PART I

THE CHIEF FACTS OF NORMAL COLOUR VISION

SECTION I

THE BASES OF COLOUR VISION

CHAPTER I

THE PHYSICAL BASIS

WHAT is generally understood by the term "light" is a composite congeries of allied manifestations of energy, comprising such apparently various phenomena as heat, light in the narrower sense of the word, and chemical action. Various as these phenomena are, they are physically identical in character, all consisting of radiant energy in the form of waves of identical character, differing only in the length, rapidity, and amplitude of the vibrations. Broadly speaking, the longest waves cause the sensation of heat, the shortest give rise to chemical action, whilst those of intermediate length cause the sensation of light.

If we take ordinary sunlight as the basis of our investigations, it is possible to split it up by appropriate means into its component "rays," differing from each other in wave-length. Of these certain are visible, and constitute light in the narrower sense of the word, but instead of giving rise to the sensation of white light, they, to the majority of people, show certain pure colours, viz. red, orange, yellow, green, blue, and violet, in order, the red having the longest and the violet the shortest wave-length. The visible spectrum extends from about 723 $\mu\mu$ at the red end to 397 $\mu\mu$ at the violet end. v. Helmholtz under the most favourable conditions was able to see as far as about 835 $\mu\mu$. The limitation of the spectrum at the violet end is less precise, because the rays in this neighbourhood are changed into rays of greater wave-length by the media of the eye, particularly the lens and retina. This "fluorescence" causes them to produce a lavender-hued sensation, which does not denote true visibility of the short wave-length rays. Beyond the red end are waves of greater length (extending to 60,000 $\mu\mu$), which when absorbed cause a rise in temperature; beyond the violet end are waves of smaller wave-length, which are capable of causing chemical action. So striking is the physiological phenomenon of the visibility of the intermediate series that the heat rays are commonly spoken of as "infra-red," and the actinic or chemical rays as "ultra-violet." This custom is unfortunate, since it tends to obscure the importance of the physical uniformity of the series. For example, not every normal individual is able to see all the rays from 723 $\mu\mu$ to 397 $\mu\mu$; for most people the range is less extensive, roughly from 700 $\mu\mu$ to 400 $\mu\mu$. Again, though the ultra-violet rays are particularly potent in inducing chemical action, the visible rays are also, but in less degree, actinic, and the same is true, in still less degree, of the infra-red rays. Further, all rays when absorbed cause a rise in temperature. The most convenient and striking method of demonstrating actinicity is by the photographic film, so that we have come to regard a photograph of the spectrum as a complete analysis of the light under observation, too often forgetting that the photographic effect varies with the specific sensitiveness of the film to particular groups of waves. Thus it is only by specially sensitised films, invented by Sir William Abney, that it is possible to demonstrate infra-red rays photographically.

It is further essential that the methods employed for analysis of the light be suitable for their purpose. For example, an ordinary spectroscope, with glass prisms and lenses, suffices to demonstrate the visible spectrum, but is almost useless for showing the ultra-violet rays, since these are absorbed by the glass. In order to demonstrate the full extent of the spectrum it is necessary to use a train of lenses and prisms made of quartz or Iceland spar, which allows a maximum of rays to pass unimpeded.

Probably more error has crept into the subject of colour vision from inexact description of experimental conditions and the nature of the stimuli employed than from any other cause. Two green lights may appear identical in colour to the eye, yet their physical characters may differ widely. Again, mixing a yellow and a blue pigment will produce a green pigment, yet the more general statement that green results from mixing yellow and blue is not accurate.

