The Physiology of Vision

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CHAPTER I

INTRODUCTION

THE nature and properties of light and its interactions with material bodies obviously play a fundamental role in the functioning of our visual organs. A clear understanding of the physical constitution of light and of the phenomena resulting from its incidence on the visual organs is therefore essential for any valid interpretation of our visual sensations. It is precisely in these respects that the excursions into the field of visual physiology made in the nineteenth century were at fault. As is well known, light was regarded in the nineteenth century as a form of energy which propagates itself as wave-motion, and is distributed through space in a continuous manner. Its interactions with material bodies were also interpreted on the same basis. Present-day ideas regarding these matters are, of course, altogether different. There is therefore no reason to believe that the ideas regarding the nature of vision and of visual processes inherited from the nineteenth century would be sustainable at the present time, either on theoretical grounds or even as purely empirical descriptions or interpretations of the observed phenomena.

Two beliefs or hypotheses handed down from the nineteenth century figure prominently in the literature of the physiology of vision. The first is the trichromatic hypothesis usually associated with names of Thomas Young and Hermann von Helmholtz. The other is the duplicity theory of vision which postulates that there are two distinct kinds of vision, known as photopic vision and as scotopic vision which function respectively at the higher and at the lower levels of luminosity, photopic vision enabling us to perceive both light and colour, and scotopic vision only light but no colour. Of more recent origin is the so-called photochemical theory of vision which has received a measure of acceptance from several authors but has not escaped criticism by others.

The purpose of the present volume is to set out in a systematic manner the methods and results of the experimental investigations on diverse aspects of vision carried out by the author during recent years. The aim of the studies was to obtain an insight into the subject by independent study without being influenced by ideas and beliefs inherited from the past. It has emerged from the author's studies that none of the notions referred to in the preceding paragraph is reconcilable with the actual facts of the case. The studies have led to a new picture of the nature of vision and new interpretations of our visual experiences. These have been described in detail and discussed in the chapters which follow.

CHAPTER II

WAVES AND CORPUSCLES

THE phenomena which light presents to us for study fall into two groups. The first class of phenomena comprises those which can be described or explained on the assumption that light is a species of wave-motion in space which possesses a great velocity and other characteristics related to its propagation. In the second class of phenomena, we are concerned with light as a form of energy which is emitted or absorbed or scattered by material substances and which changes its form as the result of its incidence on such substances. In all cases of this kind, it becomes necessary to recognise the corpuscular nature of light, in other words to assume that it consists of discrete units of energy of which the magnitude is related to the frequency of wave-motion as recognised in the first class of phenomena by the simple relation $\epsilon = h\nu$. Here ϵ is the energy of the corpuscle, ν is the frequency and h is Planck's constant of action. These two descriptions of the nature of light are mutually complementary. In other words, they refer to two distinct and non-overlapping sets of cases. But both descriptions have to be accepted to enable us to obtain a complete picture of the nature and behaviour of light.

Wave-optics includes within itself the entire body of theory and practice known as geometrical optics. This concerns itself with the functioning of optical instruments, treated on the basic assumptions of the rectilinear propagation of light and that the media traversed by light possess known refractive indices and dispersive powers. But the wave-like characters of light are most clearly manifested in the class of phenomena designated as interference and diffraction. In these phenomena, the periodic nature of wave-motion and its relation to the wavelength come directly within the reach of observation. The length λ of the waves as thus determined is connected with their frequency ν and their velocity c in the medium by the simple relation $\lambda = c/\nu$. The cases in which λ has a definite value and hence the frequency ν and the energy $h\nu$ of the light corpuscle are precisely known are of special importance. The light which can thus be specified appears as a single sharp line in the spectrum of the radiation as exhibited by a prismatic spectrograph or by a diffraction grating. It is then referred to as monochromatic light and it is composed of corpuscles all having the same energy. If, on the other hand, the spectrum as exhibited by such instruments is a continuous band of light, the wavelength λ and hence the frequency ν and the corpuscular energy $h\nu$ show corresponding ranges of variation.

