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The Luminous Efficiency of Monochromatic Rays Entering the Eye Pupil at Different Points and a New Colour Effect

By W. S. Stiles

From The National Physical Laboratory

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INTRODUCTION

It has been found by the writer, in collaboration with B. H. Crawford (1933), that light rays entering the eye pupil near its periphery are less efficient in producing the impression of brightness than rays entering centrally, the patch of retina stimulated (the fovea) being the same in both cases. Reasons were put forward in the paper cited for thinking the effect to be retinal in origin, i.e. due to a variation of visual sensitivity with angle of incidence of the light on the retina, rather than the result of a greater absorption of the peripheral rays in transit through the optic media of the eye. Most of the observations were made with white light and, although the absence of any pronounced coloration of the field illuminated by the peripheral ray indicated that the reduction of apparent brightness could not be very different for different colours, it was considered desirable to test this point directly by observations with monochromatic light throughout the spectrum. In Part I of this paper an investigation on these lines is described from which it appears that for the writer's eye the ratio of the luminous efficiencies of rays entering centrally and peripherally varies systematically to a limited extent in passing through the spectrum. It was also found that within a considerable range of intensity the value of the ratio for a given wave-length is independent of intensity.

Since the publication of the original paper, Dziobek (1934) and Wright and Nelson (1936) have both made measurements confirming the existence of a marked variation of luminous efficiency with point of entry. The latter workers employed white light and coloured lights obtained with the aid of filters. Goodeve (1936) has also measured the effect, in the extreme red.

In making measurements with monochromatic light it was observed that as the point of entry of the light ray moved across the pupil, the corresponding half of the photometric matching field exhibited in some parts of the spectrum a change of colour in addition to the change of brightness. This colour change, which as far as is known has not previously been recorded, is of particular interest as it provides evidence of a difference in properties of the three types or groups of types of receptor postulated in the trichromatic theory other than differences in their spectral excitation curves. Part II of the paper gives an account of measurements of the colour effect together with certain deductions from the results so far obtained.

PART I—THE EFFECT OF WAVE-LENGTH ON THE LUMINOUS EFFICIENCIES OF RAYS ENTERING THE EYE PUPIL AT DIFFERENT POINTS

Apparatus and Method

A diagram of the apparatus used is shown in fig. 1. The source S is a ribbon filament gas-filled tungsten lamp (6 V, 100 W) placed so that the length of the ribbon is horizontal and inclined at an angle of 45° to the axes of the two optical trains. Lens L_1 ($f = 17$ cm.) forms an image of S on the entrance slit of the Hilger constant deviation spectrometer I which has collimator and telescope lenses of 28·5 cm. focal length. In front of the exit slit of spectrometer I (here used as a monochromator) two gelatine neutral wedges W_1 and W_2 are arranged to move in vertical guides, W_1 having a continuous variation of density and W_2 a stepwise variation. The light from the exit slit of spectrometer I is rendered parallel by lens L_2 ($f = 24$ cm.); the beam is delimited by a square aperture in the diaphragm T_1 and, after passing through the glass cube C, is brought to a focus ω_1 approximately in the plane of the subject's eye pupil (at O) by the lens L_3 ($f = 24$ cm.). The cube C, of 5 cm. side, consists of two right-angled prisms enclosing between their opposed hypotenuse faces a thin half-platinized glass plate, the prisms and plate being cemented together with Canada balsam and firmly clamped in a brass frame.

In the second optical train the lenses L_6 ($f = 17$ cm.) and L_5 ($f = 25$ cm.) produce an image of S on the entrance slit of the Tutton monochromator spectrometer II which has collimator and telescope lenses of focal length 18·5 cm. A wedge W_3 having a continuous variation of density moves in vertical guides in front of the exit slit of spectrometer I. Lens L_4 ($f = 24$ cm.) and diaphragm T_2 delimit a small parallel beam of square section as in the first optical train. This beam is partially reflected at the half-platinized plate in the cube C and is brought to a focus ω_2 in the plane of the subject's eye pupil by the lens L_3.

The diaphragms T_1 and T_2 can be adjusted vertically and laterally so that the eye at O sees by Maxwellian view two juxtaposed square fields in contact along a horizontal edge and forming together a bipartite photometric matching field of total angular dimensions 1·8 × 0·9° (approx.). The diaphragms T_1 and T_2 are normally placed at such a distance from the cube C that they lie at the focus of lens L_3 (allowing for the presence of the glass cube) and are seen by the subject at infinity. Owing to the chromatic aberrations of the eye and residual chromatic aberrations of the optical system, it was found convenient to adjust the distances of the diaphragms T_1 and T_2 for each wave-length studied to give a field of optimum sharpness as seen by the subject with his eye as far as possible in the unaccommodated condition. It may be noted here that all the lenses used in the apparatus are achromatic doublets.

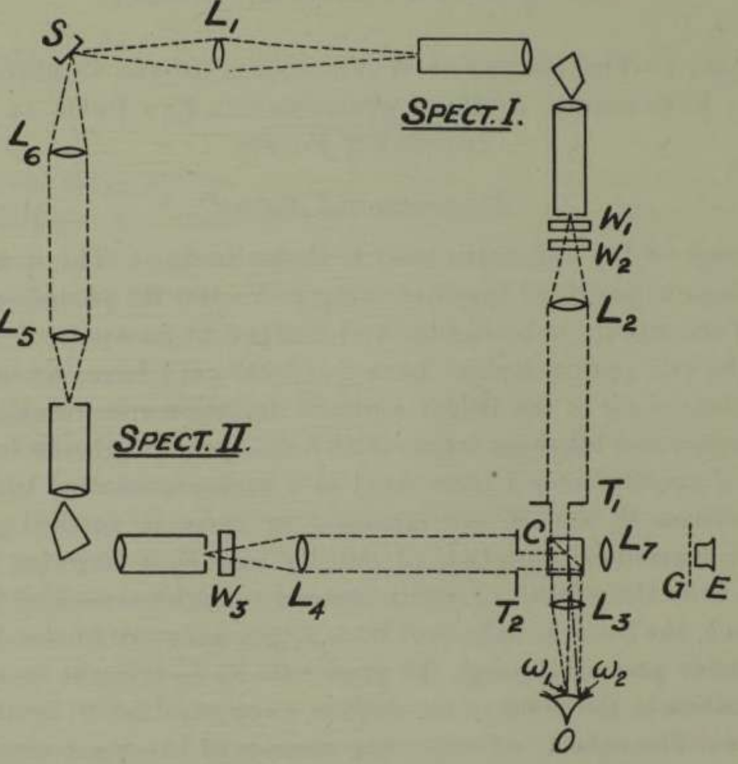

FIG. 1—Diagram of apparatus (not to scale).

The cube C is arranged to rotate about a vertical axis through its centre, the amount of rotation being controlled by means of a micrometer screw.

As the cube rotates, the image ω_2 moves on a horizontal line across the subject's pupil while the image ω_1 remains practically stationary. When such a rotation is made, the subject sees the two square fields separate laterally. This is due in the main to an actual change in the position of the virtual image of T_2 formed by reflexion in the half-platinized plate of the cube. There is in addition an apparent shift in the position of T_2 due to the spherical aberration of the subject's eye. The two fields can be brought back into position by a displacement of the diaphragm T_2. For determining the relative positions of ω_1 and ω_2 in the plane of the subject's pupil, an auxiliary optical system comprising the lens L_7 ($f = 24$ cm.), a graticule G at the focus of L_7 and an eye-piece E for viewing the graticule, is used. Images ω_1' and ω_2' of the exit slits of spectrometers I and II respectively are formed in the plane of the graticule, ω_1' by reflexion in the cube and ω_2' by transmission through the cube. When ω_1 and ω_2 are coincident, so are ω_1' and ω_2'. When C is rotated, ω_2 moves away from ω_1 and at the same time ω_1' moves away from ω_2' by a proportional amount. By setting up a travelling microscope to view ω_1 and ω_2 in the plane normally occupied by the subject's eye pupil, the displacement of ω_1' and ω_2' on the graticule corresponding to a given displacement of ω_1 and ω_2 in the eye plane can be determined.

In using the apparatus it is clearly essential for the observing eye to remain in a fixed position. The head is kept in a fixed position by making the subject bite on a sealing wax impression of his teeth carried on a brass plate fixed to a heavy metal frame which is itself clamped firmly to the table carrying the apparatus. When the head is in a fixed position and the gaze is directed to the centre of the matching field, it may be assumed that the subject's eye is also in a fixed position. The metal frame incorporates adjustments which enable the sealing wax "bit" to be displaced in three directions at right angles so that the centre of the subject's pupil can be brought into coincidence with the fixed image ω_1.

Principle of the Measurements

With the images ω_1 and ω_2 coincident and entering the subject's pupil at its centre, and with both spectrometers selecting light of the same wavelength λ, the subject adjusts the wedge W_3 until the two halves of the photometric field formed by the diaphragms T_1 and T_2 appear equally bright.

The setting is repeated several times. The experimenter then turns the micrometer screw to rotate C by a certain amount and notes the displacement of the image ω_1' on the graticule. The subject readjusts the diaphragm T_2 to restore the juxtaposition of the two fields and makes a new series of settings of the wedge W_3 to give equality of brightness between the two fields. If $\varDelta$ is the density, for wave-length λ, corresponding to the initial mean setting of the wedge and if $\varDelta_d$ is the density for the mean setting when ω_2 is displaced d mm. from the pupil centre, then the luminous efficiency η for the displaced position of entry of the light is given by

$$\log_{10}\eta = \varDelta_d - \varDelta.$$

Continuing the measurements in the above manner the whole diameter of the pupil can be traversed and a curve drawn relating $\log_{10}\eta$ to d.

(In the previous paper η and not $\log_{10}\eta$ was plotted against d. The present procedure has some advantages.)

Spectrometer Adjustments, etc.

