be due to not being able to keep the accommodation of a single eye so adjusted that the fixation light is always in focus, unless so bright a fixation light is used as to interfere with the extinction settings. The actual annulus readings obtained are plotted in figs. 13, 14, and 15. It will be seen that for W. at 5 degrees from the fovea the

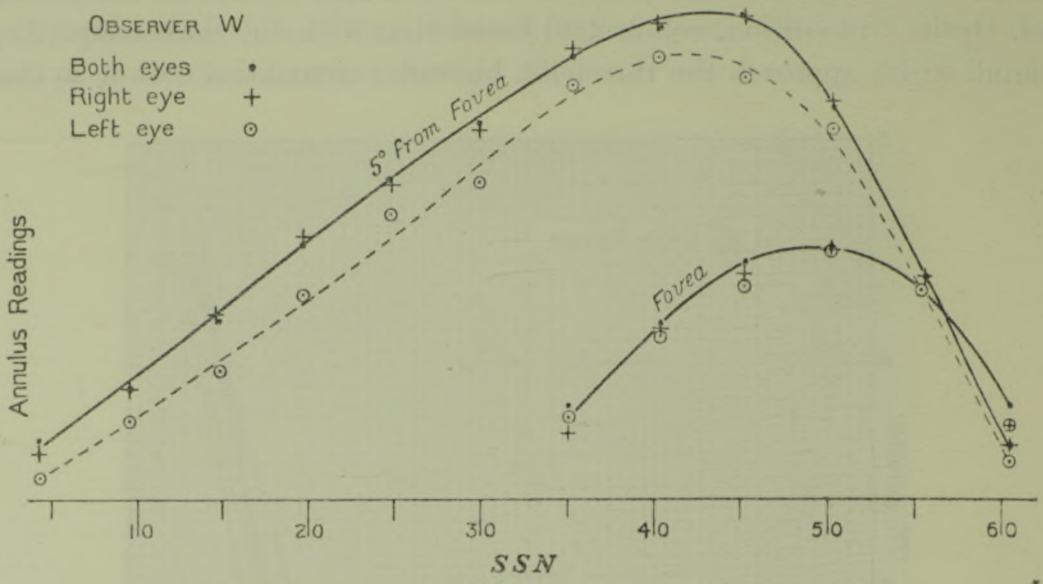

Fig. 13.

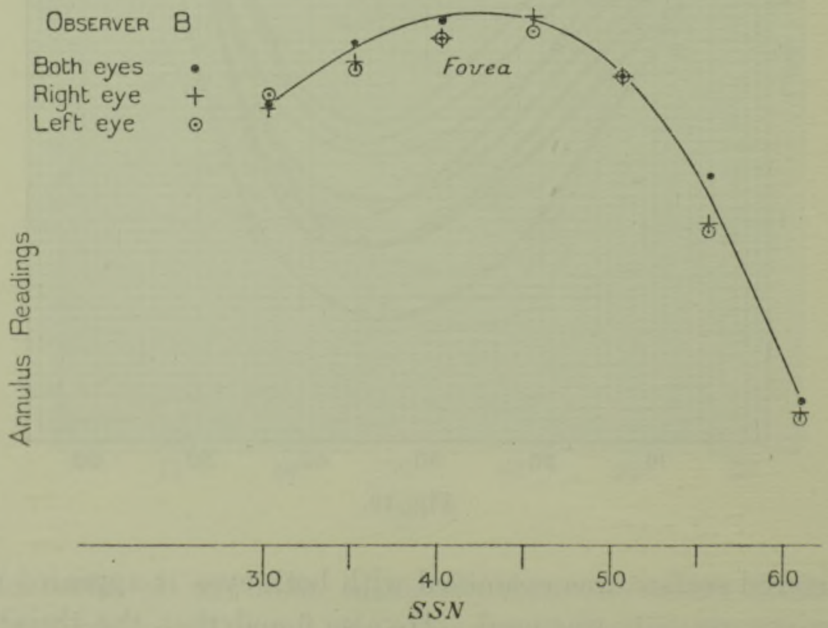

Fig. 14.

readings for the left eye are decidedly lower (a lower annulus reading corresponds to a higher threshold value) than for the right eye. Further, that with the two eyes together the threshold values agree with those corresponding to the better of the two eyes taken alone. At the fovea the threshold values are the same whether both eyes are used or either eye separately. In the case of B., figs. 14, 15, the values obtained with each eye separately agree with the values obtained with both eyes used together. These experiments are at variance with those of Piper, and show that for a typical observer of either class and for an object subtending an angle of 34 minutes and using momentary stimuli there is no evidence of binocular summation. Whether the difference can be accounted for by retinal fatigue, where as in Piper's experiments the light was kept on continuously, must be left for further experimental investigation.

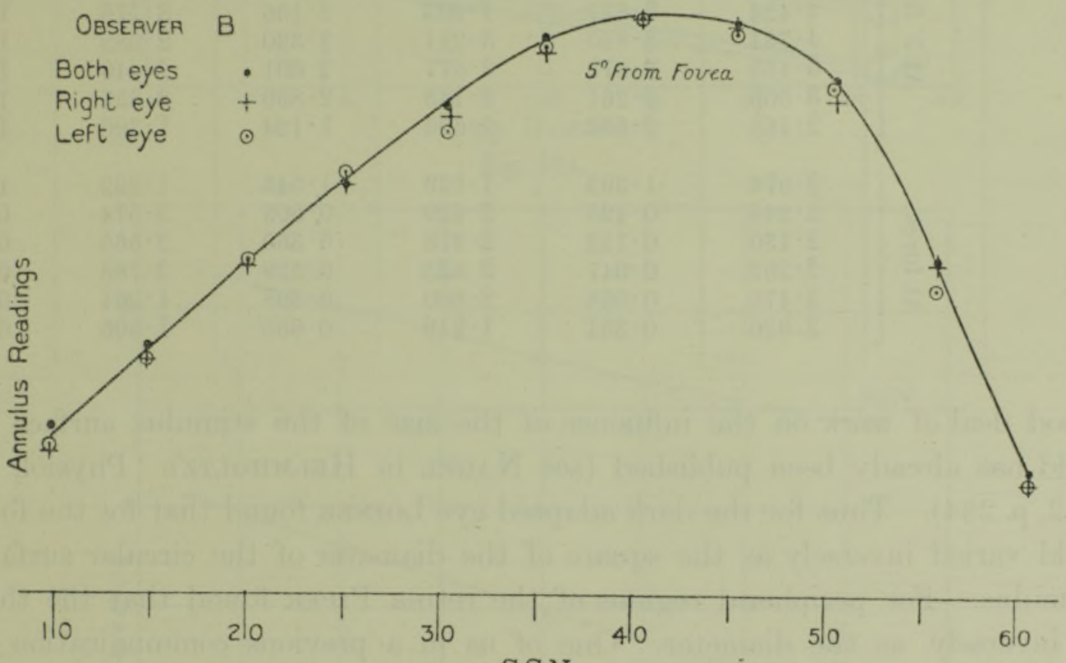

Fig. 15.

Another point which has been examined is the question as to the influence of the size of the stimulus light on the threshold values. In Table III. and figs. 16A and 16B are given the results obtained by W. using discs of diameters 2·8, 6·33 and 13·0 mm. which subtended at the eye angles of 14 and 31 minutes and 1 degree 2 minutes respectively. Observations were made both at the fovea and at 5 degrees from the fovea. When comparing these results with those given in Table II. it must be observed that owing to loss of accommodation during the interval which elapsed between the two sets of observations W. had to use spectacles when making these latter measurements. In the figure the logarithms of the energy at the threshold have been plotted against the logarithm of the diameter of the disc on which the stimulus light fell.

TABLE III.