The complete range of simple colours can be obtained in a pure state by only two methods, dispersion and diffraction. When white light is passed through a glass prism, as in Sir Isaac Newton's original experiment, a spectrum is obtained. Only under certain, now well-defined conditions is such a spectrum pure, *i.e.* the colours do not overlap. It is commonly said that the white light is "split up" into its component parts, which are coloured. The late Lord Rayleigh has given sound reasons for the view that white light is not thus analysed into component parts, but that the periodicities characteristic of the several rays are in reality imposed by the prism and are not antecedently present in the white light. Be this as it may, dispersion of white light by prisms enables us to obtain coloured light in a pure state. By passing white light through a diffraction grating a pure spectrum can also be obtained. This method has the advantage that the deviation of the component rays varies within narrow limits directly with the wave-length, *i.e.* equal differences of wave-length are separated by equal distances in the spectrum. It suffers, however, from the disadvantage that the spectrum is less bright and less extended than the prismatic spectrum, and from the still greater objection that the interference spectrum is never free from scattered light. In the prismatic spectrum the dispersion increases as the wave-length diminishes, so that the violet end is much more extended than the red end and its intensity is diminished. Moreover the amount of dispersion depends upon the character of the prism or prisms employed. Hence it is necessary for accurate observations that each prismatic spectrum shall be calibrated. The Fraunhofer lines, being absolutely constant in situation, afford a series of fixed points from which the calibration curve of the given spectrum can be constructed[1]. The table gives the principal lines in Ångström units (1 Å.U.—one ten millionth part of a millimetre = 0·1 $\mu\mu$).

	Å. U.
	A = 7606 in extreme red.
	B = 6869 in deep red.
Lithium	= 6707 in bright red.
Hydrogen	*C* = 6564 in bright red.
Sodium	D_1 = 5897 in orange.
Sodium	D_2 = 5891 in orange.
Thallium	= 5351 in yellow green.
	E = 5271 in green.
Magnesium	b_1 = 5184 in green.
Magnesium	b_2 = 5174 in green.
Hydrogen...	*F* = 4862 in blue green.
Strontium	= 4609 in blue.
	G = 4308 in violet.
Calcium	*H* = 3969 in extreme violet.
Calcium	*K* = 3934 in extreme violet.

The most convenient method of calibration, however, is by the mercury lines as given by the "mercury arc[2]."

In spite of the necessity for calibration the prismatic spectrum is more generally suited than the diffraction spectrum for physiological experiments on account of its greater brightness and relative freedom from scattered light.

Whatever spectrum be employed the source of light must be constant.

[1] Burch, *Practical Exercises in Physiological Optics*, p. 102, Oxford, 1912.
[2] Watson, *Practical Physics*, p. 309, 1906.

Lights which we commonly regard as giving "white light," such as sunlight, the arc light, incandescent light, and so on, vary much in character and consequently in the constitution of their spectra. Sunlight varies so much that it is generally unsuitable for the purposes in view, the variations being not only in intensity but also in composition, owing to the unequal absorption of different rays by the atmosphere, and this absorption again varies greatly according to the amount and nature of the matter suspended in the air. The arc light is the most satisfactory, and after this probably the Nernst lamp, though the latter has not yet been sufficiently investigated[1]. Less satisfactory are gas light, petroleum and so on, but as many of the experiments of earlier observers have been made with such sources they have to be considered if these researches are to receive due appreciation. Some sources of illumination, especially used for investigation of the ultra-violet rays, such as the Schott uviol mercury vapour lamps, are wholly unsuited, since they do not give continuous spectra. For experiments on colour vision many such details which cannot be discussed here must be attended to[2].

Suffice it to say that by taking proper precautions it is possible to obtain a spectrum which is practically constant during the time necessary to take a series of observations and which can be reproduced from time to time with a minimum of variation.

If such a spectrum is viewed through the eyepiece of an ordinary spectroscope a *direct* spectrum is seen. This method has usually been adopted, as for example by Aubert, von Helmholtz, Clerk-Maxwell and others. By a slight change in the optical arrangements the spectrum can be accurately focussed upon a screen. Such a *projected* spectrum can then be viewed by several observers at the same time, a very considerable advantage in testing colour vision. The use of a projected spectrum necessitates further care in detail, for the character of the spectrum will depend upon the optical properties of the screen[3]. A matt white surface must be used, and that obtained with magnesium oxide is probably best.

In order to obtain the most accurate information from the experiments the observations must be as far as possible *quantitative* and not merely qualitative. In many physiological experiments this counsel of perfection cannot be complied with and we are reduced to the information which can be obtained from merely qualitative observations. When, however, it

[1] Abney, *Researches in Colour Vision*, 1913, Chap. v; Golant, *Ztsch. f. Sinnesphysiol.* XLIII, 70, 1908.