The focusing rings on the spectrometers were calibrated to enable the image of the entrance slit to be brought into focus in the plane of the exit slit at each wave-length. A wave-length calibration curve was used for spectrometer I but was unnecessary for spectrometer II. The telescope and collimator of spectrometer I were each equipped with a microscope interchangeable objective holder (Beck) modified to take fixed slits in place of objectives. The device enabled slits to be removed and then replaced in exactly the same position. For the exit slit a fixed slit of width 0·48 mm. and height 0·50 mm. was used throughout the measurements. For the entrance slit, fixed slits of height 2 mm. and widths 0·23, 0·45, 1·06 and 2·01 mm. respectively were used as required. Spectrometer II was fitted with symmetrically opening micrometer slits supplied with the instrument (Hilger). The slit height could be controlled by the V-shaped slides provided but with the small height of exit slit here required the irregularities at the apex of the V gave trouble. The slits were therefore delimited vertically by adjustable bevelled brass strips screwed to the V slides. For the entrance and exit slits, heights of 0·32 and 1 mm. respectively were used for most of the measurements.

The difference of wave-length $\varDelta\lambda$ between the extreme limits of the spectrum band passed by the spectrometer may be used to specify the nominal purity of the light if the slit widths are equal. When this is not the case it is necessary to state in addition the ratio ρ of the exit and entrance slit widths. The actual purity obtained will depend on the amount of light scattered or irregularly reflected in the spectrometer. The parasitic light arising in this way was reduced to a point at which it could have little, if any, effect on the measurements by inserting suitably chosen coloured glass filters in the optical system between the source and the entrance slits of the spectrometers. The effectiveness of the glasses used was checked qualitatively by letting the images ω_1 and ω_2 fall on the entrance slit of a direct vision spectrometer and observing the spectrum produced.

Calibration of the Wedges

The wedges W_1, W_2 and W_3 were calibrated in the apparatus by the usual photometric methods, employing a series of rotating sectors of known transmissions. The photometric matches for these measurements were made of course with the images ω_1 and ω_2 coincident and entering the eye centrally. With a sector of density Δ (density $= \log_{10}(1/\text{transmission})$) inserted between L_5 and the entrance slit of spectrometer II and with wedge W_3 raised out of the beam emerging from the exit slit, wedge W_1 was adjusted to give a photometric match between T_1 and T_2. Leaving this setting of W_1 unchanged, the sector disk was removed and wedge W_3 lowered into the beam and adjusted to restore the photometric match. The reading r on the vertical scale of the index mark carried by W_3 is then known to correspond to a wedge density Δ. The calibration curve relating Δ and r was determined for W_3 for light of wave-length $\lambda_0 = 540\,\text{m}\mu$. The range of density equalled approximately 2·5 and the calibration curve was nearly, but not quite, rectilinear. Further measurements showed that for any other wave-length λ, the wedge density Δ was related to the density Δ_0 for λ_0, by the equation

$$\Delta = a + b\Delta_0,$$

where a and b are constants depending on wave-length but approximately independent of density. Fig. 2 shows the variation of a and b with wave-length. The two curves of fig. 2 together with the calibration curve for $\lambda = 540\,\text{m}\mu$ provide a complete calibration of the wedge W_3 for light of any wave-length. Wedges W_1 and W_2 were calibrated similarly although their calibrations were not required for the main measurements.

Sizes of Images ω_1 and ω_2, Centring of the Eye, etc.

The optical system is such that the images ω_1 and ω_2 are of the same size as the corresponding exit slits. Their vertical dimensions were therefore 0·50 mm. (ω_1) and 0·32 mm. (ω_2) approximately and the width of ω_1, 0·48 mm. The width of ω_2 depended on the wave-length used but never exceeded 0·50 mm. The accurate centring of the eye was accomplished by setting ω_2 and ω_1 to be coincident and traversing the subject's head in a vertical or horizontal direction with the aid of the movements on the bit-holder until the images ω_1 and ω_2 crossed the edge of the dilated pupil.

This was apparent by the sudden extinction of the light in the fields T_1 and T_2 as seen by the subject. The midpoint of the two settings for extinction gave the setting for central entry. A mydriatic (euphthalmine) was used to obtain a steady and fully dilated pupil. The subject sat in a small enclosure formed of black curtains and the idle eye was covered with an eye shade. An aperture in the front curtain disclosed the lens L_3. Thus the field was dark save for the two fields to be matched.

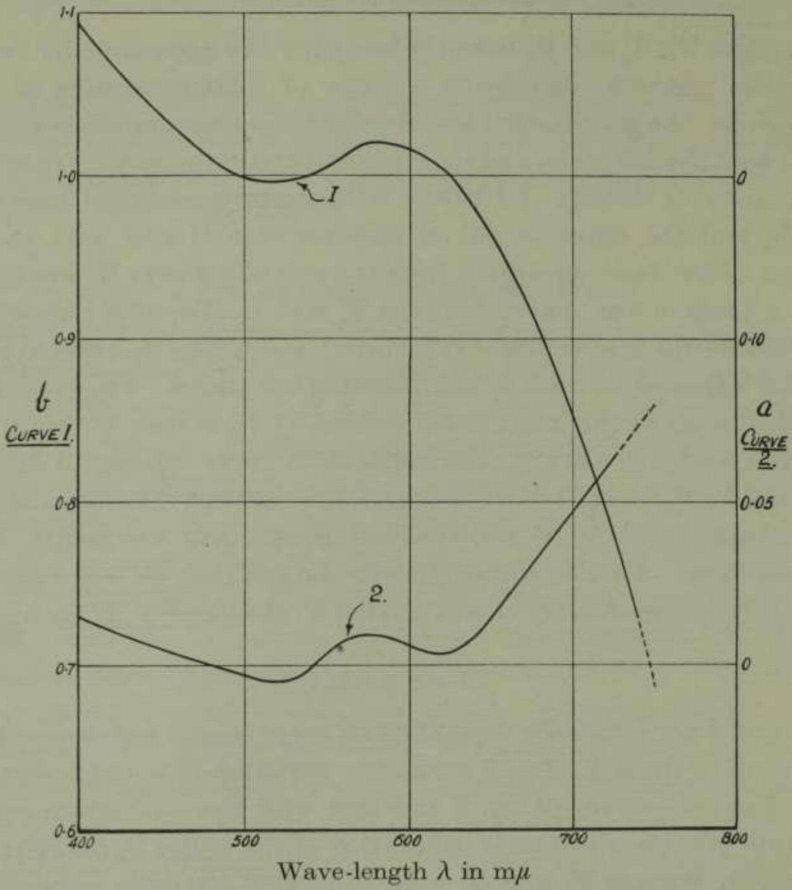

FIG. 2—Wave-length corrections to density calibration curve of wedge W_3.

Possible Errors due to the Adjustment of T_2

When the image ω_2 is traversed across the eye horizontally it is necessary to move the diaphragm T_2 slightly to keep the matching fields juxtaposed. This means that a slightly different portion of the parallel beam issuing from the lens L_4 is selected by the diaphragm and a slightly different part of the half-platinized plate is employed in the reflexion. Estimates of the possible errors arising in this way from non-uniformity in the beam and in the half-platinized plate showed them to be small and probably not greater than about 5 % in the worst case.

Absolute Intensities

Although the measurements were primarily concerned with the change in apparent brightness with change in the point of entry of the ray in the eye pupil, it was desirable to know, at least approximately, the absolute intensity of the matching field. Suppose θ° K. is the colour temperature of the source S when run at a given voltage. We can determine from tables such as those of Skogland (1929) the radiational energy in the wave-length interval λ to $\lambda + d\lambda$ emitted per sec. in all directions by 1 sq. cm. of a black body at temperature θ. Putting this equal to $J(\theta, \lambda)\, d\lambda$, the corresponding quantity for a tungsten emitting surface will be $\epsilon(\theta) . J(\theta, \lambda)\, d\lambda$, where $\epsilon(\theta)$ is an empirical constant termed the colour emissivity of tungsten at the temperature (θ) (Forsythe and Worthing 1926).

It can now be shown without difficulty that the total energy flux in eyes per sec. incident on the eye at O from that part of the photometric field illuminated by spectrometer I is equal to

$$\frac{\epsilon(\theta)}{\pi} . J(\theta, \lambda)\, h \sigma_1 \sigma_2 S_\lambda t_\lambda \tau_\lambda \Phi, \qquad \text{......(1)}$$

where

σ_1 = width in cm. of entrance slit of spectrometer I.

σ_2 = width in cm. of exit slit of spectrometer I.

h = height in cm. of entrance or exit slit of spectrometer I whichever is the lesser. In our case the exit slit has the lesser height.

S_λ = dispersion of spectrometer I expressed as the width in microns of the band of spectrum passed per cm. width of exit slit, when the entrance slit is a mathematical line.

t_λ = overall transmission for wave-length λ of all the optical parts between light source and eye including the transmission of any stray light glass which may be used.

τ_λ = transmission for wave-length λ of the wedges W_1 and W_2 at any particular settings.

Φ = solid angle in steradians subtended at the eye by that part of the photometric field illuminated by spectrometer I.

It is more appropriate to express the intensity as the energy flux incident on the eye per unit solid angle of the field, and it is also convenient to express solid angle in square degrees rather than in steradians. Thus we shall put

U_λ equal to the energy flux incident on the eye expressed in ergs per sec. per square degree of the field. U_λ is given simply by the expression (1) above with the omission of the factor Φ and the introduction of a constant factor $(1/57{\cdot}3)^2$ which takes account of the use of square degrees in place of steradians. A closely similar expression to (1) is obtained for the intensity in energy units U_λ of the part of the field illuminated by spectrometer II.

An accurate determination of the absolute field intensity was not required and the values of U_λ quoted in what follows must be regarded only as very approximate.