Angle subtended by disc.		1° 8′.		34′.		17′.	
SSN.		log reduction.	log energy.	log reduction.	log energy.	log reduction.	log energy.
60	At 5° from fovea.	$\bar{1}\cdot 012$	1·429	$\bar{1}\cdot 327$	1·744	$\bar{1}\cdot 795$	2·212
55		$\bar{3}\cdot 873$	0·052	$\bar{2}\cdot 308$	0·487	$\bar{2}\cdot 876$	1·055
50		$\bar{4}\cdot 848$	$\bar{2}\cdot 830$	$\bar{3}\cdot 333$	$\bar{1}\cdot 315$	$\bar{2}\cdot 031$	0·013
45		$\bar{4}\cdot 293$	$\bar{2}\cdot 089$	$\bar{4}\cdot 676$	$\bar{2}\cdot 472$	$\bar{3}\cdot 521$	$\bar{1}\cdot 317$
40		$\bar{4}\cdot 126$	$\bar{3}\cdot 724$	$\bar{4}\cdot 555$	$\bar{2}\cdot 153$	$\bar{3}\cdot 388$	$\bar{2}\cdot 986$
35		$\bar{4}\cdot 198$	$\bar{3}\cdot 629$	$\bar{4}\cdot 660$	$\bar{2}\cdot 091$	3·531	$\bar{2}\cdot 962$
30		$\bar{4}\cdot 424$	$\bar{3}\cdot 677$	$\bar{4}\cdot 903$	$\bar{2}\cdot 156$	$\bar{3}\cdot 776$	$\bar{1}\cdot 029$
25		$\bar{4}\cdot 761$	3·840	$\bar{3}\cdot 241$	$\bar{2}\cdot 320$	$\bar{2}\cdot 082$	$\bar{1}\cdot 161$
20		$\bar{3}\cdot 155$	$\bar{2}\cdot 079$	$\bar{3}\cdot 677$	$\bar{2}\cdot 601$	$\bar{2}\cdot 440$	$\bar{1}\cdot 364$
15		$\bar{3}\cdot 505$	$\bar{2}\cdot 261$	$\bar{2}\cdot 143$	$\bar{2}\cdot 899$	$\bar{2}\cdot 855$	$\bar{1}\cdot 611$
10		$\bar{2}\cdot 165$	$\bar{2}\cdot 683$	$\bar{2}\cdot 606$	$\bar{1}\cdot 124$	$\bar{1}\cdot 306$	$\bar{1}\cdot 824$
60	At fovea.	$\bar{2}\cdot 976$	1·393	$\bar{1}\cdot 129$	1·546	$\bar{1}\cdot 292$	1·709
55		$\bar{2}\cdot 246$	0·425	$\bar{2}\cdot 429$	0·608	$\bar{2}\cdot 574$	0·753
50		$\bar{2}\cdot 130$	0·112	$\bar{2}\cdot 378$	0·360	$\bar{2}\cdot 565$	0·547
45		$\bar{2}\cdot 251$	0·047	$\bar{2}\cdot 533$	0·329	$\bar{2}\cdot 788$	0·584
40		$\bar{2}\cdot 470$	0·068	$\bar{2}\cdot 800$	0·398	$\bar{1}\cdot 064$	0·662
35		$\bar{2}\cdot 920$	0·351	$\bar{1}\cdot 219$	0·650	$\bar{1}\cdot 505$	0·736

A good deal of work on the influence of the size of the stimulus surface on the threshold has already been published (see NAGEL in HELMHOLTZ's 'Physiol. Optik,' 3 edit., 2, p. 284). Thus for the dark adapted eye LOESER found that for the fovea the threshold varied inversely as the square of the diameter of the circular surface used as a stimulus. For peripheral regions of the retina PIPER found that the threshold varied inversely as the diameter. One of us in a previous communication ('Phil. Trans.' A, vol. 190, 168, 1897) found that for the fovea and for discs which did not subtend a greater angle than 4 degrees the threshold varied inversely as D/·65 where D is the diameter of the stimulus disc or the angle subtended at the eye. If the threshold value, T, varies inversely as D^n, then on plotting the logarithms of the threshold values against the logarithms of D we should obtain a straight line, the tangent of the inclination of which to the D axis will be equal to n. In figs. 16A and 16B dotted curves are drawn for values of n equal to 1, 1·65 and 2, that is corresponding to the results obtained by PIPER, ABNEY, and LOESER respectively. From figs. 16A and 16B it will be seen that the numbers obtained by W. by the method described in this paper give approximately straight lines at the fovea and at the red end of the spectrum at 5 degrees from the fovea, but depart very appreciably from a straight line throughout the rest of the spectrum at 5 degrees. At the fovea the inclination of the lines joining the observed points agrees fairly closely with that corresponding to the threshold value varying inversely as the diameter. At 5 degrees on the other hand the inclination of the lines joining the observed points is approximately that corresponding to the threshold

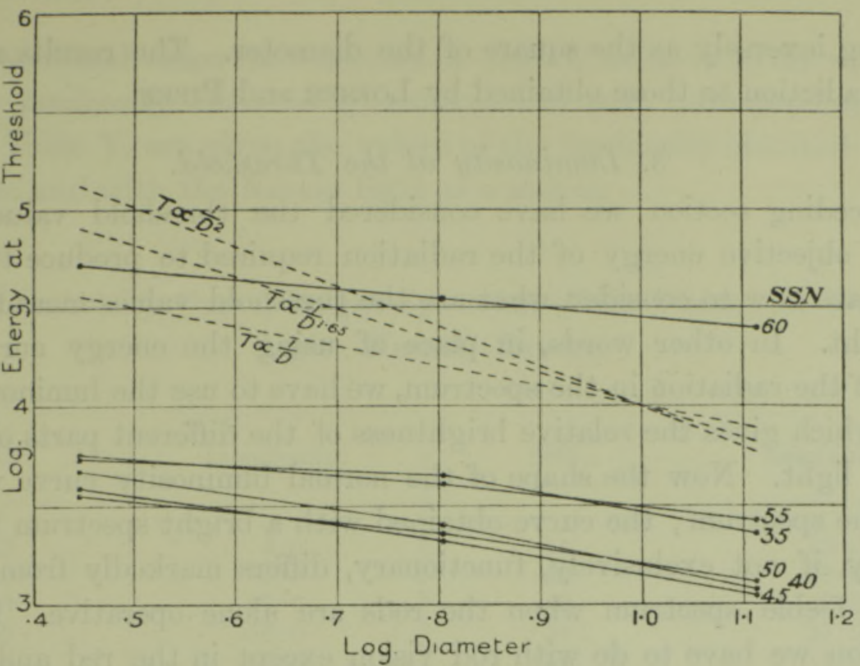

Fig. 16A.