From what has been said above, it follows that the formation of optical images by the dioptric media of our eyes on their retinae falls within the scope of wave-optics. But, on the other hand, the actual perception of such light following its incidence on the retinae lies entirely outside its scope. For, the perception of light involves the absorption of the incident light as well as the transformation of its energy to a form that can be transmitted through the optic nerves to the centres of perception in the brain.

The role played by the corpuscular nature of light in its visual perception will occupy us in later chapters. It will be useful, however, to devote the rest of the present chapter to the consideration of the wave-optical properties of light. For, as we shall see later, the phenomena encountered in this field are helpful to us in the study and interpretation of our visual perceptions.

The simplest technique for exhibiting the interference of light is to lay one clean glass plate on another such plate and to view the air-film enclosed between the two plates by reflected light, making use of an extended source of light. The two streams of light reflected respectively at the two surfaces bounding the air-film reach the eyes practically in the same direction and with intensities which are nearly identical. But the optical paths traversed by them differ by twice the thickness of the air-film, if we assume that it is viewed in the direction of the normal to the surfaces. Interference then results either in the extinction of the reflected light or in a four-fold increase of its brightness according as the two streams of light are in opposite phases, or in agreement of phase. The varying thickness of the air-film then manifests itself as an alternation of dark and bright bands over its area, provided that the light employed has a definite wavelength, as is the case if, for example, the light of a sodium-vapour lamp is used for the observations. The two nearly coincident yellow lines in the spectrum of the lamp then give us the needed "monochromatic" light.

Photographs of two interference patterns of this kind recorded with the yellow light of a sodium lamp are reproduced as Fig. 1 (A) and 1 (B) in Plate I. In Fig. 1 (A), the interferences appear as concentric circular rings around a central dark region where the two plates were in actual contact, the thickness of the air-film increasing rapidly as we proceed outwards from this centre. In Fig. 1 (B), the fringes appear as a series of approximately parallel bands, commencing from the region where the plates (which were both optical flats) had been forced into contact and the air-film between the plates is thus a wedge of small angle. As already stated, the fringes were in each case observed and photographed with monochromatic light, and the interferences are therefore seen at their best. In a later chapter, we shall describe and discuss the phenomena observed in such cases, when instead of the light of a sodium-vapour lamp, white light is employed for viewing the interferences.

A tungsten filament heated to a high temperature by the passage of an electric current emits a brilliant white light. Examined through a prismatic spectroscope, the emitted light appears as a continuous spectrum exhibiting the usual sequence of colours. The wavelength of the light in such a spectrum increases progressively from one end to the other, from say 4000 Angstrom units at the violet end to say

7000 Angstrom units at the red end. The principle of interference may be utilized to exhibit this progression of wavelength to the observer's eye, the continuous spectrum being transformed into a succession of sharply-defined bands of progressively increasing wavelength. The technique needed to achieve this result is fairly simple. Two circular plates of optical glass are made use of. Their faces are ground flat and polished to a high degree of perfection. One face of each plate is half-silvered, and the two plates are held within a tubular support in such manner that the silvered faces are adjacent and parallel, their separation being a millimetre or less. The gap between them should be capable of being varied from zero upto the desired value, while their parallelism remains perfect. The use of suitable guides and a fine screw permits of this being achieved. The plates thus mounted are held normally before the slit of a spectroscope. White light from a small but brilliant source, *e.g.*, a glowing tungsten-filament, passes normally through the plates and enters the slit of the spectroscope. The spectrum as seen through the eye-piece then exhibits a succession of bright lines on a dark field. The spacing of these lines can be varied by moving the two plates closer together or further apart as desired.