[2] *See* Tigerstedt, *Handb. d. physiol. Methodik*, Bd. III, Abt. 2, *Sinnesphysiologie* II, Leipzig, 1909: Luckiesh, *Colour and its Applications*, New York, 1921.

[3] Abney, p. 46.

is possible to obtain quantitative results it is generally necessary to have a constant light for purposes of comparison. Now, photometry is admittedly one of the most faulty of physical measurements, chiefly because of variable conflicting physiological factors[1]. One of the most important and unique features of Sir William Abney's apparatus is that the intensity of the comparison light bears a constant physical relationship to that of the spectrum used, since it is obtained by the reflection of a portion of the original beam of light from the surface of the first prism. Hence any variation in the original beam will cause similar and simultaneous variations in both the spectrum and the comparison light[2]. Measurable changes in the intensity of the light are best obtained by the use of rotating sectors, sometimes called the episcotister (Aubert), or by the annulus, a gelatine wedge impregnated with ivory black[3]. A convenient variable sectored disc has been devised by Hyde[4]. Reduction of intensity by means of Nicol prisms as in v. Helmholtz' spectrophotometer, may not be free from error, since quite an appreciable amount of polarisation of the light is produced by the prisms used to form the spectrum. Much of the German work has been done by this method, and care has by no means always been taken to calculate the corrections necessary owing to this cause.

It has already been pointed out that photometric observations equate intensities of physiological responses. Such observations are merely comparative for the given sources of light, and cannot be directly compared with observations made with other sources. To obtain directly comparable observations it is necessary to know the intensities of the physical stimuli in terms of energy.

The radiation from an incandescent solid depends upon its physical and chemical constitution and its temperature. The total range of wave-lengths emitted may be termed the energy spectrum (Luckiesh) of the radiator. The distribution of energy among the different wave-lengths can be measured by appropriate instruments (the bolometer, radiometer, thermo-pile) and plotted as a curve with wave-lengths as abscissae and relative energies as ordinates. Such a curve is called the *radiation curve* (Fig. 1). A "black body" is a body which will absorb all radiation incident

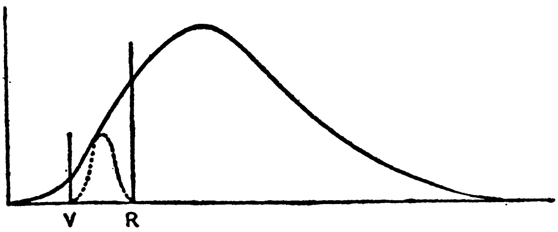

Fig. 1. Radiation curve of an incandescent solid. Abscissae, wave-lengths; ordinates, relative energies. (Luckiesh.)

[1] *See* Parsons, *Nature*, cx, 824, 1922
[2] Abney, Chap. iv.
[3] Abney, Chap. vi; *Phil. Trans.* A, cxc, 156, 1897.
[4] *Astrophys. Jl.* xxv, 239, 1912.

upon it and reflect none. When it radiates it emits in each wave-length more energy than any other body at the same temperature. If the temperature of such a body is gradually raised the radiation curve, at first limited to relatively long wave-lengths, changes, so that the maximum is displaced

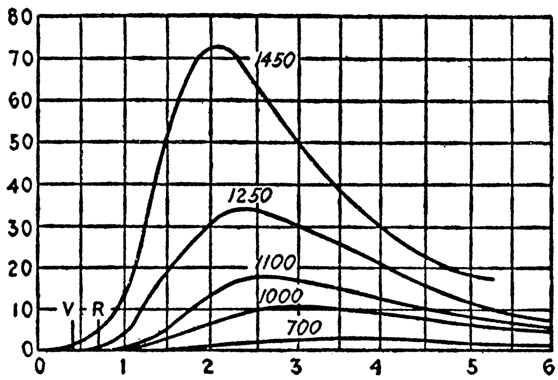

Fig. 2. The effects of rise of temperature on the radiation from a "black body." Abscissae, wave-lengths; ordinates, relative energies. (Luckiesh.)