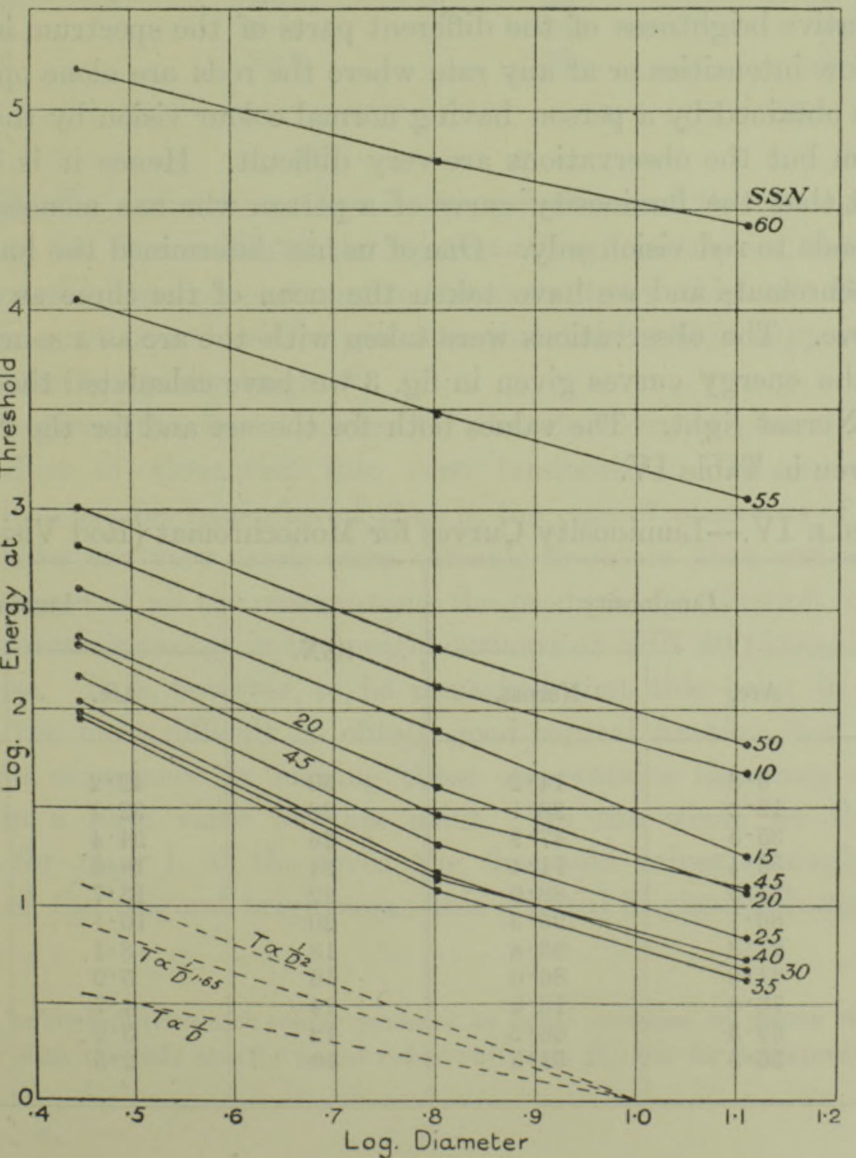

Fig. 16B.

values varying inversely as the square of the diameter. The results are therefore in marked contradiction to those obtained by LOESER and PIPER.

3. *Luminosity at the Threshold.*

In the preceding section we have considered the threshold values measured in terms of the objective energy of the radiation required to produce the sensation of light. We have now to consider what are the threshold values measured in terms of subjective light. In other words, in place of using the energy curve to give the distribution of the radiation in the spectrum, we have to use the luminosity curve, that is the curve which gives the relative brightness of the different parts of the spectrum considered as light. Now the shape of the normal luminosity curve varies with the intensity of the spectrum; the curve obtained with a bright spectrum when the cones are principally, if not exclusively, functionary, differs markedly from that obtained with a very feeble spectrum when the rods are alone operative. In the case of threshold vision we have to do with rod vision except in the red and for the foveal values obtained by observers of class I., and hence the luminosity curve to be employed to give the relative brightness of the different parts of the spectrum is that obtained at extremely low intensities or at any rate where the rods are alone operative. Such a curve can be obtained by a person having normal colour vision by the use of a very feeble spectrum but the observations are very difficult. Hence it is better to make use of the fact that the luminosity curve of a person who has monochromatic colour vision corresponds to rod vision only. One of us has determined the luminosity curves of three monochromats and we have taken the mean of the three as giving the rod luminosity curve. The observations were taken with the arc as a source of light but by means of the energy curves given in fig. 3 we have calculated the corresponding curve for the Nernst light. The values both for the arc and for the Nernst as light sources are given in Table IV.

TABLE IV.—Luminosity Curves for Monochromat (Rod Vision).

SSN.	Luminosity.		SSN.	Luminosity.	
	Arc.	Nernst.		Arc.	Nernst.
52	8·8	14·2	30	42·2	37·5
50	19·2	28·1	28	32·1	27·5
48	35·5	47·9	26	24·4	20·4
46	56·4	71·4	24	18·6	15·1
44	74·5	88·0	22	13·7	11·1
42	86·1	95·3	20	10·1	8·1
40	87·8	93·8	18	8·1	6·4
38	84·8	86·0	16	5·9	4·6
36	78·8	78·0	14	4·7	3·6
34	69·3	66·2	12	3·2	1·6
32	56·5	51·5	10	2·3	

In the case of foveal vision for observers of class I. we have to do with cone vision and hence the luminosity curve to be employed is that corresponding to a bright spectrum. In Table V. are given the values of the luminosity obtained by W. with a bright spectrum and with the Nernst light as a source.

TABLE V.—Luminosity Curve, Bright Spectrum (Cone Vision) for W. Source of Light, Nernst Glower.

SSN.	Luminosity.	SSN.	Luminosity.
62	3·0	44	75·0
60	11·5	42	59·5
58	27·0	40	42·5
56	56·0	38	27·5
54	83·0	36	15·2
52	94·5	34	8·2
50	99·5	32	4·7
48	99·0	30	4·5
46	90·0	28	4·0

If we multiply the extinctions (that is the reductions of the various parts of the spectrum to give the threshold) by the corresponding luminosities, the products will give us numbers which are proportional to the amounts by which the different colours of the spectrum must be reduced to give the threshold. This supposes each colour before reduction to be equally bright.*

In fig. 17 are given the foveal curves for the observers of class I., the ordinates being the product of extinction into cone luminosity. The curves are rather irregular, but it must be remembered that in the case of observers of this class the foveal observations are very much more difficult to obtain than extrafoveal values. If we take the mean of all the observations the product of extinction into luminosity is very nearly constant except in the neighbourhood of SSN 40 ($527\mu\mu$), where there is a decided rise. It is, however, to be remarked that this point in the spectrum appears to be the most difficult to obtain good central fixation, and W., who has had much more experience in making these observations than any of the others, does not obtain a high value at this point. On the whole we think we may conclude that for class I. at the fovea the threshold values throughout have the same fraction of the original brightness; this original brightness being the same for all colours.

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* With class I. before reduction each colour produces an equal sensation by means of cones only with foveal fixation or with the rods also for foveal vision with class II., and for extra-foveal vision for both classes.

In fig. 18 are given the foveal extinctions for the observers of class II. multiplied by the rod luminosities. Except in the orange and red, where we have chiefly to do with cone vision, the curve for observer B. is a horizontal straight line, showing that throughout this region the threshold values correspond to equal brightnesses as far as rod vision is concerned. For observer A. the curve rises steadily from the yellow to the violet. This rise is probably due to a slight colouration of the lens, which is indicated also by other measurements. Owing to this colouration the values assumed for the luminosity are too high for A. In the case of Ar. we seem to have a curve intermediate in character between those corresponding to the two classes. It has a well-marked maximum at SSN 45.

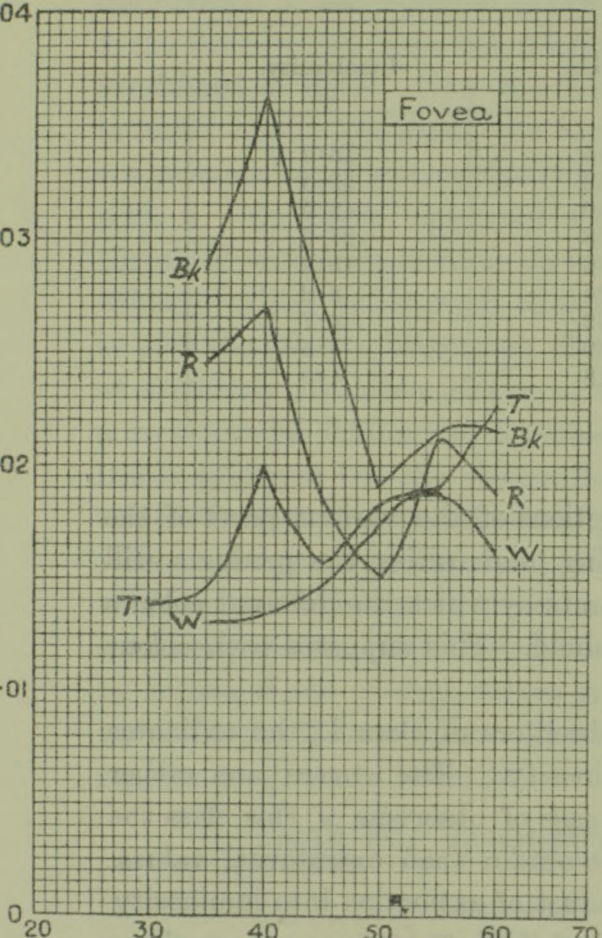

Fig. 17.