In a later chapter, we shall see that the technique here described can be used to study the progression of colour in the spectrum of white light and to estimate by simple inspection, the capacity of human vision to detect colour differences. An interesting feature of the technique is that the bands in the spectrum produced by it are equally spaced in respect of wave-number differences, in other words, the successive lines represent equal increments of the corpuscular energy of the light. This follows from the fact that the successive bands correspond to successive integral values of the number $2d/\lambda$, where d is the separation of the plates and λ is the wavelength of the light. Figure 2 (A), (B), (C) in Plate II reproduce the banded spectrum of the light of a tungsten lamp photographed in the manner described with

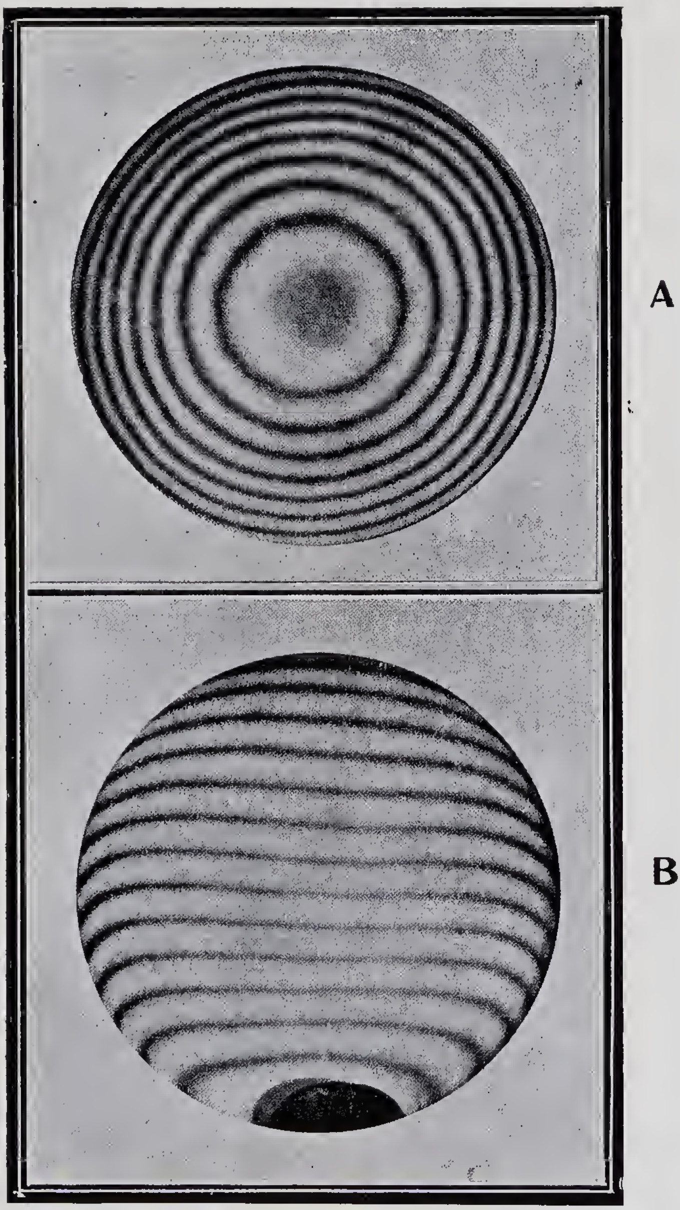


FIG. 1. Interference patterns in Sodium Light.

three different separations of the plates in the interference apparatus. The number of bands into which the spectrum is channelled is 120, 60 and 30 while the wave-number separation between each band and the next is 72, 144 and 288 respectively in the three figures.

CHAPTER III

THE STRUCTURE AND FUNCTIONING OF THE RETINA

A ROLE of outstanding importance in the functioning of the organs of vision is played by the retina, which is the sensitive screen at the back of the eye on which the picture of the world outside formed by its dioptric media falls. Indeed, it may be said that what the retina is capable of accomplishing determines what we can see and recognise in the objects under view. We shall concern ourselves in the present chapter with the methods of observation which enable us to view the living retina and thereby to gain some understanding of its structure and functioning.