In addition to U_λ, the photometric brightness B of the field, defined in the following conventional manner, will also be given. B is equal to the brightness in candles per square which, if viewed through an artificial pupil of 10 sq. mm. area by an eye possessing the standard relative luminosity curve, would match in brightness the monochromatic field as seen in the apparatus. Actually the existence of the pupil effect calls for certain refinements in this definition, but for the present purpose these may be neglected. It is then easy to show that B equals

$$U_\lambda V_\lambda \frac{57{\cdot}3^2}{15000 \times 1{\cdot}08 \times 10^{-5} \times 10} = 2{\cdot}02 \times 10^3 U_\lambda V_\lambda, \qquad \text{......(2)}$$

where V_λ is relative luminosity factor for wave-length λ.

By arranging to illuminate one-half of the photometric field of the apparatus with a diffusely emitting white surface and by matching this surface seen through an artificial pupil with the other half of the photometric field illuminated by yellow light of wave-length 580 mμ from spectrometer I, a comparison was made between the brightness of the yellow half field obtained by calculation from the expressions (1) and (2) and the brightness of the white half field obtained by direct measurement with an illuminometer set up in the eye position (the artificial pupil was removed for this purpose). The values obtained differed by 26 %, which is not a large discrepancy bearing in mind the approximations made.

Results

Fig. 3 shows the variation of $\log_{10}\eta$ with d for two horizontal traverses through the centre of the pupil using light of wave-length 500 mμ. Each plotted point is the mean of four settings. The circles represent observations obtained in a traverse in the direction nasal to temporal, the crosses observations obtained in a second traverse in the reverse direction (additional points at $d = 0$ are shown as squares). Similar sets of data were obtained for other wave-lengths ranging from $\lambda = 440$ to $\lambda = 720$ mμ, the details of these runs being given in Table I. In each case a continuous curve was drawn through the plotted points as shown in fig. 3. The data for $\lambda = 500\,\mathrm{m}\mu$ are among the best in showing agreement between the observations for the

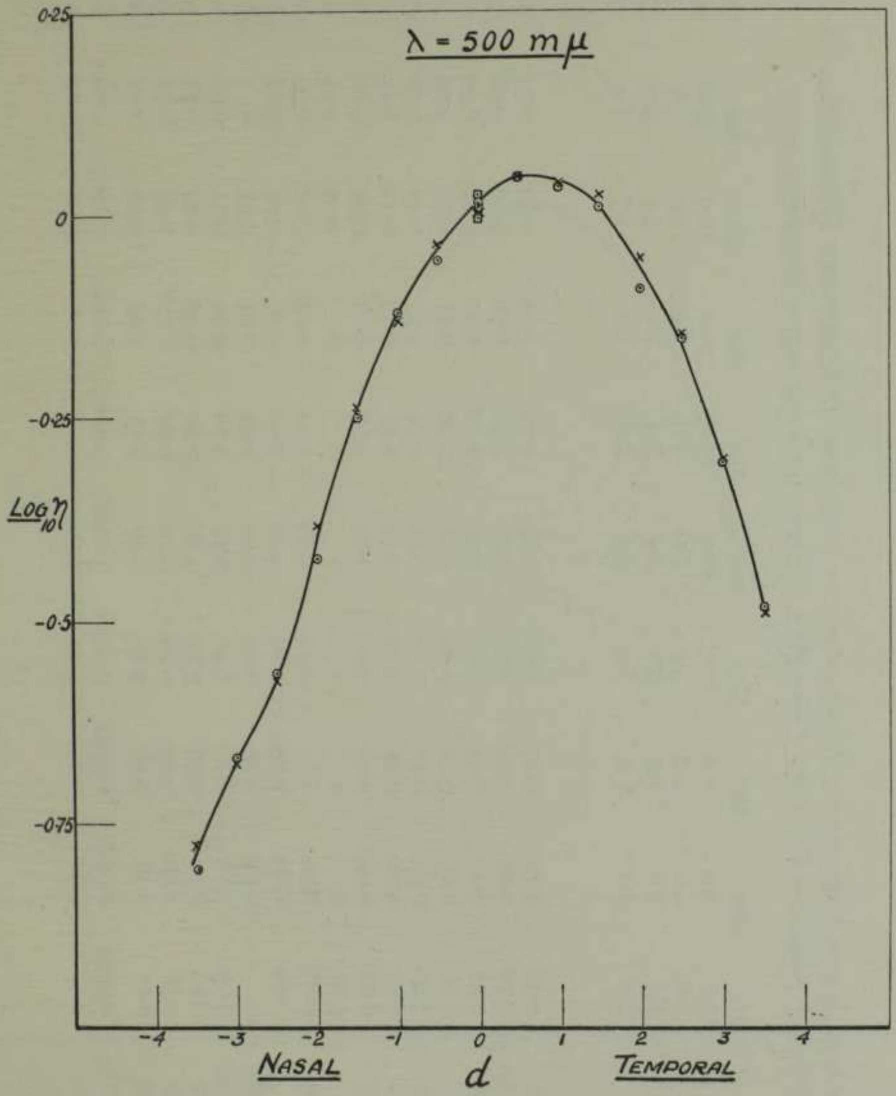

Fig. 3

two traverses. All the results are for the author's left eye dilated with euphthalmine.

As anticipated, the general form of the curve of $\log_{10}\eta$ against d is not very different for different wave-lengths. However, an analysis of the data on

TABLE I—VALUES OF $\log_{10}\eta$ FOR DIFFERENT WAVE-LENGTHS OBTAINED IN COMPLETE HORIZONTAL TRAVERSES OF THE PUPIL. SUBJECT W. S. S. LEFT EYE. PUPIL DILATED WITH EUPHTHALMINE

λ (mμ)	440	460	480	500	520	540	560	580	600	620	660	720	
$\Delta\lambda$ (mμ)	9·6	10·1	10·0	9·8	10·2	10·0	10·0	10·3	10·0	10·0	10·0	25·0	
ρ	1·0	1·0	1·0	1·0	1·0	1·0	1·0	1·0	1·0	1·0	1·0	1·0	
$\log_{10} U_\lambda$	$\bar{4}$·0	$\bar{4}$·0	$\bar{4}$·4	$\bar{4}$·6	$\bar{4}$·5	$\bar{4}$·3	$\bar{4}$·9	$\bar{4}$·8	$\bar{4}$·8	$\bar{4}$·8	$\bar{4}$·9	$\bar{3}$·7	
$\log_{10} B$	$\bar{3}$·6	$\bar{2}$·1	$\bar{2}$·8	$\bar{1}$·4	$\bar{1}$·6	$\bar{1}$·6	0·2	0·0	$\bar{1}$·9	$\bar{1}$·7	$\bar{1}$·0	$\bar{2}$·0	
d (mm.)													Mean data
−3·5 nasal	0·97	0·86	0·86	0·79	0·70	0·69	0·73	0·72	0·74	0·74	0·71	0·73	0·770
−3·0 ,,	0·79	0·82	0·76	0·67	0·60	0·52	0·60	0·60	0·60	0·66	0·62	0·61	0·655
−2·5 ,,	0·60	0·66	0·62	0·57	0·44	0·41	0·43	0·49	0·47	0·52	0·50	0·50	0·519
−2·0 ,,	0·44	0·47	0·46	0·40	0·28	0·30	0·33	0·36	0·31	0·37	0·36	0·39	0·373
−1·5 ,,	0·26	0·27	0·27	0·24	0·17	0·18	0·21	0·24	0·22	0·24	0·23	0·22	0·231
−1·0 ,,	0·15	0·17	0·12	0·13	0·08	0·10	0·12	0·11	0·13	0·14	0·11	0·08	0·120
−0·5 ,,	0·05	0·07	0·05	0·05	0·05	0·05	0·06	0·02	0·04	0·08	0·04	0·02	0·050
0 ,,	0	0	0·01	0	0	0	0	0	0	0·02	0·01	0	0·004
0·5 temporal	−0·01	−0·04	−0·03	−0·05	0	0·01	−0·02	−0·04	−0·02	0·01	−0·05	−0·02	−0·018
1·0 ,,	0·01	0	−0·03	−0·03	0·03	0·04	−0·02	−0·03	−0·01	−0·01	−0·03	−0·02	−0·009
1·5 ,,	0·06	0·02	0	−0·02	0·06	0·08	0·03	0·02	0·01	0·02	0	−0·01	0·023
2·0 ,,	0·13	0·05	0·05	0·07	0·13	0·18	0·12	0·10	0·10	0·12	0·07	0·02	0·095
2·5 ,,	0·28	0·19	0·17	0·15	0·25	0·24	0·26	0·20	0·19	0·25	0·23	0·22	0·219
3·0 ,,	0·46	0·37	0·35	0·30	0·39	0·38	0·40	0·39	0·37	0·42	0·39	0·35	0·381
3·5 ,,	0·61	0·53	0·50	0·49	0·48	0·57	0·50	0·43	0·42	0·53	0·48	0·50	0·503
p	0·0721	0·0712	0·0688	0·0627	0·0532	0·0538	0·0567	0·0595	0·0540	0·0604	0·0639	0·0618	0·0612
d_m (mm.)	0·49	0·65	0·69	0·68	0·35	0·28	0·50	0·57	0·57	0·58	0·59	0·59	0·56

the following lines reveals a small systematic variation through the spectrum.