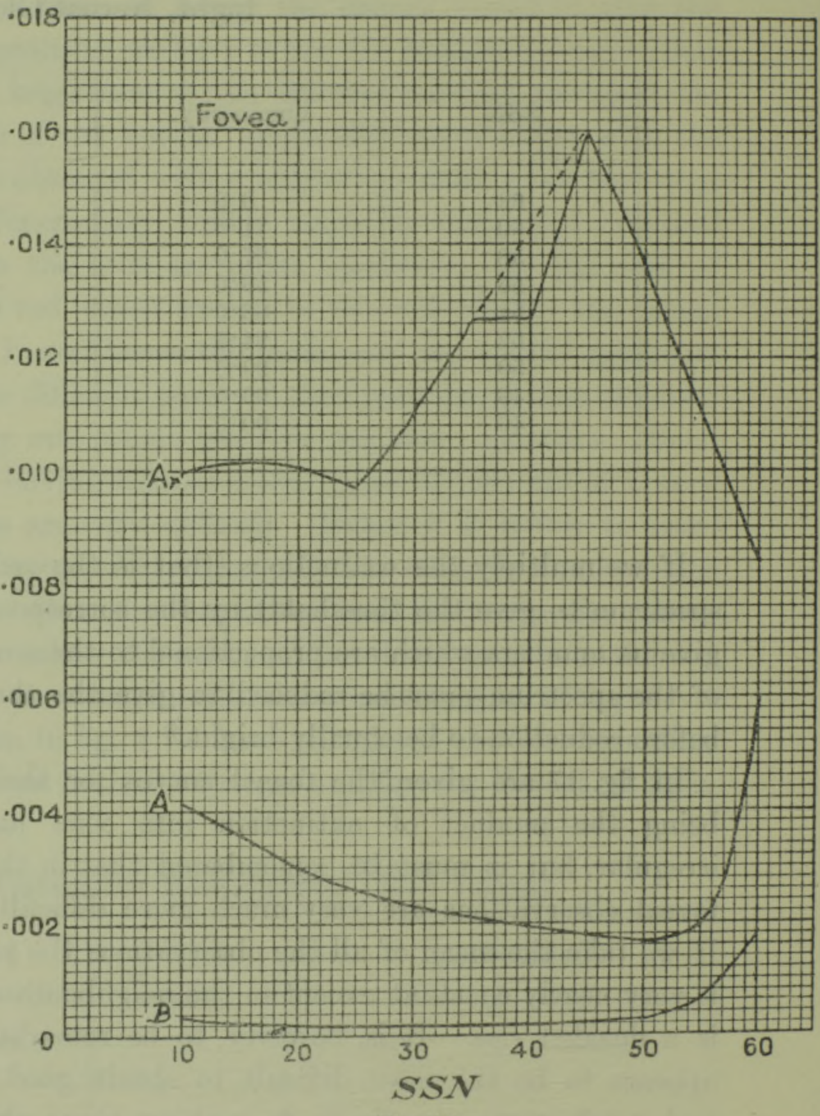

Fig. 18.

At 1·25 degrees from the fovea the results for the observers of class I. obtained by using the rod luminosity curve approximate in the case of three observers to those of class II., fig. 19. In the case of R. and W. there is a marked rise at the violet end of the spectrum. Of the observers of class II., A. and B. have nearly horizontal curves throughout the greater part of the spectrum, while Ar.'s curve rises markedly towards the violet end, here again resembling the values obtained by class I.

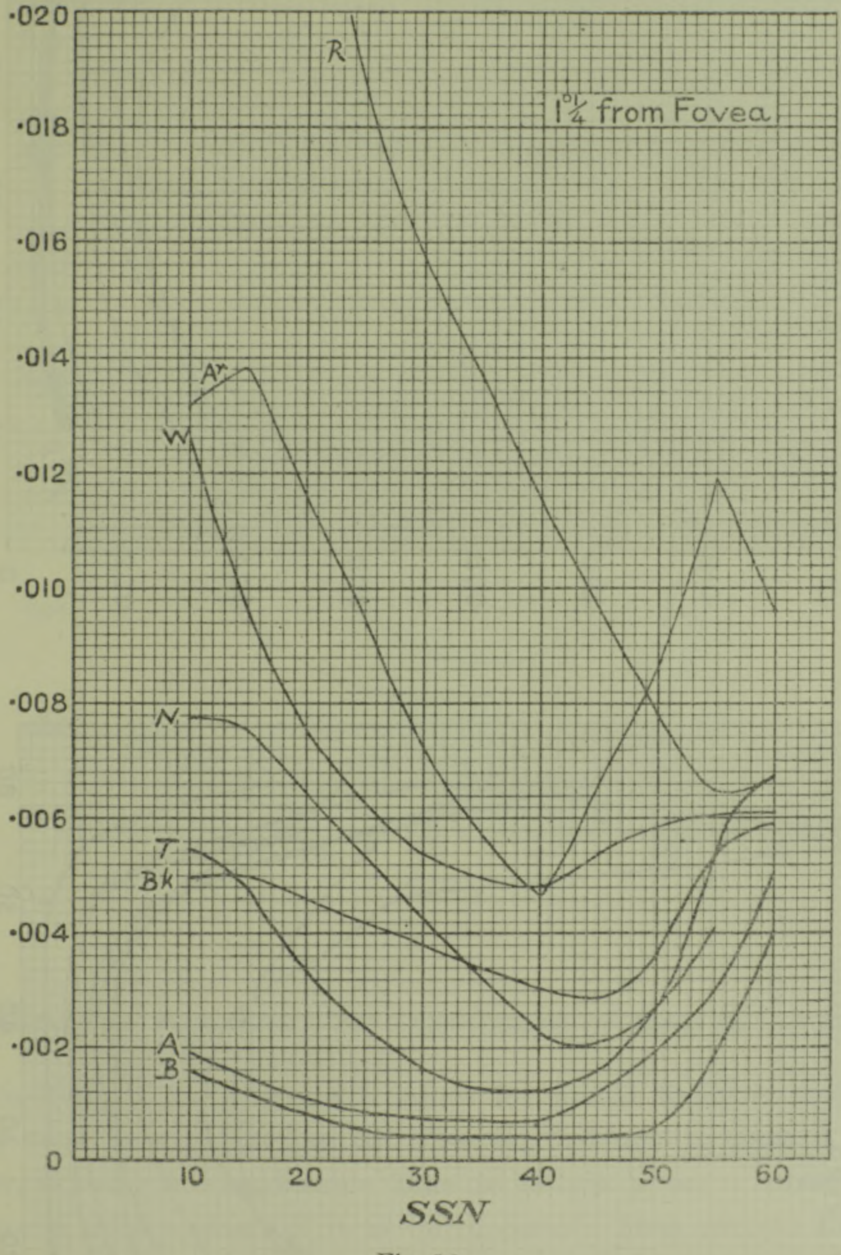

Fig. 19.

At 2·5 degrees, 5 degrees, and 10 degrees from the fovea, as shown in figs. 20, 21, and 22, the results obtained by the two classes resemble one another, and, except at the red end of the spectrum, the product of the extinction into the rod luminosity is nearly constant. There is in the case of some observers a tendency for the product to increase towards the violet, but it must be remembered that the luminosity

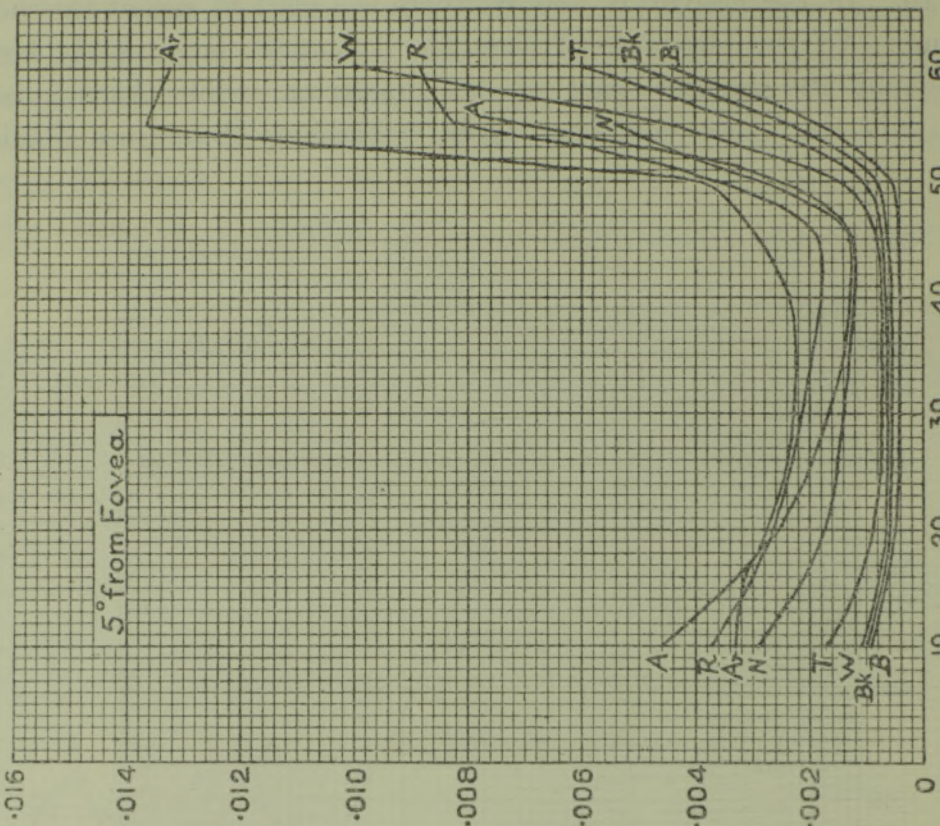
5° from Fovea
·016
·014
·012
·010
·008
·006
·004
·002
0
10
20
30
40
50
60
SSN
A
R
Ar
N
T
W
Bk
B