The instrument referred to as the ophthalmoscope enables the interior of the eye to be illumined and to be viewed by another observer. What is known as the fundus of the eye then comes into view. The position of the details seen on it naturally depends on the direction in which the eye which is observed is orientated with respect to the illuminating beam. Pictures in colour of the appearance of the fundus are to be found reproduced in numerous treatises. Particularly striking are those which appear in Polyak's monumental treatise entitled *The Vertebrate Visual System* published by the Chicago University Press in the year 1957. We may here refer to Figs. 148, 165 and 363 which appear facing respectively pages 258, 280 and 606 of that work. These three pictures between them serve to give us a fairly complete idea of the structure of the retina, so far as the ophthalmoscope can reveal it.

It is a remarkable fact that the central part of the retina, in other words, the area which is made use of when we turn our eyes towards the objects which particularly interest us appears comparatively featureless as viewed through the ophthalmoscope. It is possible, however, to recognise a

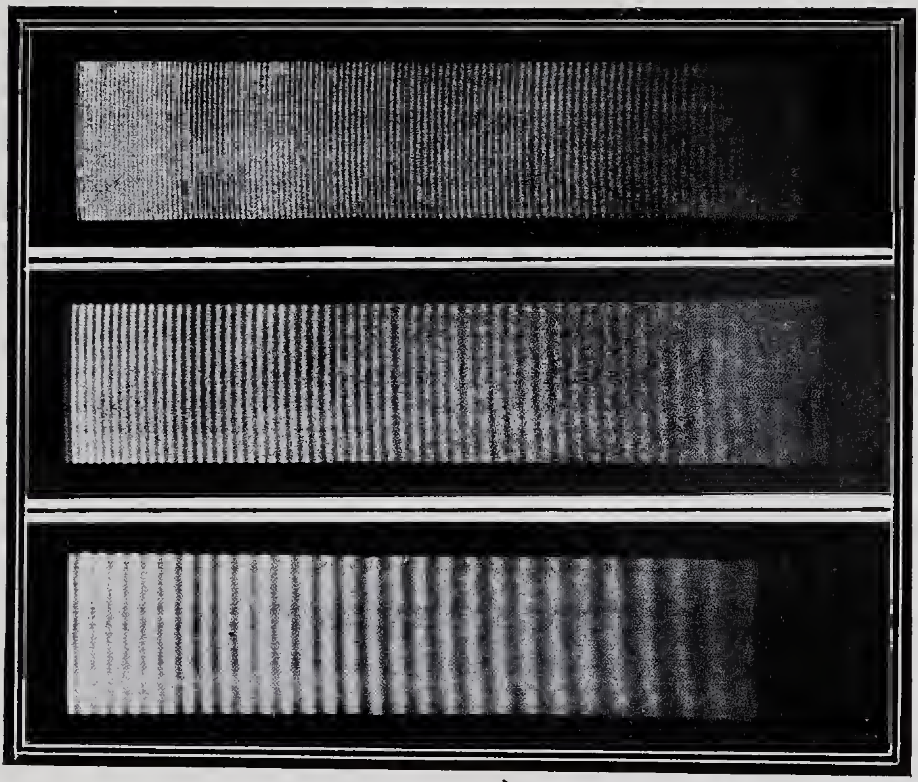


FIG. 2. Channelled spectra of white light.

circular patch at its centre which appears different in colour or in brightness from its surroundings. At a considerable distance from this central region, and indeed almost on the periphery of the fundus, if the former appears at the middle of the picture, is seen the most conspicuous feature of the retina, *viz.*, the region known as the optic papilla. This appears as a round disc. Surrounding it and emerging at various points inside the area, blood vessels are seen, both arteries and veins, traversing the retina. A feature particularly worthy of remark is that these larger blood-vessels curve round so as to avoid the central region of the retina. Blood-vessels of smaller diameters which take off from the larger vessels however traverse the retina and proceed towards the central area. But even these do not actually extend to or reach the central area.