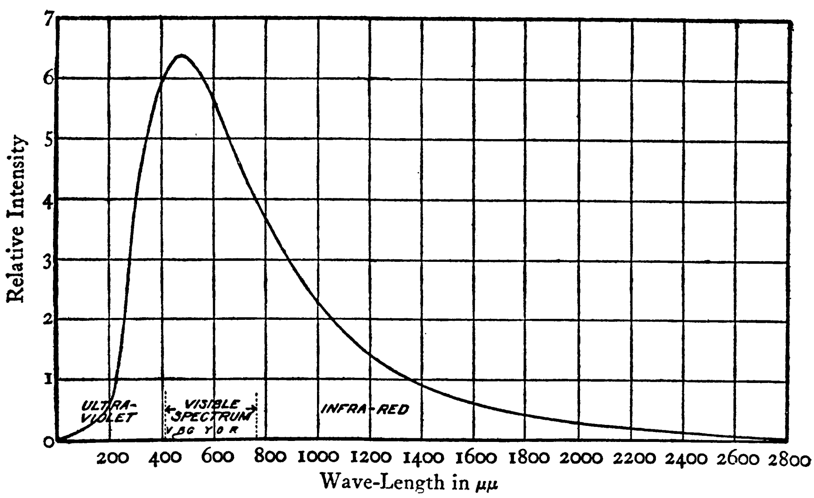

Fig. 3. Energy distribution curve of the radiation from a "black body" at 6200° absolute. (Troland.)

toward the shorter wave-lengths (Fig. 2). Fig. 2 shows that the visible spectrum (*V* to *R*) occupies a very small part of the total range of the energy spectrum. It further shows that as the temperature rises the long wave-lengths of the visible spectrum first appear, so that the body appears dull red. Next the body appears orange, yellow, and finally white. The radiation curve now shows that the distribution of energy in the visible

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spectrum increases from the violet towards the red. Such is the type of radiation curve obtained from artificial illuminants. In the case of sunlight the maximum of the curve is actually in the visible region: the relatively greatest proportion of total energy is in this region, and hence

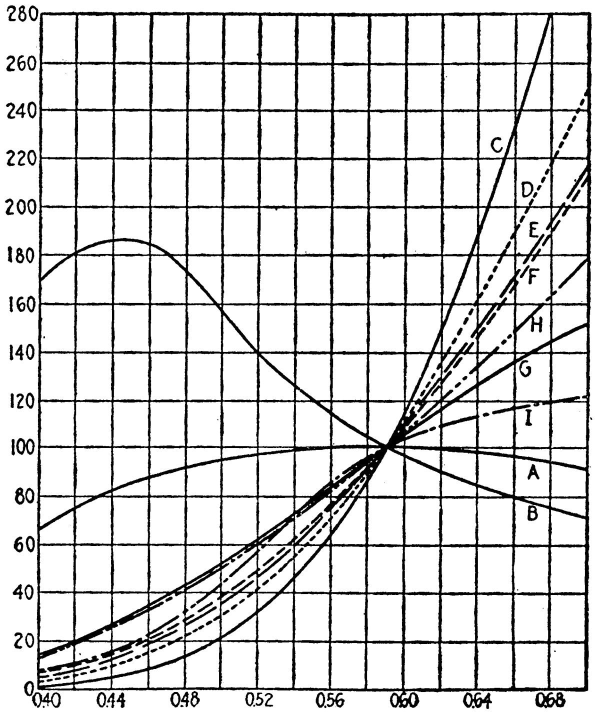


Fig. 4. Energy distribution in the visible spectra of various illuminants (Luckiesh). Abscissae, wave-lengths; ordinates, relative energies. A, "Black body" at 5000° absolute; B, Blue sky; C, Hefner lamp; D, Incandescent carbon lamp; E, Acetylene; F, Tungsten (vacuum) incandescent lamp; G, Tungsten (gas) incandescent lamp; H, Direct current arc (open); I, Welsbach gas mantle.

luminous efficiency is at a maximum (Fig. 3)[1]. Fig. 4 shows the distribution of energy in the visible spectra of various illuminants.

If the radiation curve for any particular luminous spectrum is experimentally determined it becomes possible to express stimulus values in terms of physical energy, and the results obtained are independent of the particular source of light.