Fig. 21.

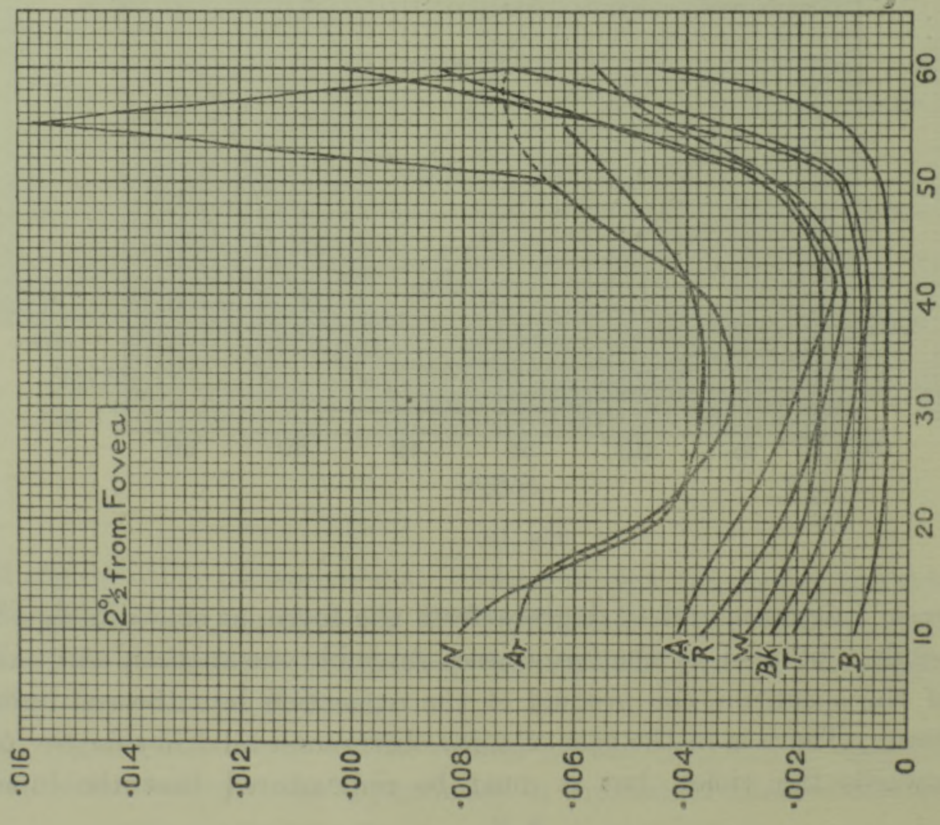
2½° from Fovea
·016
·014
·012
·010
·008
·006
·004
·002
0
10
20
30
40
50
60
SSN
N
Ar
A
R
W
Bk
T
B

Fig. 20.

measurements in this region are more uncertain than in the brighter parts of the spectrum. Differences in the absorption values of the eye-media are also most likely to have the greatest effect in this region.

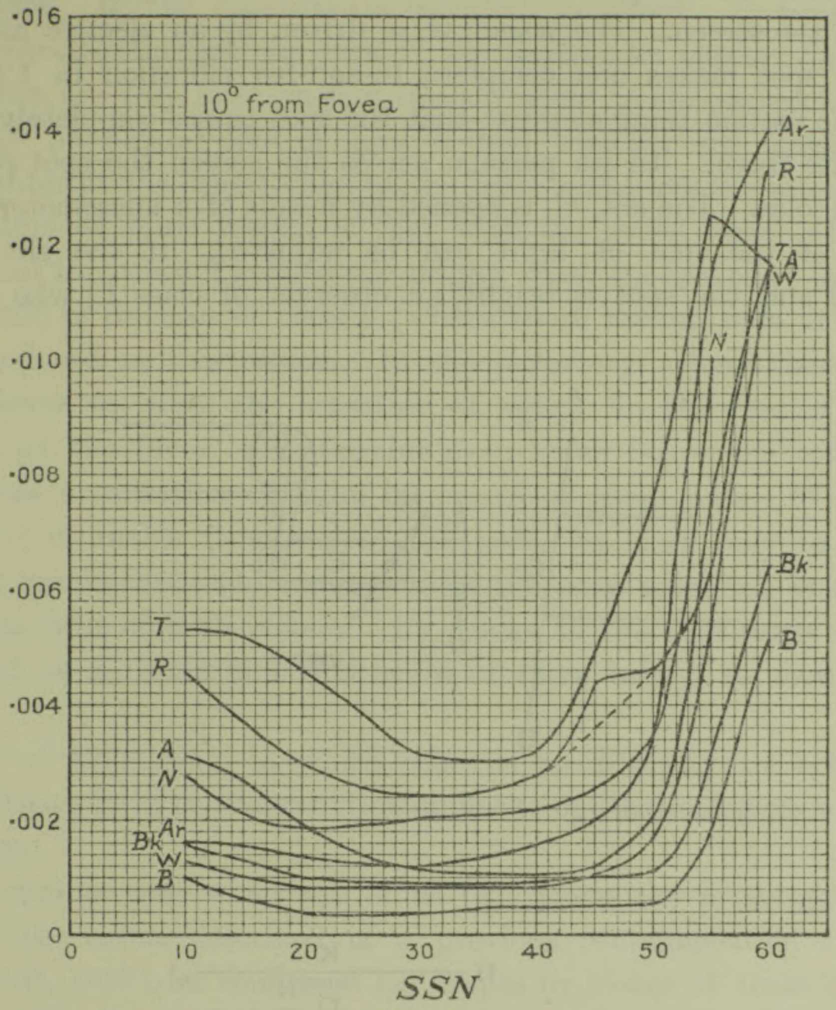

Fig. 22.

4. *Method of Examining the Distribution of Rods in the Retina.*

The determination of the threshold values for foveal fixation, as described above, enables us at once to say whether an observer belongs to class A. or to class B. Since, however, it takes a considerable time to obtain a set of observations, as it is necessary to go on taking sets till it is quite certain that correct foveal fixation is being obtained, examining any number of persons by this method is a very lengthy process. Hence we have devised another method which enables one in a few minutes to settle to which class an observer belongs.