The optic papilla is also the region towards which the nerve-fibres converge from various parts of the retina. Here they are bunched together and finally emerge as the optic nerve from the eye-ball towards the brain. This feature is well shown in Fig. 148 of Polyak's book and even better shown in Fig. 165 which is a picture of the fundus of a Nubian youth aged 17. Translucent bundles of optic nerve-fibres can be traced for a great distance beyond the disc of the optic papilla. Another noteworthy feature is that the nerve-fibres from other parts of the retina do not proceed across its central region but arch round it, both above and below, to avoid traversing it.

The avoidance of the central area of the retina by the larger blood-vessels, as also by the nerve-fibres streaming towards the optic papilla from other parts of the retina, is a feature which evidently favours the clear perception of the images of external objects falling on the central region. Apart from giving this indication, the ophthalmoscopic view does not really tell us very much about how the retina actually functions. Much less does it reveal the great differences in the activity of the retina over its different areas. These aspects of the structure and functioning of the retina are, however, exhibited in a most striking fashion when it is studied making use of a technique devised and perfected by the author which will presently be described.

The technique employed is the use of a colour filter which freely transmits light over the entire range of the visible spectrum except over a limited and well-defined region which it completely absorbs. It is possible by the use of suitable dye-stuffs in appropriate concentrations to prepare colour filters of gelatine films on glass exhibiting the spectroscopic behaviour described. Holding such a colour filter before his eye, the observer views a brilliantly illuminated screen for a brief interval of time and then suddenly removes the filter while continuing to view the screen with his attention fixed at a particular point on it. He then observes on the screen a picture in colours which is the chromatic response of the retina to the light of the colour previously absorbed by the filter and which impinges on it when the filter is removed. Actually, as will become clearer presently, what the observer sees is a highly enlarged view of his own retina projected on the screen and displaying the response of the retina in its different areas produced by the incidence of the light of the selected wavelengths. By using a whole series of colour filters whose characteristic absorptions range from one end of the visible spectrum to the other, we are enabled to explore the behaviour of the retina over an extensive region under excitation by light of different wavelengths which in the aggregate cover the entire visible spectrum.

Why the phenomenon described above manifests itself is not difficult to understand. A colour filter completely absorbing a selected part of the spectrum when placed before the eye of the observer protects the retina from the incidence of light from that part of the spectrum, and if such protection continues for a sufficient period of time, it has the result of sensitising the retina for the reception of light of those wavelengths when the filter is removed. *Per contra*, light of wavelengths not absorbed by the filter being incident on the retina both when the filter is in position and after its removal, the visual sensation which it excites becomes enfeebled by the continued exposure. Accordingly, when the filter is removed, the visual response of the retina to light of the wavelengths for which its sensitivity has been enhanced is far stronger than the continuing response to the other wavelengths and manifests itself vividly to perception. The nature of the picture seen is determined by the part of the spectrum which is absorbed by the colour filter and differs enormously for the different filters employed in the study. The usefulness of the technique for the study of the functioning of the retina over its different areas is thereby greatly enhanced. Here, we should mention the essentially fugitive nature of the phenomenon. But this is no obstacle to the study of the effects. For, the image of the retina seen by the observer on removing the colour filter and which fades away is restored and can be examined again and again merely by putting back the filter in front of the eye for a little while and then removing it.

For an observer to study the results of using the colour filters in the manner explained above, a screen of the kind used for projection work containing a great many small glass spheres embedded in plastic is found to be particularly suitable. Placed facing the windows in a well-lighted room, such a screen is quite brilliant and this indeed is necessary for any impressive phenomena to be observed. With a screen 175 cm. × 120 cm. in area, 350 cm. is a convenient distance from the screen for the observer to station himself. The area of the screen under observation is then of sufficient width to include an enlarged picture of an extensive region of the retina. That what the observer notices when the filter is removed is a picture of his own retina becomes evident when it is remarked that the foveal disc is the central feature seen in every case. This is located at and around the point on the screen at which the observer's attention is fixed at the instant of withdrawing the filter from before his eye.