Whilst it is true that stimulus values are stated most accurately in terms of physical energy, *i.e.* the quantity of heat generated, physiological problems deal with physiological responses. Here the recording instru-

[1] Troland, *Jl. of Exp. Psych.* II, 1, 1917.

ment is a living organ, subject to continual variations. The responses can only be expressed in relative terms, or at most in mathematical terms founded upon somewhat doubtful bases (*v.* p. 23). Moreover, the energy of a physiological response is not derived from the stimulus, but is merely released by it. Further, radiometers measure indiscriminately the energy of all types of radiation, whether visible or not, so that unless great care is taken to eliminate infra-red and ultra-violet radiation the results will be wholly misleading[1]. The fact remains that the subject of investigation is physiological and comparative values in terms of physiological response, usually brightness or luminosity, are of the greatest value. The ideal condition is that in which both photometric and radiometric values are known, since the former are equal to the latter multiplied by the appropriate luminosity factor[2].

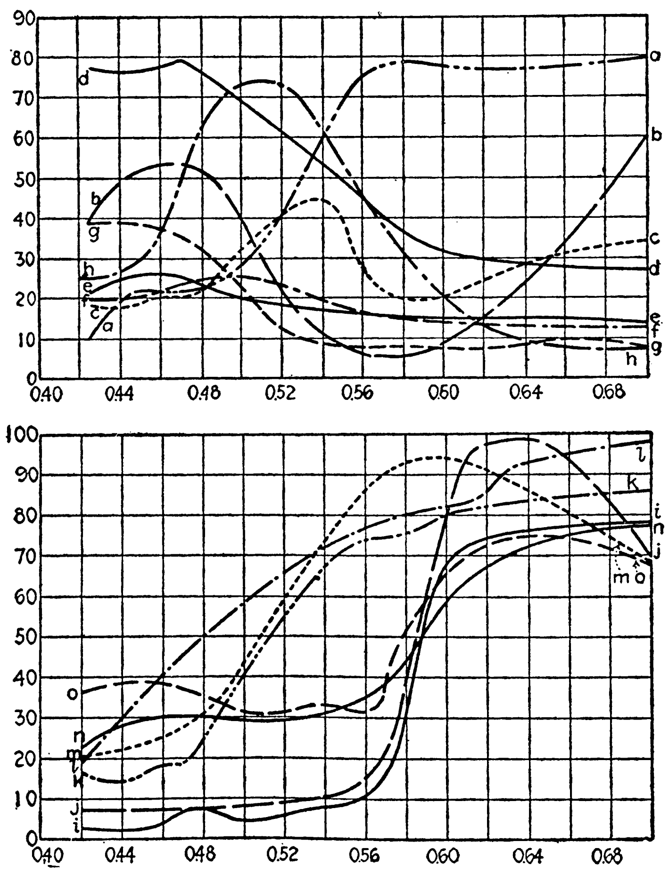
Pure spectral colours rarely occur in nature, and much of the literature on colour vision is devoted to observations with pigments, coloured glasses and so on. It is necessary, therefore, to say a few words about these complex colours, chiefly with the object of putting the reader upon his guard. When white light passes through a red glass or transparent red fluid certain rays are absorbed. The red rays are transmitted in greatest quantity, so that the dominant colour of the light reaching the eye is red; but it is not pure red. Most blue substances, such as copper salts, allow the blue rays to pass, but also some of the green and violet, though few of the red and yellow. Yellow substances allow much red and green to pass as well as the yellow, but little blue and violet. The true composition of the transmitted light can only be determined with the spectroscope.