By means of a plane mirror, M, fig. 23, to which is imparted an oscillatory motion about a vertical axis, the light passing through the slit, C, attached to a slide, AB, which is in the plane of the spectrum, is reflected on to a white screen, HJ. By means of a diaphragm placed against the first face of the prism train of the colour patch apparatus, a spot of light having a diameter of 12 mm. is formed on the screen. At the middle, K, of the screen are pierced two pinholes, one vertically over the other and 1 inch apart. Behind these holes is placed a lamp, L, and a piece of red glass, N. These holes provide fixation points for the observer, who is placed at P at a distance of 1 metre from the screen. The wheel, G, is driven by an electric motor at such a speed that the spot makes one complete to-and-fro vibration in 1·4 seconds, the amplitude of the motion being so great that the spot passes completely off the screen at each end of its travel. In its passage across the screen the spot passes half-way between the pinholes. The slit, C, is opened by means of a micrometer screw so that the brightness of the spot of light can be adjusted. If the slit is placed at SSN 40 ($527\mu\mu$) and the spot is bright, an observer of class I., who keeps his eye fixed half-way between the two fixation spots, sees a band of light across the screen each time the spot crosses. This band of light appears dark green at the centre and a much lighter green and brighter at the sides. As the intensity of the light is reduced the centre becomes a darker and duller green while the sides remain bright but lose their colour. Finally an intensity is reached when no light at all is seen at the centre although the sides are quite bright. It is interesting to notice how very well marked is the centre area over which the sensation of light is not perceived, this area corresponding of course to the rod-free region of the retina.

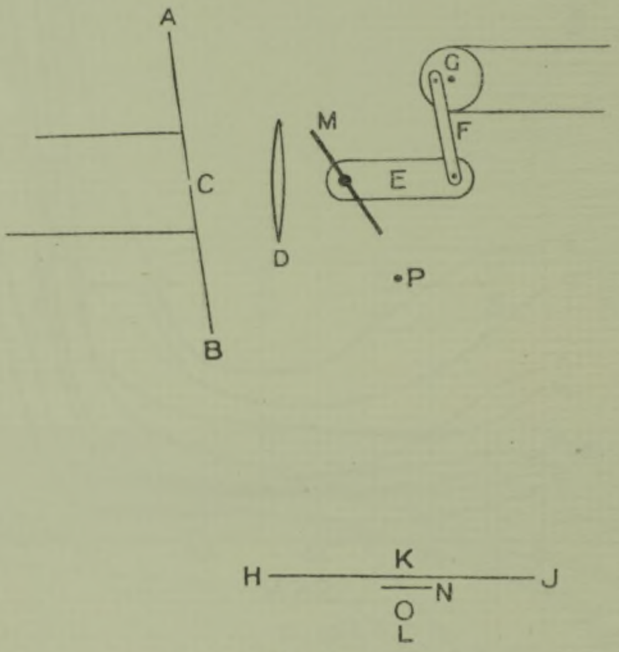

Fig. 23.

If the same series of changes is repeated with an observer of class II., the results obtained are quite different. At fairly high intensities there seems little difference between the centre and the sides in colour, though the centre generally seems slightly less bright. When the intensity of the light is reduced to such an extent that to an observer of class I. there is no sensation of light in the centre, an observer of class II. sees a continuous streak of light, the brightness at the centre being little less than that at the sides. If the intensity is reduced to about one-twentieth of that required for central extinction for class I., the centre also appears dark for class II., but the sides then are very faint, in fact the threshold is almost reached throughout.

If a red (SSN 50, $632\mu\mu$) spot of light is used, then for both classes the streak of light looks brighter at the centre than at the sides, whatever the intensity.

The explanation of these results is that with the green light, which stimulates both the rods and the cones if sufficiently bright, when the intensity is reduced below the cone threshold in the case of class I. (where there are no rods at the fovea), no sensation is produced in this region. In the periphery, where there are rods, the stimulus is sufficient to cause the sensation of light. In the case of class II., since there are rods at the fovea, the stimulus even when below the cone threshold is sufficient to cause a sensation of light by means of these rods. With a red light, since this colour is unable to stimulate the rods, we have only to do with cone vision, and the results obtained indicate that the cone sensation is a maximum at the fovea for observers of both classes. By means of this apparatus we have tested ten persons, and as a result find that eight of them belong to class I. and two to class II.

This method of examining, in which there is no difficulty in obtaining correct fixation, may perhaps be of considerable assistance to ophthalmologists when examining a central scotoma.

It is rather curious that when one of us (A.) made the investigation as to the sensitiveness of the retina described in a previous communication ('Phil. Trans.,' A, vol. 190, p. 155, 1897) he confirmed his results by means of those obtained by B., and as they agreed, he concluded that the results obtained applied to all normal eyes. We now know that both A. and B. belong to a class which seems to form only a small proportion of normal eyes.

There has been some considerable discussion whether the secondary image or BIDWELL'S ghost which is seen to follow a moving spot of light when the eye is kept stationary occurs at the fovea. Using the arrangement described above, but causing the spot of light to travel much more closely, we have examined this question in the case of a typical observer of each class. Using a green stimulus light the ghost is very well marked, and to W., an observer of the first class, the ghost always appears to jump the fovea. In the case of an observer of the second class, B., the ghost is seen to follow the primary right across the field, no interruption at the fovea taking place. It would thus appear that the rods and not the cones are involved in the production of this secondary image.*

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* [When this was in print we were not aware of McDOUGAL'S experiments on the Bidwell ghost. His paper should be examined in connection with the results given in the above paragraph.—*October 20, 1915.*]

5. *Visibility of Radiation.*

Having determined the energy distribution for the two sources of light we have employed, it seemed of interest to obtain the visibility that is the quotient of the luminosity by the energy throughout the spectrum. We have done this in the case of the observer W. (who has no rods at his fovea), taking care to use, when making the luminosity measurements, a photometer field of such a size that the image formed on the retina was confined to the fovea. The luminosity values obtained are given in Table V. and the corresponding visibilities are plotted in fig. 24, the values obtained with the arc light being shown by the continuous line and those with the Nernst by the dotted curve. The two curves are in very fair agreement except on the blue side of the maximum, a region of the spectrum where it is always difficult to make concordant measurements of luminosity by the equality of brightness method which was employed in this case. These results, together with those obtained by previous workers, are shown in fig. 25, where the mean of the values obtained with the arc and Nernst instruments are shown by the full line curve. Nutting* and Ives† both used the flicker method of measuring the luminosity. Nutting measured the energy distribution directly, while Ives calculated it from the energy distribution in the source as obtained by other observers and the measured

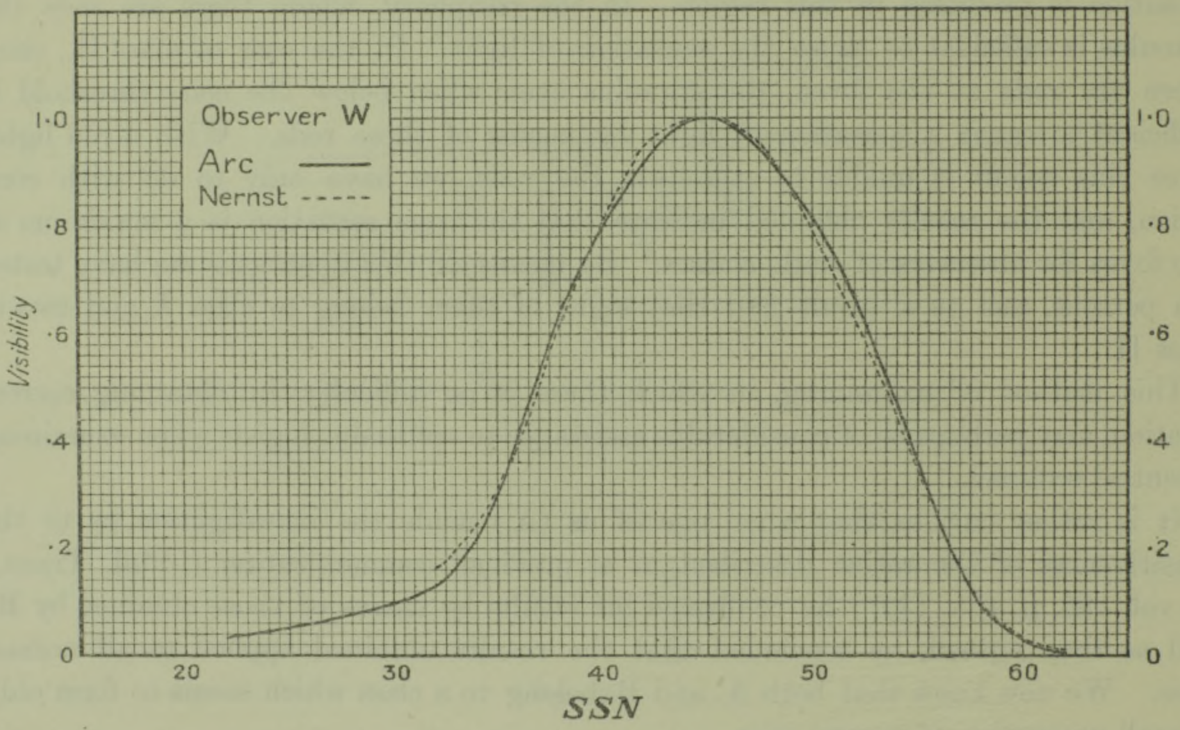

Fig. 24.