We shall in a later chapter return to the subject and discuss the significance of the results obtained by the technique using many different colour filters. Here we shall content ourselves with reproducing sketches in colour of the effects observed using colour filters with two of the numerous dyes employed in the study. The effects observed with a colour filter of crystal violet are exhibited in Fig. 3, and those observed with lissamine-green in Fig. 4. The foveal disc and the foveola at its centre are the most conspicuous features in both cases, the fovea appearing of a greenish-yellow hue in the phenomenon as seen with the crystal violet filter, and lemon-yellow as seen with the lissamine-green filter. The colours seen in the outer regions are also different in the two cases (Plate III).

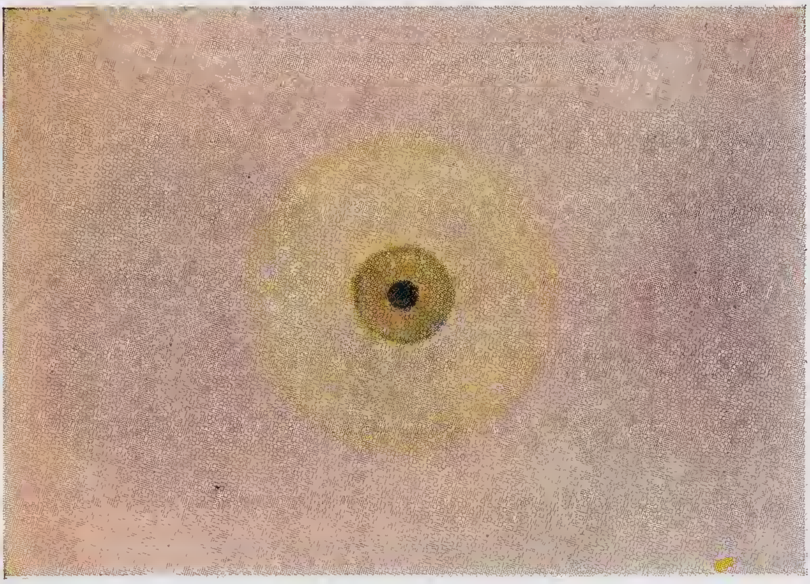


Fig. 3

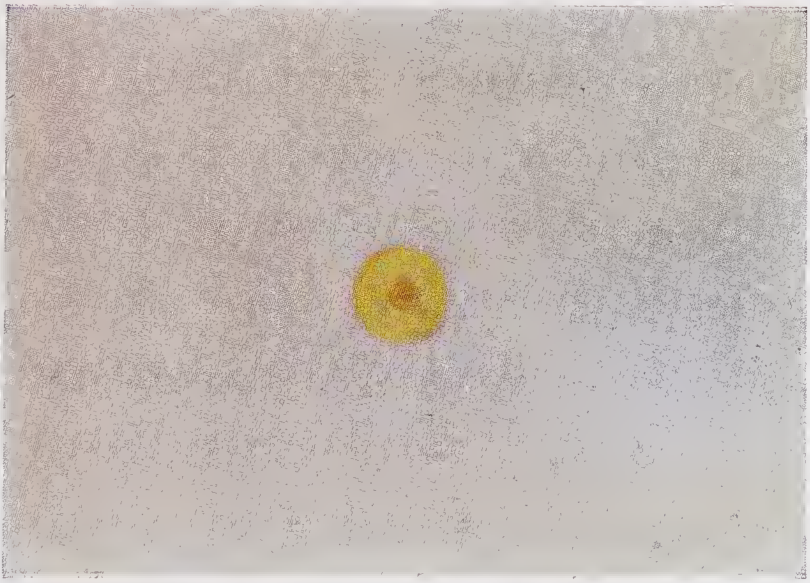


Fig. 4

Views of the Retina

CHAPTER IV

THE BASIC VISUAL SENSATIONS

FROM the standpoint of wave-optics, a beam of light has three specifiable characters. The first is the wavelength, the second is its intensity, in other words, the energy carried across unit area per unit of time, and finally, the state of polarisation of the light. Hence, if we accept the wave-optical description of light as determining the visual sensations excited by it, the two physiological characters of colour and brightness would be completely independent; the colour is associated with the wavelength, and the brightness with the intensity. But as has already been remarked in earlier chapters, wave-optics is no guide to the physiological perceptions of light. Considering the matter from the corpuscular point of view, we are concerned with two quantities: the first is the energy of the individual corpuscle, and the second is the number of corpuscles which contribute to the sensory impression produced. It then follows that we are no longer justified in regarding colour and brightness as completely independent sensations. Both have, of necessity, to be regarded as the cumulative effect of a great number of individual corpuscles. As the number which is effective increases, the sensation also may be expected to be intensified. In other words, as the total energy of the light-beam which is perceived increases, the sensations of colour and of brightness would both be progressively enhanced. *Vice versa*, as the energy of the light-beam progressively diminishes to zero, brightness and colour would both fade away.

The argument set forth above indicates the existence of a relationship between colour and luminosity as a direct and observable consequence of the corpuscular nature of light. This relationship may be demonstrated in an impressive and convincing fashion by the aid of a simple technique devised by the author. A portable screen of moderate size, 50 cm.