The case of pigments is similar. Each speck of powder is a small transparent body which absorbs certain rays of light. When light falls upon such a powder a small portion is reflected from the upper surface; this is white. The remainder passes deeper and is reflected from deeper layers. The deeper it passes the greater is the absorption and the more intense the colour. Hence a coarse powder appears more intensely coloured than one which is finely divided. Reflection varies with the number of surfaces, not with the thickness of the particles. The larger the latter the deeper the light must penetrate for the same number of surfaces to be met as

[1] Troland, *loc. cit.*

[2] *See* Ives, *Trans. Ill. Eng. Soc. Amer.* x, 259, 1915; Crittenden and Richtmyer, *ibid.* xi, 331, 1916; *also* Troland, *Jl. of Exp. Psych.* ii, 1, 1917; *Trans. Ill. Eng. Soc.* (*U.S.A.*), xiii, 26, 1918; Ferree and Rand, *Jl. of Phil. and Psych.* xiv, 457, 1917; Laurens and Hooker, *Amer. Jl. of Physiol.* xliv, 500, 1917 (Methods); Coblentz and Emerson, *Bureau of Standards*, 1917; *Amer. Jl. of Physiol. Optics*, i, 41, 174, 1920; Blondel, *Compt. rend. de l'Acad. des Sc.* clxix, 830, 1919; Nutting, *Amer. Jl. of Physiol. Optics*, i, 142, 1920; Weve, *Arch. néerl. de Physiol.* iv, 243, 1920.

when the particles are smaller. The absorption is therefore greater in a coarse than in a fine powder. The reflection at the surfaces is diminished when the intervals between the particles are filled with a fluid of refractive index nearer their own than that of air. Hence powders are generally whiter when dry than when mixed with water or oil.



Figs. 5 and 6. Spectral analyses of pigments (Luckiesh). Abscissae, wave-lengths; ordinates, relative energies. *a*, yellow ochre; *b*, cobalt blue; *c*, chromous oxide; *d*, Antwerp blue; *e*, indigo; *f*, terre verte; *g*, French ultramarine; *h*, emerald green; *i*, mercuric iodide, *j*, vermilion; *k*, gamboge; *l*, Indian yellow; *m*, cadmium yellow; *n*, Indian red; *o*, carmine.

The amount of absorption of light by a transparent body can be measured and expressed in the form of a coefficient. If a spectrum is viewed through an orange glass very little red, orange and yellow, but much green and all the blue are absorbed, as shown by dark bands in the regions of absorption. In this case the coefficient of absorption increases as the blue is approached.

By knowing the coefficients of absorption of different media the effects of combining them in various ways can be calculated. By empirical experiments colour screens or filters can be made which transmit certain portions only of the spectrum, and in some cases approximately monochromatic light can be obtained in this manner. These filters are much used for photographic purposes. The characters of the absorption by Jena glass filters and by various fluid media are described in Tigerstedt's *Handbuch der physiologischen Methodik*[1], which also gives an excellent *résumé* of the methods which have been employed for the investigation of colour vision.

No pigments accurately represent spectral colours, for the reflected light is always more or less impure. The nearest approach is given by the following list:

Red—vermilion (not scarlet vermilion) mixed with a small quantity of permanent violet.
Orange—orange cadmium.
Yellow—chrome yellow.
Green—Prussian blue mixed with aurelin.
Blue-green—viridian mixed with a small amount of cobalt blue.
Blue—ultramarine.
Violet—permanent violet mixed with a small amount of blue. (Abney.)

The spectral analyses of several pigments are shown in Figs. 5 and 6.

CHAPTER II

THE ANATOMICAL BASIS

I do not propose to discuss fully the anatomy and physiology of the eye and visual paths, but it is necessary to draw attention to certain features of special importance in colour vision. This course will doubtless emphasise the great complexity of the subject, which is too often wilfully ignored.

The eye resembles a photographic camera, in which the cornea and crystalline lens represent the lens-system, the iris the diaphragm, and the retina the sensitive plate. The size of the pupillary aperture is not under voluntary control, but varies with the intensity of light entering the eye and other causes. This fact has to be taken into consideration in many experiments. (The reader is recommended to read the earlier chapters in the author's *Manual of Diseases of the Eye*, 4th edition, J. and A. Churchill, London, 1923.) The optical system of the normal eye at rest is focussed for distant objects, *i.e.* parallel rays are brought to a focus upon the retina. Focussing for near objects is brought about by automatically altering the

[1] Bd. III, Abt. 2, *Sinnesphysiologie* II, pp. 47 and 52; *also* Reeves, *Psych. Bulletin*, XIV, 249, 1917; Luckiesh, *loc. cit.*; *Jl. of Franklin Inst.* CLXXXIV, 73, 227, 1917.