The mean value of $\log_{10}\eta$ for all wave-lengths at each d value was first determined, and the mean curve so obtained is shown as the continuous

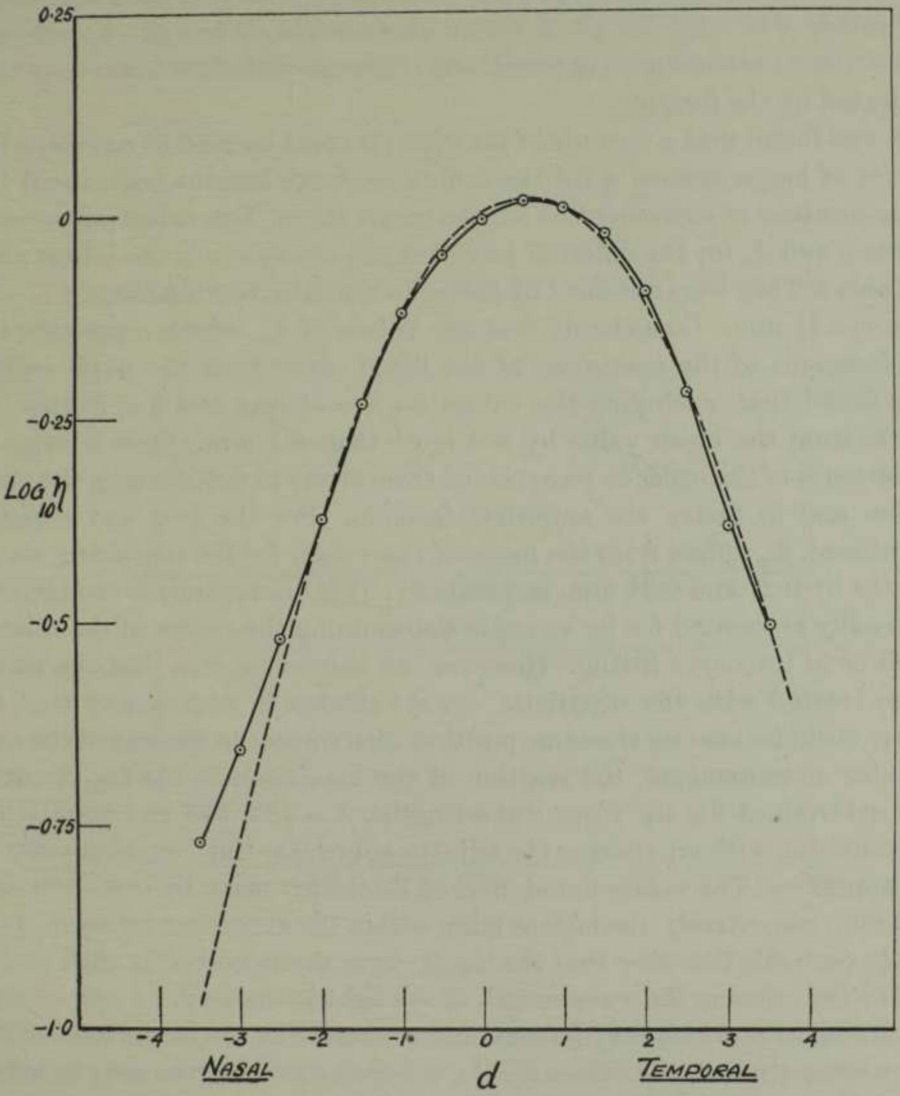

FIG. 4—Mean curve for all wave-lengths.

curve on fig. 4. (Mean data of Table I.) The curve is nearly, but not quite, symmetrical about an ordinate displaced 0·6 mm. to the temporal side. Thus the luminous efficiency is a maximum for rays entering slightly to the temporal side of the pupil centre.

The broken curve shown in fig. 4 is represented by the formula:

$$\log_{10}\eta - \log_{10}\eta_m = -p\,(d-d_m)^2, \qquad \text{......(3)}$$

with $p = 0{\cdot}0612$, $d_m = +0{\cdot}56$ mm., where η_m is the value of η at $d = d_m$. The broken curve and the observed mean curve are in tolerably good agreement for values of $(d-d_m)$ not greater than about 3 mm. When $(d-d_m)$ exceeds 3 mm. (only obtainable on the nasal side) the observed effect is less than that indicated by the formula.

It was found that a formula of the type (3) could be used to represent the curves of $\log_{10}\eta$ against d for the individual wave-lengths with about the same measure of agreement as for the mean curve. The values of the constants p and d_m for the different wave-lengths are shown in the lowest rows of Table I. They were obtained by fitting to the data over the range $d = -2\frac{1}{2}$ to $d = +3\frac{1}{2}$ mm. Considering first the values of d_m, which represents the displacement of the maximum of the fitted curve from the pupil centre, it is found that, excluding the values for $\lambda = 520\,\text{m}\mu$ and $\lambda = 540\,\text{m}\mu$, d_m differs from the mean value by not more than 0·1 mm. Such a range of variation is of the order to be expected from errors in determining the pupil centre and in fitting the empirical formula. For the two wave-lengths mentioned, d_m differs from the mean of the values for the remaining wave-lengths by 0·27 and 0·31 mm. respectively. This discrepancy is too large to be readily accounted for by errors in determining the centre of the dilated pupil or in the curve fitting. However, we cannot be sure that the pupil, when treated with the mydriatic, always dilates in such a way that its centre occupies exactly the same position with respect to the rest of the eye. In later measurements, the position of the maximum in the $\log_{10}\eta$ curve was determined for the three wave-lengths, $\lambda = 480$, 530 and $600\,\text{m}\mu$, on the same day without altering the adjustment of the "bit" or other parts of the apparatus. The values found differed from their mean by 0·06, 0·04 and 0·01 mm. respectively, deviations lying within the experimental error. It is highly probable therefore that the $\log_{10}\eta$ curve shows no bodily shift to one side or the other as the wave-length of the light is changed.

Turning to p, which may be regarded as specifying the magnitude of the effect being studied, the values for the different wave-lengths are plotted in fig. 5. It appears that the effect is greatest in the blue end of the spectrum, smallest in the green and intermediate in the red.

Since the curves on which fig. 5 is based were determined over a period of several weeks, it was desirable to make further measurements in which the complete range of wave-lengths was covered in a single run. In the previous runs the traversing image ω_2 was moved across on a horizontal line through the pupil centre and the greatest luminous efficiency for any point on this line was found to occur at about 0·5 or 0·6 mm. to the temporal side of the pupil centre. It does not follow, and for the author's left eye it is not the case, that the luminous efficiency at $d = 0{\cdot}5$ mm. is greater than for any other point of the pupil. By determining the luminous efficiency at different points on a *vertical* line 0·5 mm. to the temporal side of the pupil centre, it was found that the maximum efficiency occurred at a point 0·5 mm. above the horizontal through the pupil centre. This point, which will be referred to as P_M, corresponds approximately to the maximum luminous efficiency obtainable for any point of entry. In the measurements now to be recorded, the luminous efficiency, when the traversing beam (ω_2) entered at P_M, was compared with that obtained when it entered at a point Q, 2·75 mm. to the nasal side of P_M. The fixed comparison beam was arranged to enter at P_M for both observations. Measurements for all the wave-lengths studied were made without interruption in one run, the adjustment of the whole apparatus being kept unchanged save for varying the wave-length.

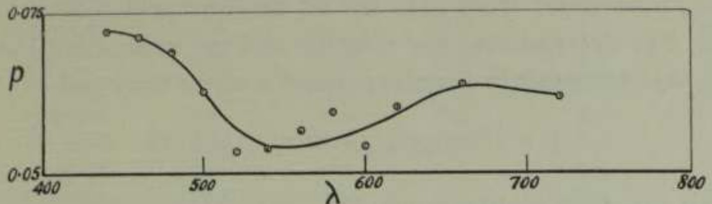

FIG. 5

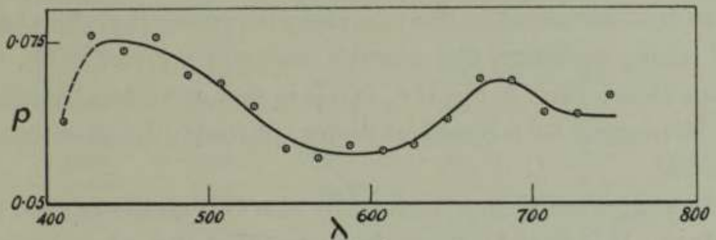

FIG. 6

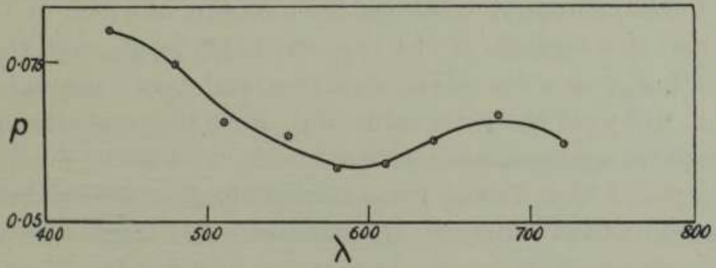

FIG. 7

Assuming that a formula of the type (3) will apply for a horizontal traverse through the point P_M, it follows that

$$(\log_{10}\eta)_{P_M}-(\log_{10}\eta)_Q=-p(0-r_m)^2-\{-p(-2\cdot75-r_m)^2\}=p\{7\cdot56+5\cdot5r_m\},$$

where r_m is the displacement from the point P_M of the position in the traverse at which the luminous efficiency is a maximum. By our choice of P_M, r_m should be zero but owing to errors in determining P_M this may not be strictly true and r_m may differ from zero by an amount probably not exceeding $\pm 0\cdot1$ mm. For determining the relative change with wave-length of the value of p, this uncertainty is unimportant and we may put

$$p=\{(\log_{10}\eta)_{P_M}-(\log_{10}\eta)_Q\}/7\cdot56.$$

The mean values of p obtained in this way in three independent runs are shown in fig. 6. The general character of the variation of p with wave-length is similar to that obtained in the complete traverses (fig. 5). Owing to the method of taking readings, the relative values of p given in fig. 6 are more reliable than those of fig. 5, but if r_m is not in fact zero the absolute values of fig. 6 may be in error by a constant factor, probably lying within the range 1·08 and 0·92.

It may be suggested that p derived by the two methods need not be the same constant. It is easy to show, however, that if the luminous efficiency falls off in the same manner whatever the direction in which we move away from P_M, and if a formula of the type (3) holds good, then the curve of variation of $\log_{10}\eta$ on a line of any direction, and drawn through any point in the pupil, will yield the same value of p. Both the conditions mentioned are known to be approximately true.