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* 'Phil. Mag.,' p. 304, Feb., 1915.

† 'Phil. Mag.,' p. 859, Dec., 1912.

dispersion and absorption of his instrument. Koenig's* values given are those recalculated by Nutting, and in this case also the energy distribution was not directly† measured. Houston's‡ values are the mean of those obtained by a number of observers and the energy was again calculated. It is fairly evident that in this case some serious error has been made in determining the energy distribution. At first sight it looks as if the intensity of the spectrum used by Houston was so low that he was dealing mainly with rod vision. That this is not the true explanation is shown by the fact that he also publishes results obtained with a much less intense spectrum, and the maximum he obtains for this rod visibility curve is as much below the value obtained by other observers for the rod curve as is the maximum he obtains for the bright or cone visibility curve.§ Our curve lies considerably below those obtained by other observers in the blue and violet. This is probably almost entirely due to the fact that we are dealing with pure cone vision, while other observers, who apparently used a much larger photometric field, were probably dealing with a mixed

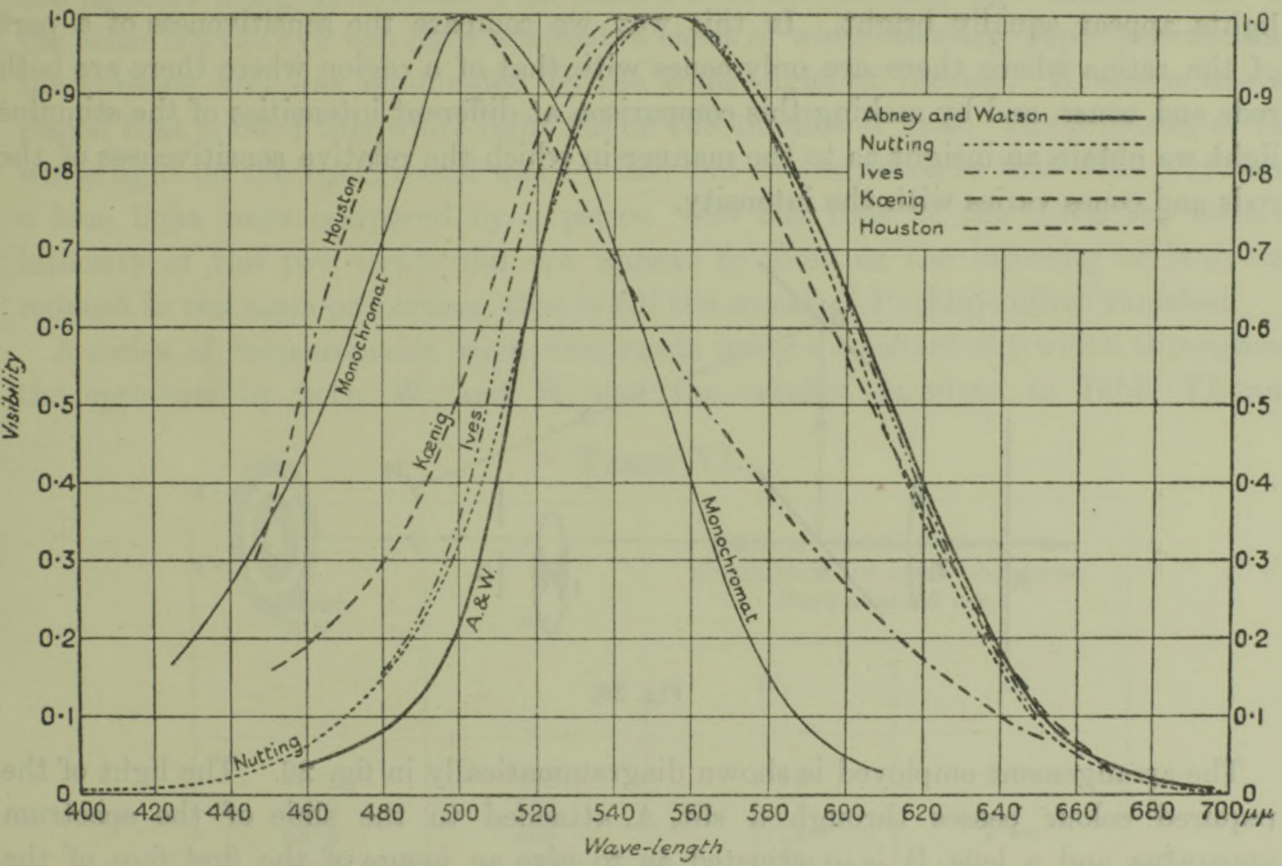

Fig. 25.

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* 'Bull. Bureau of Standards,' 7, 238, 1911.

† 'Phil. Mag.,' p. 715, May, 1913.

‡ The calculations of energy can only be considered as close approximations of the radiation from perfectly black bodies. If not black deviation from absolute measurement of energy is to be expected.

§ Displaced from the mean of all the other observers.

rod and cone sensation which would increase the luminosity values in the blue and violet.

Using the luminosity values given in Table IV. for rod vision, as deduced from experiments on monochromats, we have calculated the corresponding visibility curve and it is shown in fig. 25.

6. *Relative Sensitiveness of the Foveal and Parafoveal Regions.*

Observer W., with a rodless fovea, made a series of measurements of the relative intensities of two lights, one of which falls on the fovea and the other on the parafoveal region, when the sensations produced are the same, that is when the two lights appear equally bright. In this way we compare the sensitiveness of a part of the retina where there are only cones with that of a region where there are both rods and cones, and by making this comparison at different intensities of the stimulus light we obtain an insight as to the manner in which the relative sensitiveness of the rods and cones varies with the intensity.

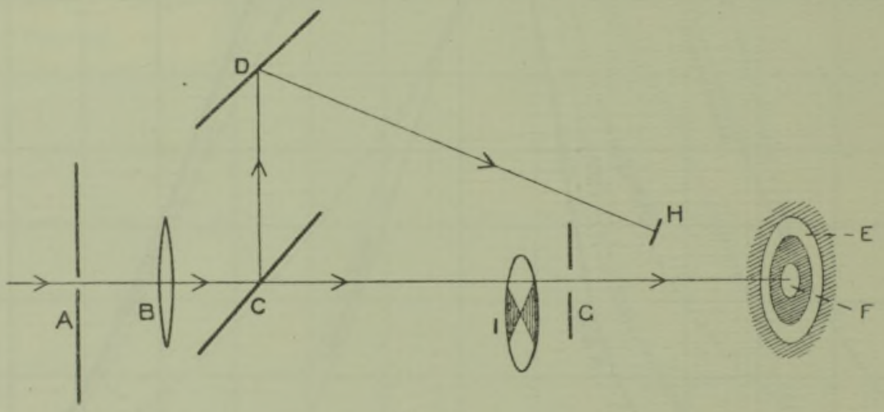

Fig. 26.