It will be noted from Tables I and II that the photometric brightness B of the test field varied widely for the different wave-lengths. The variation of intensity expressed in energy units (U_λ) is less, but is still considerable. It is clear that if the magnitude of the effect varies with intensity the variation of p with wave-length shown in figs. 5 and 6 might be attributed wholly or in part to variations in the field brightness. A series of four runs was then made on the same lines as those reported in Table II, but keeping the photometric intensity of the matching field approximately constant. The mean data for these runs are given in Table III, and, in fig. 7, p is plotted against λ. The agreement between the values of figs. 6 and 7 is as good as can be expected with this kind of measurement, and we may conclude that the variation of p with wave-length is not to be explained as the result of variations of the field brightness.

TABLE II—VALUES OF p DEDUCED FROM THE RELATIVE LUMINOUS EFFICIENCIES FOR A RAY ENTERING AT P_M AND A RAY ENTERING 2·75 MM. TO THE NASAL SIDE OF P_M

		Conditions for one of the three runs*				
λ mμ	p (Mean data for three runs)	λ mμ	$\Delta\lambda$ mμ	ρ	$\log_{10} U_\lambda$	$\log_{10} B$
410	0·0624†	420	12·9	0·25	$\bar{4}\cdot 4$	$\bar{3}\cdot 3$
427	0·0756	440	15·2	0·5	$\bar{4}\cdot 7$	$\bar{2}\cdot 4$
447	0·0731	460	10·9	1·0	$\bar{4}\cdot 4$	$\bar{2}\cdot 4$
467	0·0753	480	8·4	0·5	$\bar{4}\cdot 8$	$\bar{1}\cdot 2$
487	0·0695	500	7·4	0·5	$\bar{4}\cdot 7$	$\bar{1}\cdot 5$
507	0·0682	520	8·6	0·5	$\bar{4}\cdot 8$	0·0
527	0·0646	540	9·8	0·5	$\bar{3}\cdot 2$	0·5
547	0·0580	560	11·0	0·5	$\bar{3}\cdot 3$	0·6
567	0·0566	580	12·5	0·5	$\bar{3}\cdot 4$	0·6
587	0·0585	600	13·4	0·5	$\bar{3}\cdot 5$	0·6
607	0·0577	620	15·0	0·5	$\bar{3}\cdot 4$	0·3
627	0·0586	640	17·0	0·5	$\bar{3}\cdot 5$	0·1
647	0·0625	660	18·8	0·5	$\bar{3}\cdot 6$	$\bar{1}\cdot 6$
667	0·0688	680	19·8	0·5	$\bar{3}\cdot 7$	$\bar{1}\cdot 2$
687	0·0684	700	22·0	0·5	$\bar{2}\cdot 0$	$\bar{2}\cdot 9$
707	0·0635	720	23·4	0·5	$\bar{2}\cdot 0$	$\bar{2}\cdot 3$
727	0·0631	740	23·3	0·5	$\bar{2}\cdot 1$	$\bar{3}\cdot 8$
747	0·0661					

* The conditions for the other two runs were not very different and need not be given.

† One observation only.

TABLE III—VALUES OF p DEDUCED FROM THE RELATIVE LUMINOUS EFFICIENCIES FOR A RAY ENTERING AT P_M AND A RAY ENTERING 2·75 MM. TO THE NASAL SIDE OF P_M. BRIGHTNESS B OF TEST FIELD APPROXIMATELY CONSTANT AND EQUAL TO 0·1 C./FT.^{2}

λ mμ	$\Delta\lambda$ ($\rho = 1$) mμ	p (mean data for four runs)
440	22·5	0·0799
480	33·4	0·0721
510	40	0·0659
550	40	0·0636
580	40	0·0588
610	40	0·0593
640	40	0·0629
680	40	0·0670
720	40	0·0625

Some additional runs were made, keeping the wave-length constant and varying the field intensity. For all wave-lengths, the effect as specified by p was found to be approximately independent of intensity over a considerable range. For wave-lengths in the middle of the spectrum there was an indication of a marked increase in the effect at very high brightnesses of the order of $B = 200$ c./sq. ft. This intensity could not be reached in the blue, blue-green and red. There was also some tendency for the effect to increase at very low intensities ($B = 0{\cdot}01$ c./sq. ft.) in the orange and red. As only a single run was made with each wave-length, the above observations are of a tentative character.

PART II—THE CHANGE IN COLOUR OF A MONOCHROMATIC LIGHT AS THE POINT OF ENTRY OF THE RAY IN THE PUPIL IS VARIED

Experimental

Attention was drawn in the Introduction to the change of colour which occurs when the traversing beam is moved across the pupil. For investigating this colour change, arrangements were made to enable the wave-length drum of spectrometer II to be operated by the subject who was then given the task of varying both the wave-length and intensity of the beam from spectrometer II until the two halves of the photometric field matched in brightness and colour. Owing to the use of Maxwellian view with beams of very small cross-section at the eye pupil, a perfectly uniform structureless field is not obtained even when both the images ω_1 and ω_2 are located at the centre of the eye pupil. As the traversing image ω_2 moves away from the centre the imperfections of the corresponding half field tend to increase, and at the extreme position of ω_2 the half field acquires a fuzzy appearance. The difficulties of making a colour and brightness match under these conditions are considerable. An additional difficulty is experienced in the blue and red ends of the spectrum owing to the rapid change of photometric intensity which occurs as the wave-length drum of the spectrometer is turned. This is a serious drawback to the method of colour matching used here, a method which was adopted only because it involved very little modification of the apparatus. Finally, in the green and blue-green the change of colour as the traversing beam is moved across the pupil is not a simple change of hue which can be eliminated by a change of wave-length, but is a change of both hue and saturation. Where this occurred, the subject adjusted wave-length and intensity to give the best hue and brightness match.

Results

If λ_2' is the mean setting of the wave-length of the traversing beam to give a colour and brightness match with the fixed beam, when the point of entry is at the centre of the pupil, and λ_2'' is the corresponding quantity when entry is at any point P of the pupil opening, then we shall express our results by giving the value of $(\lambda_2' - \lambda_2'')$. The results of a series of readings corresponding to two horizontal traverses through the pupil centre one in the direction nasal to temporal (circles), the other in the reverse direction (crosses), are shown in fig. 8. Each plotted point is the mean of four settings in which the difference between the maximum and minimum settings of λ_2'' equalled on the average 0·85 mμ. The wave-length λ_1 of the fixed comparison beam entering through the centre of the pupil was 578·0 mμ. With the traversing beam also entering centrally the mean setting equalled 578·8 mμ. The difference is hardly more than the experimental error. In other cases somewhat larger differences were obtained, attributable to differences in the band width $\Delta\lambda$, slit ratio ρ and stray light glasses used in the two optical trains. Such differences need not occupy us here and we can confine our attention to the values of λ_2.

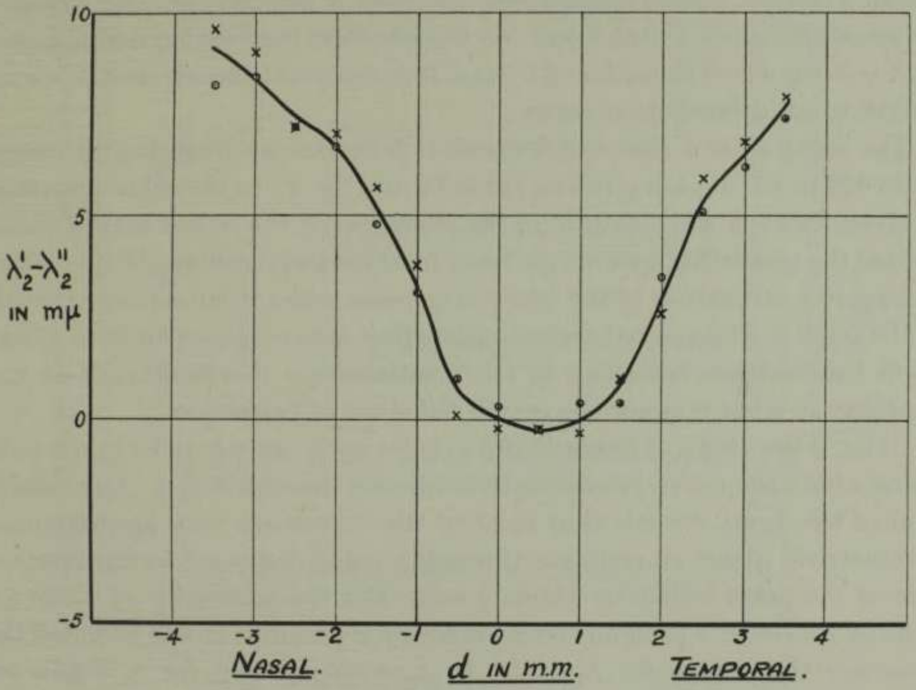

FIG. 8—Hue change with position of point of entry. $\lambda_2' = 578 \cdot 8\,\mathrm{m}\mu$.

It will be noted that the curve of fig. 8 is approximately symmetrical about an ordinate through a point P_M at about 0·5 mm. to the temporal side of the pupil centre. It will be recalled that the curve of the intensity effect was found to be symmetrical about an ordinate similarly situated. The direction of the colour change is such that as the point of entry moves away from P_M the colour of the traversing beam appears to become relatively redder, so that its wave-length has to be reduced to maintain colour match with the comparison field. At this part of the spectrum a reasonably good colour match is obtainable wherever the traversing beam enters the pupil. Thus the colour change is in the main a hue change. The change at its greatest equals about 9 mμ. As the smallest perceptible hue difference at $\lambda = 579$ mμ is of the order of 1·5 mμ, it is clear that the effect at this wave-length is not difficult to observe.

The results for a series of horizontal traverses at wave-length ranging from 656 to 457 mμ are given in Table IV and fig. 9. In the table a comment is given for each wave-length on the character of the colour match obtainable as the traversing spot moves away from the pupil centre. At $\lambda_2' = 500$ mμ the greater saturation of the traversing beam when it enters near the edge of the pupil is well marked and a similar effect is in evidence for $\lambda_2' = 478$ mμ. With the matches described as fairly satisfactory it was difficult to state precisely in what manner the match fell short of perfection.

In fig. 9 the origin of the ordinate axis for each curve is to be taken as the point where the curve intersects the ordinate through $d = 0$. An examination of the figure reveals that most of the curves are very approximately symmetrical about an ordinate through a point displaced to the temporal side of the pupil centre by about $\frac{1}{2}$ mm. For the curves for $\lambda_2' = 636$ and 656 mμ, however, a pronounced asymmetry is present. It will be noted that although the curves for $\lambda_2' = 657$ to $\lambda_2' = 562$ mμ and for $\lambda_2' = 478$ and 457 mμ show a fairly steady increase in $(\lambda_2' - \lambda_2'')$, starting from the value of d at which $(\lambda_2' - \lambda_2'')$ is a minimum and moving away either to the temporal or nasal side, the curves for $\lambda_2' = 542$, 522 and 500 mμ are of a more complex character. The manner in which the magnitude of the hue change varies with wave-length is best seen with the aid of fig. 10 in which the values of $(\lambda_2' - \lambda_2'')$ are plotted against λ_2' for $d = -3·5$ mm. (nasal), $d = -2·5$ mm. (nasal), $d = +3·5$ mm. (temporal). Owing to the displacement of the centres of symmetry of the curves of fig. 9 to the temporal side, the values for $d = -3·5$ mm. correspond to maximal effect. The values for $d = -2·5$ mm. and $+3·5$ mm. would be the same if all the curves were symmetrical about the ordinate $d = +0·5$ mm. Examining the graphs of fig. 10 it is clear that for these d values the hue change has a maximum in the neighbourhood of

TABLE IV—VALUES OF $(\lambda_2'-\lambda_2'')$ IN Mμ. HORIZONTAL TRAVERSE THROUGH THE PUPIL CENTRE. SUBJECT W. S. S. LEFT EYE. PUPIL DILATED WITH EUPHTHALMINE

λ_2' (mμ)	656	636	622	601	579	562	542	522	500	478	457
$\Delta\lambda_2 (\rho=1)$	10·0	10·4	10·0	10·0	10·0	10·0	10·0	10·2	9·8	10·0	10·1
$\log_{10} U_\lambda$	$\bar{3}$·1	$\bar{3}$·0	$\bar{4}$·9	$\bar{4}$·9	$\bar{4}$·7	$\bar{4}$·9	$\bar{4}$·3	$\bar{4}$·5	$\bar{4}$·1	$\bar{4}$·1	$\bar{4}$·3
$\log_{10} B$	$\bar{1}$·2	$\bar{1}$·6	$\bar{1}$·8	0·0	0·0	0·2	$\bar{1}$·6	$\bar{1}$·6	$\bar{2}$·9	$\bar{2}$·5	$\bar{2}$·4
d (mm.)											
−3·5 nasal	12·6	6·6	8·3	8·8	8·9	7·1	3·1	—	2·9	6·2	4·6
−3·0 ,,	8·7	6·4	6·5	7·5	8·7	6·9	1·8	−2·2	2·3	6·1	6·2
−2·5 ,,	11·1	6·1	7·1	6·8	7·2	5·6	2·5	−0·4	−0·6	6·3	4·7
−2·0 ,,	9·1	5·2	4·5	5·4	6·8	5·7	2·3	0·6	+0·1	4·8	4·8
−1·5 ,,	8·2	2·2	2·7	4·1	5·2	4·1	2·8	1·7	0	3·1	2·8
−1·0 ,,	3·3	0·4	1·1	1·5	3·4	2·5	3·1	2·0	0·5	1·1	0·7
−0·5 ,,	3·1	0·8	0·7	0·8	0·6	1·3	1·2	0·4	0·9	0·9	−0·5
0 ,,	−0·3	0·4	0·3	−0·4	0	0·1	−0·1	0·2	−0·1	0·1	0·2
0·5 temporal	−0·5	−0·5	0	−0·2	−0·2	−0·9	0·1	−0·5	−0·7	−0·4	0·7
1·0 ,,	−1·3	0·6	−0·7	−0·2	0	0	−0·7	1·0	−0·1	−0·8	0·5
1·5 ,,	−2·3	−1·1	1·0	0·2	0·7	1·1	0·9	0·6	−0·2	−0·3	1·3
2·0 ,,	−0·3	−1·8	0·5	1·0	3·0	3·8	1·8	0·6	−0·4	0·9	2·3
2·5 ,,	1·3	−0·6	2·8	3·4	5·5	4·2	2·0	1·1	−0·5	1·9	3·4
3·0 ,,	2·7	2·0	4·1	5·4	6·5	4·7	2·4	0·6	0·6	2·9	5·1
3·5 ,,	3·9	2·2	5·4	6·8	7·6	5·6*	2·6	−0·7	2·4	4·4	5·8
Remarks on colour match	Satisfactory	Satisfactory	Satisfactory	Fairly satisfactory	Fairly satisfactory	Fairly satisfactory	Fairly satisfactory	Fairly satisfactory	ω_2 more saturated than ω_1	ω_2 more saturated than ω_1	Satisfactory

* $d=3\cdot25$.

$\lambda_2' = 590\,\mathrm{m}\mu$, a minimum at $\lambda_2' = 520\,\mathrm{m}\mu$, where the hue change is negative, i.e. the traversing beam becomes relatively bluer, and, probably, a further maximum in the neighbourhood of $\lambda_2' = 470\,\mathrm{m}\mu$. Little weight can be attached to the high values of the points for $\lambda_2' = 657\,\mathrm{m}\mu$, as the difficulties of measurement are here particularly severe, largely due to the falling off of hue sensitivity in the red end of the spectrum.

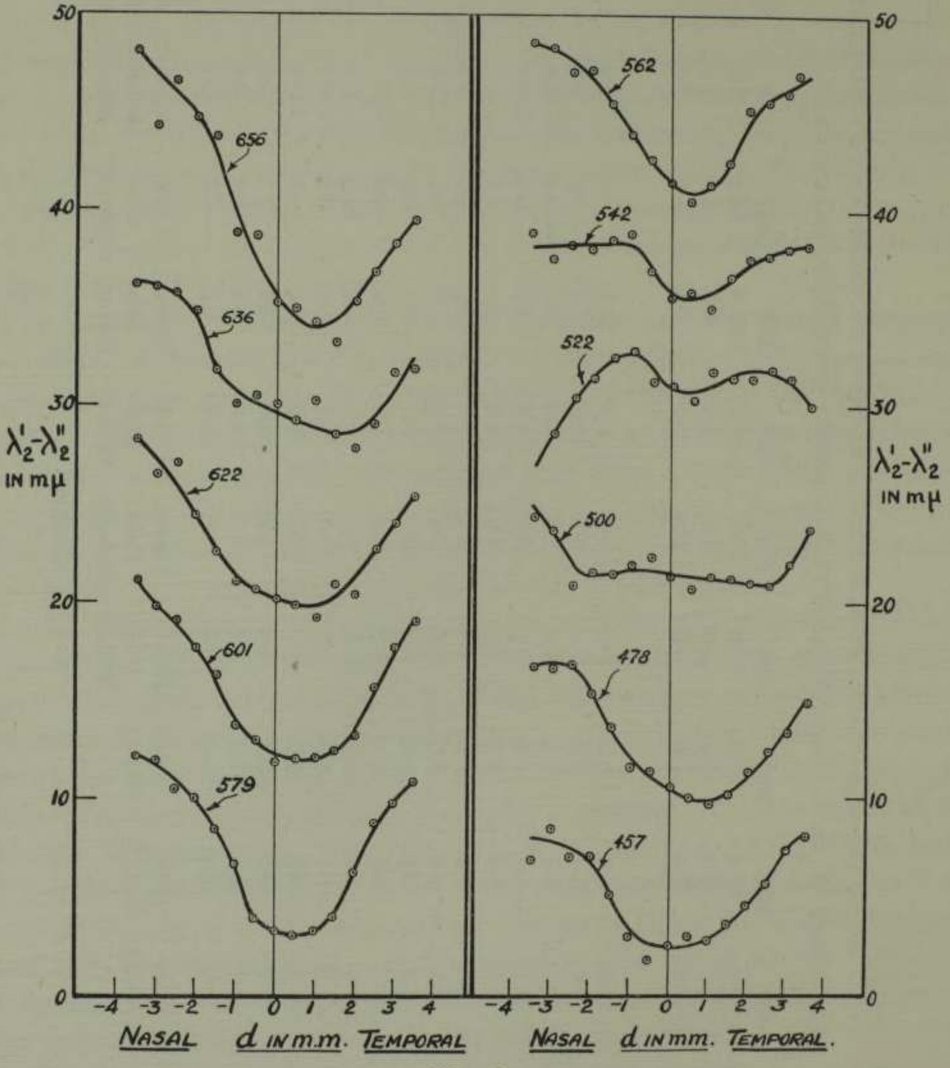

Fig. 9

As a consequence of the complexity of shape of some of the curves of fig. 9, the graph connecting $(\lambda_2' - \lambda_2'')$ with λ_2' at a particular d value is not in general obtainable by a proportional change in the ordinates of the corresponding graph for any other d value. This is clearly shown by a comparison of fig. 10 with fig. 11 in which $(\lambda_2'-\lambda_2'')$ is plotted against λ_2' for $d = -1$ mm. (nasal) and $+2$ mm. (temporal). The difference in shape of the graphs of figs. 10 and 11 in the region $\lambda_2' = 500$ to $550\,\mathrm{m}\mu$ is well marked.