The arrangement employed is shown diagrammatically in fig. 26. The light of the required colour passes through a slit, A, attached to the slide of the spectrum apparatus, and a lens, B, is so adjusted as to give an image of the first face of the prism train on the screen, EF. The light passes through a sheet of plane glass, C, placed at 45 degrees, and the part of the light reflected from this glass is again reflected from a silvered mirror, D, on to the screen. This screen consists of a central white disc, F, of such a size that its radius subtends an angle of 43 minutes at the observer's eye and a circular annulus, E, of which the radius of the inner edge subtends an angle of 2 degrees at the observer's eye and that of the outer edge 3 degrees. The space between the central disc and the annulus is painted dead black. A diaphragm, G, is so arranged that the light which passes straight through the glass plate, C, only illuminates the disc, F; while an opaque disc, H, screens this central disc from the light, which has been reflected from the mirrors C and D, so that this light only illuminates the annulus, E. A set of adjustable sectors, I, placed in the path of the light which illuminates the disc, allows of the intensity of the illumination being adjusted. By removing H and placing a rod so as to form a Rumford photometer, the intensity of the beam which goes straight through and is doubly reflected, respectively, can be compared. The experiment consists in adjusting the sectors so that when the eyes are kept fixed on the centre of the disc the disc and the annulus appear equally bright. Settings were taken alternately starting with the centre too bright and then too feeble. Observations were made throughout the spectrum with different intensities.*

Two series of measurements were made, one with the eye thoroughly dark adapted, the annulus being surrounded with black velvet and all stray light screened off. In the other set the eye was light adapted, a sheet of white blotting paper surrounding the annulus, and was illuminated by the white light of the arc. A screen was so placed that none of this white light fell on the annulus or disc. The intensity of the white light on the background was 1·5 lux, and was adjusted so that when a red and a blue light were compared by a person who has rods at the fovea the relative intensity of the two lights did not appear to alter, as the intensity of both was reduced in the same proportion, that is till the so-called Purkinje effect vanished.

A series of measurements were first made using a constant slit width throughout the spectrum by both W. and B., and the results are given in Table VI. and

TABLE VI.

Colour. SSN.	μμ.	Ratio of central to parafoveal illumination for equal brightness. Dark adapted eye.	
		W.	B.
58·7	658	1·14	1·05
56·0	632	1·17	
53·3	609	1·23	1·06
50·8	589	1·29	
48·6	576	1·15	1·16
45·4	556	1·32	
42·8	541	1·38	1·10
40·1	527	1·54	
37·6	514	1·70	1·15
35·0	503	2·42	
32·2	493	4·63	1·12
27·0	474	9·53	1·32
21·8	457	13·6	1·24
16·5	442	19·6	1·34
11·2	427	23·9	1·41
5·9	415	27·0	1·49
0·7	403	27·0	1·94

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* The slit, A, could be varied in width, the actual intensity when the slit was placed at the D line being determined by comparison with a Hefner lamp.

fig. 27. It will be observed that the two observers, one of whom belongs to class I. and the other to class II., get entirely different results. In the case of B., the ratio of the foveal to the parafoveal intensities for equal brightness does not differ greatly from unity and is very nearly constant throughout the spectrum, showing that the sensitiveness of the retina at the fovea and at 2·5 degrees from the fovea is nearly the same, a result which is confirmed by the threshold measurements. In the case of W. there is a very marked increase in the sensitiveness at 2·5 degrees as we go towards the violet, so that at SSN 5·9 (400 $\mu\mu$) the central illumination has to be 27 times the brightness of the peripheral for the brightness to appear the same. Observer A. obtains similar results to those obtained by B., except that his ratio is slightly higher at SSN 30; the maximum value of the ratio is, however, only 2. B. also made observations using a lens to view the illuminated surfaces which caused the image of the edge of the annulus to fall at 6·5 degrees from the fovea. The ratio was again practically constant, the maximum value being 1·29 at SSN 6.

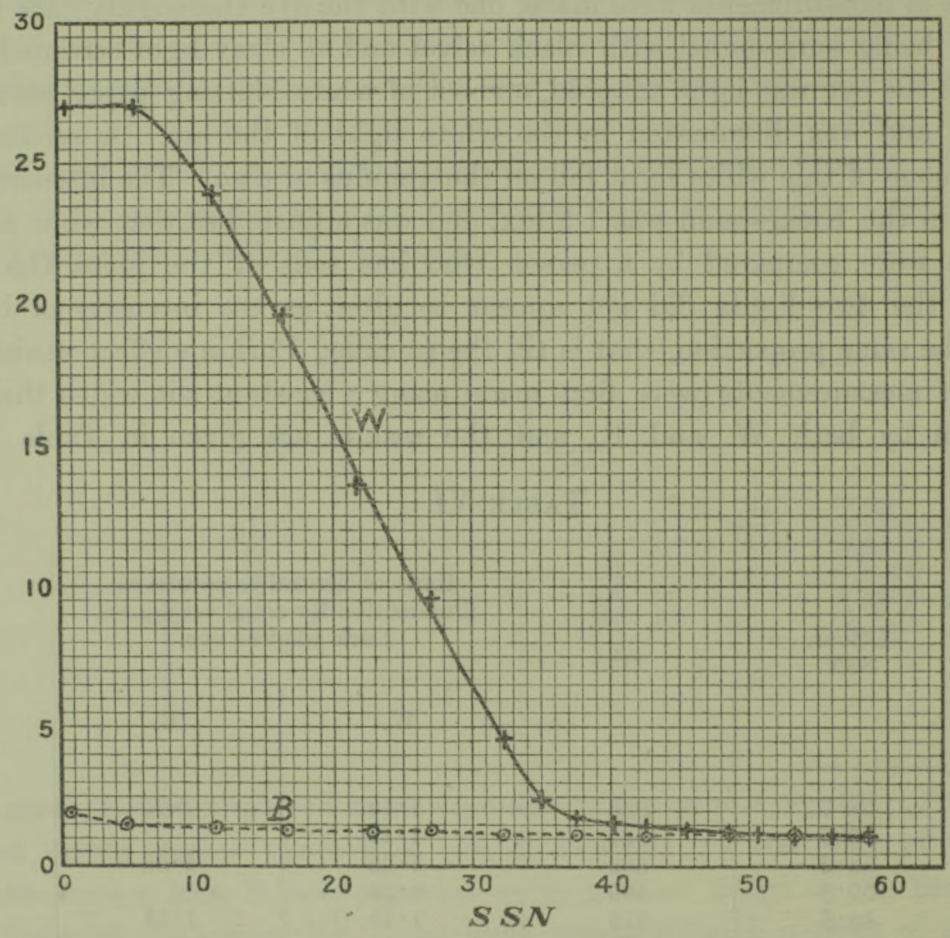

Fig. 27.

In the above series only a single intensity was used for each colour, and W. then made sets of observations with different intensities in order to study the manner in which the relative sensitiveness varies with intensity. The results obtained are contained in Table VII. With the light adapted eye it was found that the ratio was independent of the intensity so only the mean values are entered in the table. As the intensity of the illumination is increased from a very low value, the ratio of the central to the parafoveal illumination for equal brightness at first decreases rapidly, but as the intensity increases the change becomes slower and slower. Finally, for the higher illuminations, the ratio becomes practically constant and approximates to the value obtained with the light adapted eye.

Table VII.

Colour.		Intensity of peripheral illumination in terms of—	Ratio of central to peripheral illumination for equal brightness.	
SSN.	μμ.	Luminosity (lux).	Dark adapted.	Light adapted.
53·3	609	0·027	1·93	1·07
		0·10	1·67	
		0·20	1·70	
		0·40	1·42	
		0·79	1·47	
		1·85	1·17	
		2·28	1·09	
48·6	576	0·037	2·98	0·99
		0·14	2·20	
		0·26	1·83	
		0·54	1·42	
		1·07	1·38	
		2·51	0·96	
		3·08	1·02	
42·8	541	0·11	2·64	1·04
		0·21	2·00	
		0·42	1·58	
		0·85	1·41	
		1·98	1·24	
		2·44	1·29	
		4·94	1·21	
37·6	514	0·049	4·05	1·13
		0·10	2·82	
		0·20	2·28	
		0·38	1·74	
		0·78	1·44	
		0·90	1·52	
		1·11	1·39	
		1·81	1·22	
		2·24	1·33	

TABLE VII. (continued).

Colour.		Intensity of peripheral illumination in terms of—	Ratio of central to peripheral illumination for equal brightness.	
SSN.	μμ.	Luminosity (lux).	Dark adapted.	Light adapted.
32·2	493	0·012	5·35	1·45
		0·024	5·44	
		0·05	3·81	
		0·10	3·12	
		0·21	2·39	
		0·46	2·07	
		0·58	2·06	
		0·93	1·85	
21·8	457	0·0013	9·30	1·51
		0·005	13·0	
		0·010	7·11	
		0·022	3·76	
		0·030	3·88	
		0·041	2·80	
		0·060	2·33	
		0·093	2·13	
		0·13	2·06	
		0·20	1·95	
		0·25	1·87	