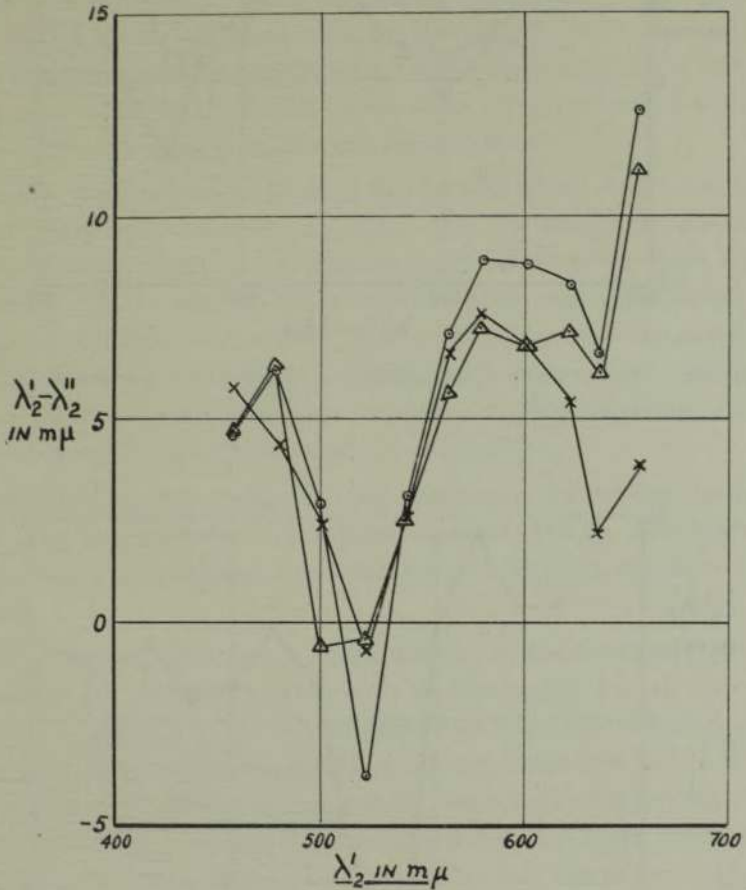

FIG. 10—⊙ $d = -3\cdot5$ mm. nasal; △ $d = -2\cdot5$ mm. nasal; × $d = +3\cdot5$ mm. temporal.

All the above results refer to one eye. Qualitative observations on other eyes confirm the existence of a colour change as the point of entry is varied and for one of these eyes (B. H. C. right) the graph of fig. 12 represents a single series of determinations of $\lambda_2' = \lambda_2''$ for a point at $d = -2\cdot5$ mm. Compared with the graphs of fig. 10, we note the very large negative value at $\lambda_2' = 520\,\mathrm{m}\mu$ and the larger positive values in the blue and blue-green than in the yellow. There is, however, a generic similarity. It is hoped to continue the investigation of the colour change effect using a trichromatic colorimeter, and the behaviour of a number of eyes will then be examined.

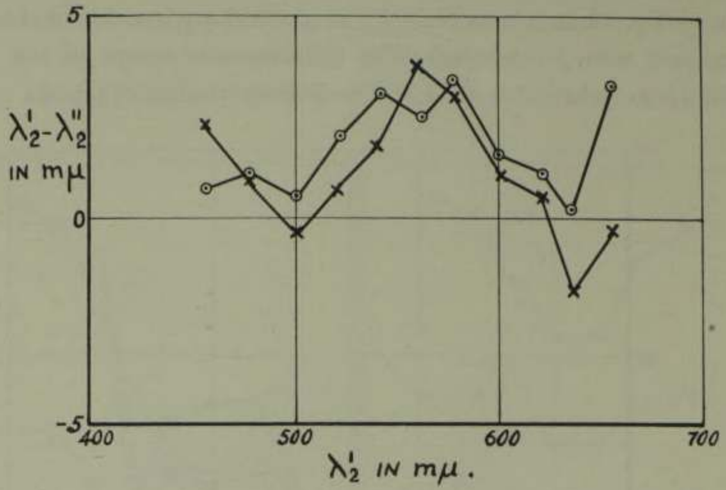

Fig. 11—⊙ $d = -1$ mm. nasal; × $d = +2$ mm. temporal.

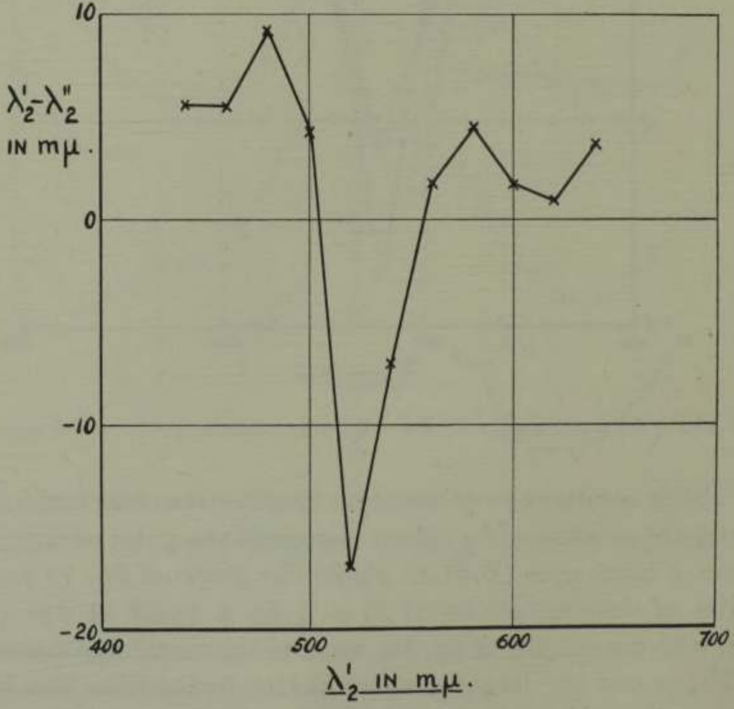

Fig. 12—× $d = -2{\cdot}5$ mm.

Colour Changes arising as Artifacts of the Method

It has been taken for granted up to now that the observed colour change is due to the fact that the colour of a physically homogeneous radiation incident on a given area of the retina depends on its point of entry in the eye. Actually spectrum bands of a total width equal to about $10\,\mathrm{m}\mu$ were used in the measurements and there are three ways in which a colour change might conceivably be produced other than by an effect of the kind just described. The three possibilities are the following:

(1) If the different wave-lengths in the traversing beam are reduced in apparent intensity to different extents when the image ω_2 moves from the centre to the edge of the pupil, the resultant colour of the field will change. This change will be due to the variation with wave-length of the pupil intensity effect which is seen from fig. 6 to be greatest in the neighbourhood of $\lambda = 640\,\mathrm{m}\mu$ and $\lambda = 515\,\mathrm{m}\mu$. Calculation shows that at these wave-lengths under the conditions of the experiments, the resulting hue change is at most of the order of $0{\cdot}1\,\mathrm{m}\mu$, which is negligible.

(2) Selectivity of the wedge W_3 may produce a colour change in precisely the same way as selectivity in the pupil intensity effect. Calculation shows, however, that the resultant hue changes will be even smaller than in the latter case.

(3) The image ω_2 is in fact a small section of the spectrum produced by spectrometer II, and the wave-length in the image varies (in our case it increases), in passing from the left-hand to the right-hand edge, by the amount $\Delta\lambda/2$. When ω_2 is displaced to the temporal side of the left eye, the left-hand edge will clearly be subject to greater pupil intensity effect than the right-hand edge, because it enters the pupil at a more peripheral point. Thus, there will occur a change in the colorimetric hue of the field, each part of which is illuminated by the whole of the image ω_2. In a traverse of the pupil this change will be of opposite sign on either side of the point at which the pupil intensity effect is maximal. The magnitude of this effect can also be calculated and it is found that under the conditions used, the resultant hue change is of the order of $0{\cdot}2\,\mathrm{m}\mu$ at most.

Thus, none of the above colour changes arising as artifacts of the method is nearly large enough to explain the observed effects. The changes are in fact too small to warrant the application of any corrections to the data.

By substituting for the continuous light source S a sodium or mercury vapour lamp and isolating individual lines in the spectrum, the change of colour with point of entry was obtained with light of a very high degree of physical homogeneity. The effect is easiest to observe with the sodium D lines and with the mercury line at 491·6 mμ.

Discussion of Results

It is highly probable that the change in luminous efficiency of a monochromatic ray with change of the point of entry in the pupil (intensity effect) and the change in colour of the ray (colour effect) are closely related in their mode of origin. That such is the case is strongly suggested by the fact that most of the curves of $(\lambda_2' - \lambda_2'')$ against λ_2' show a displacement of their axes of symmetry in the same direction and of about the same amount as shown by the curves of the intensity effect. The explanation of the colour effect is certainly to be sought in the retinal mechanism, for it is clear that an increased absorption in the optic media of the eye can only reduce the intensity of a monochromatic ray, and when this is compensated for by increasing the intensity of the incident light the colour impression must be the same. It follows that in all probability the intensity effect is also retinal. This conclusion is clinched by measurements due to Crawford of the intensity effect in determinations of foveal and extra-foveal threshold values.*

The hypothesis has been advanced (Stiles and Crawford 1933, p. 446) that the intensity effect is due to the ensheathing of the cones by pigment contained in processes of the pigment epithelium intruded between the cones. Wright and Nelson (1936) suggest on the other hand that a difference in the refractive index of the cone and of its surrounding medium may provide the explanation of the intensity effect. In the following discussion where a picture of the mechanism is required the pigment sheath hypothesis is employed. The experimental evidence is however insufficient to decide between the two views mentioned and further work may reveal other possibilities.

Both the variation of the intensity effect with wave-length and the colour effect can be represented formally in terms of the trichromatic theory in the following manner. Suppose light of wave-length λ, incident through the centre of the pupil, has the trichromatic co-ordinates r_λ, g_λ, b_λ in a particular system of primaries (unitary stimuli) R, G, B for which the luminosity coefficients equal L_r, L_g and L_b respectively. We may suppose that when the point of entry of the incident light is changed, keeping its intensity constant, the response of the eye changes in a manner corresponding to the reduction of stimulation by the R, G, B primaries to fractions x_λ, y_λ, z_λ respectively of their previous values. The intensity effect

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* These experiments will be described in another paper.

specified by η, the ratio of the brightness when the light enters in the displaced position to the brightness for central entry, will equal

$$\eta = \frac{x_\lambda r_\lambda L_r + y_\lambda g_\lambda L_g + z_\lambda b_\lambda L_b}{r_\lambda L_r + g_\lambda L_g + b_\lambda L_b}. \qquad \ldots\ldots(4)$$

The colour change will correspond to a shift in the colour triangle, from the point $r_\lambda, g_\lambda, b_\lambda$ to the point $r'_\lambda, g'_\lambda, b'_\lambda$, where

$$r'_\lambda = \frac{x_\lambda r_\lambda}{\Sigma}, \quad g'_\lambda = \frac{y_\lambda g_\lambda}{\Sigma}, \quad b'_\lambda = \frac{z_\lambda b_\lambda}{\Sigma},$$

and

$$\Sigma = x_\lambda r_\lambda + y_\lambda g_\lambda + z_\lambda b_\lambda.$$

For the observed intensity effect and colour effect which occur for a particular wave-length and for a particular point of entry in the pupil, the corresponding values of x_λ, y_λ, z_λ can always be determined. That this can be done involves no hypothesis about the visual mechanism of the retina other than that implied by the possibility of three colour matching. For every different set of primaries which may be chosen, x_λ, y_λ and z_λ will have different values.

According to the trichromatic theory, there are three types of cone concerned in colour vision. As a first step towards the explanation of the colour effect and the variation of intensity effect with wave-length, the simplest assumption is that the cones of the three types would give different intensity effects if it were possible to stimulate one type independently of the others. In terms of the pigment sheath hypothesis this might mean that the cones of one type were longer and thinner or more deeply embedded in the pigment sheathing than cones of another type. It would then follow that if the primaries R, G, B had been so chosen that each stimulated one and one only of the cone types, the coefficients x_λ, y_λ, z_λ would correspond respectively to the reduction in response of the three types of cone. The possibility that this reduction might be independent of wave-length for all three types was first investigated, i.e. x_λ, y_λ, z_λ were put equal to constants x, y and z respectively.

Adopting the cone response curves derived by Wright* (1934) from his colour adaptation experiments, the ratios y/x and z/x were chosen to give correctly the observed hue changes at $\lambda = 486\,\mathrm{m}\mu$ and $\lambda = 590\,\mathrm{m}\mu$ shown in fig. 10 for $d = -3{\cdot}5$ nasal. The values necessary were $y/x = 0{\cdot}773$ and $z/x = 0{\cdot}380$. Using these values, the hue changes for other wave-lengths in

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* The fundamental response curves are depicted in figs. 8 and 9 from which the values here used have been obtained.

the spectrum were derived. The curve of hue change obtained in this way and the curve of observed hue change for $d = -3{\cdot}5$ nasal are shown in fig. 13. The curves show complete lack of agreement. Moreover, the calculations indicate that for wave-lengths below 550 mμ the ray entering at the displaced position should be a little less saturated than the spectrum colour which it matches in hue. The opposite was found to be the case

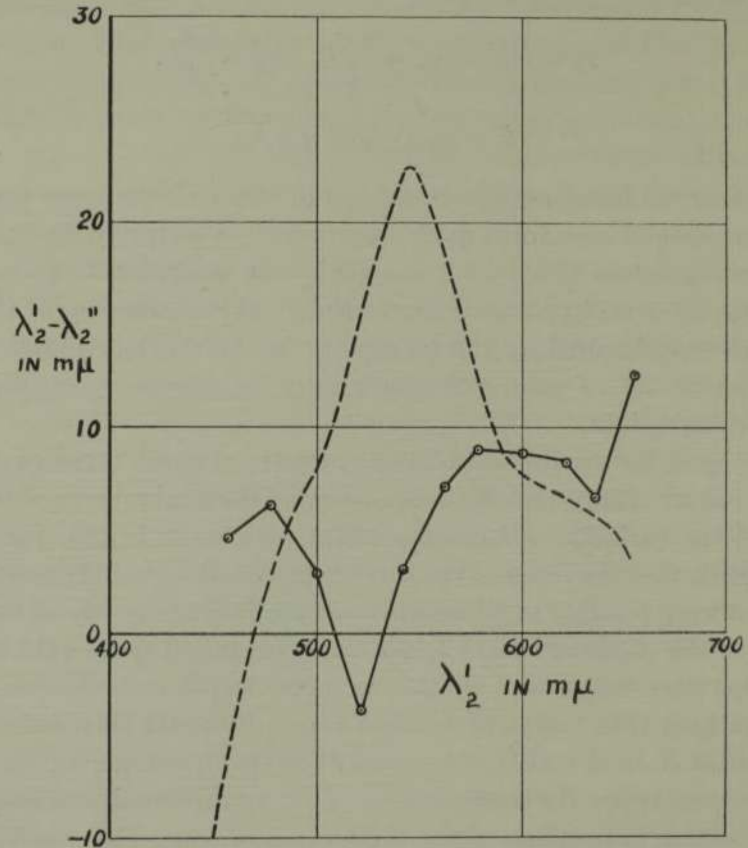

FIG. 13——- - - - - curve computed from Wright's fundamental response curves, x, y and z assumed constant; ⊙ observed hue change for $d = -3{\cdot}5$ mm. (nasal).

experimentally. Finally, the relative change in η was determined from equation (4). Fig. 14 gives curve of $\log_{10}\eta$ against λ for $d = -3{\cdot}5$ mm. (nasal) obtained from the experimental values of p shown in fig. 6, together with the theoretical curve from equation (4) fitted at $\lambda = 530$ mμ by putting $x = 0{\cdot}095$. The two curves show little agreement.

Similar calculations were tried using Hecht's response curves for the cone primaries. These also failed to yield the experimental curves of the colour and intensity effects. It would be possible to choose a set of primaries to give the agreement sought, but such a derivation is not warranted (*a*) because of the scanty data on the colour effect available at present, (*b*) because it appears from a preliminary exploration that the primaries so obtained would differ radically from those acceptable on other grounds.

Abandoning the view that x, y and z are constants, we might assume them all to be proportional to a single function of wave-length. This would enable the variation of $\log_{10}\eta$ with λ to be adjusted to agree with the experimental curve, but the difficulty of the hue change would remain. It appears most probable therefore that the relative reductions in response of the different types of cone for light incident obliquely must vary in passing through the spectrum, i.e. y/x and z/x must be functions of wave-length. A physical picture of how this might come about is obtained in the following way. Suppose each cone to be filled with a photochemical substance which attenuates the light in its passage through the cone. As a consequence the photochemical action will also decrease in amount in passing from the inner to the outer extremity of the cone. Since the pigment sheath gives rise to

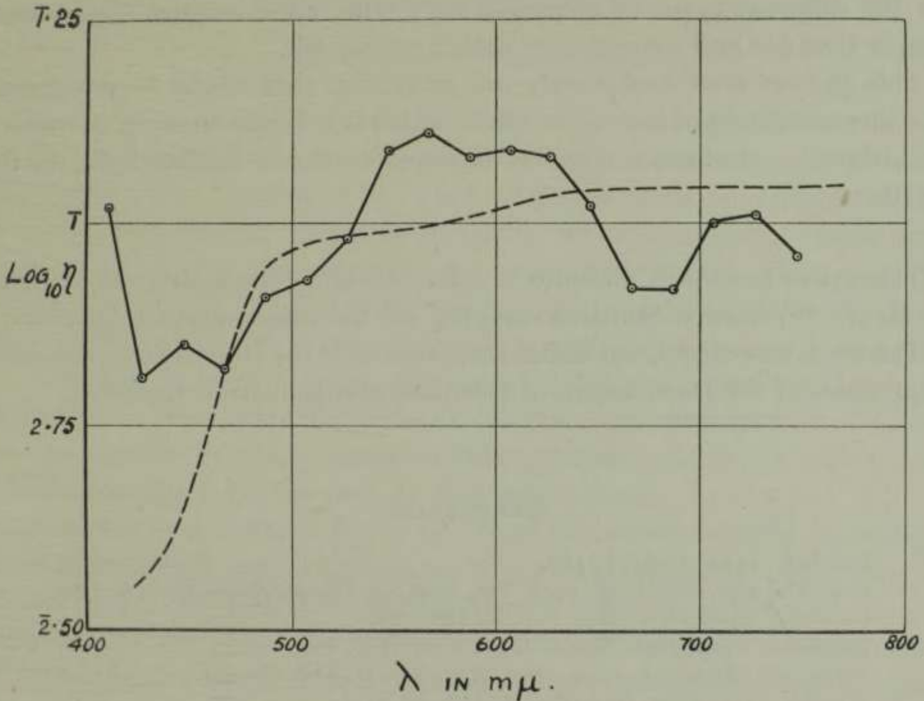

FIG. 14—- - - - - curve computed from Wright's fundamental response curves, x, y and z assumed constant; ⊙ values based on experiment.

the intensity effect by shielding the outer extremity of the cone from obliquely incident light it follows that the intensity effect will be less, the less the contribution of the outer extremity of the cone to the photochemical action. Thus at the wave-length at which the absorption of the photochemical substance is greatest the intensity effect will be smallest and there will be a variation of intensity effect with wave-length corresponding to the absorption curve of the photochemical substance. Admitting that the different types of cone must contain photochemical substances of different spectral absorption curves it is clear that the ratio of the intensity effects for the different types of cone will vary with wave-lengths. This means simply that y/x and z/x will vary with wave-length.

This picture is of course only one of several that might be developed. The measurements of the colour effect which it is hoped to carry out with a trichromatic colorimeter may be expected to throw further light on the matter.

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REFERENCES

Dziobek 1934 *Licht*, **4**, 150.
Forsythe and Worthing 1926 *Int. Com. on Illumination, Proc.* **6**, 100.
Goodeve 1936 *Proc. Roy. Soc.* A, **155**, 664.
Skogland 1929 *Bur. Stand. Misc. Publ.*, No. 86.
Stiles and Crawford 1933 *Proc. Roy. Soc.* B, **112**, 428–50.
Wright 1934 *Proc. Roy. Soc.* B, **115**, 49–87.
Wright and Nelson 1936 *Proc. Phys. Soc.* **48**, 401.