$\times$ 25 cm. mounted on a stand is used for the observations. The material of the screen is a sheet of milk-white plastic with a smooth polished surface. It is illuminated by an extended source of light and is viewed by the observer who is close to the source, while the screen itself is at some distance and can be moved as far away as desired from him and the source. The screen is visible to the observer by reason of the light diffused by it. The image of the light source reflected at the surface of the screen is also seen at the same time. As the screen is moved away, its brightness as seen by the diffused light falls off rapidly, but the reflected image, though apparently diminished in size, continues to be seen with undiminished brightness. With these arrangements, the difference in the perceived colours of the reflected and of the diffused light becomes obvious. It is readily noticeable even when the screen is close to the observer, and becomes more and more conspicuous as the screen is moved away from him, and the difference in brightness is therefore accentuated. When the screen is sufficiently far away from the source of light, its colour as seen by the diffused light is barely noticeable, while the reflected image exhibits the full colour of the original source.

The observations described above should be made in a completely darkened room of adequate size and the source of light should be covered up on all sides except that which faces the screen, so that no stray light can fall on the screen and vitiate the results. A sodium-vapour lamp may be used to study the phenomena with the monochromatic yellow light furnished by it. Likewise, a mercury vapour lamp may be used for observations with the green and with the violet radiations respectively; a plate of deep-blue glass placed before the lamp effectively isolates the λ 4358 violet rays, while a gelatine filter dyed with lissamine-green transmits only the green λ 5461 light.

A different technique which is very convenient in practice is the following. Diffuse light from the sky is admitted into a darkened room through a circular window covered with pin-headed glass at some height above the floor of the room. The light which emerges falls on a milk-white plastic screen placed facing the window and at a convenient distance from it. The observer faces the screen, placing himself at some distance from it; the illumination of the screen can be controlled over a wide range of values by the use of an iris-diaphragm covering the window which admits the light into the room. The opening of the iris can be varied from 20 cm. down to 2 millimetres, thereby allowing the illumination of the screen to be reduced by any desired factor upto 10,000. When the iris is fully open, the plastic screen is brightly illuminated. Even so, it is much less bright than the aperture which admits the light into the room when viewed directly. The observer holds a colour filter before his eye and views the screen and the window alternately. Even when the iris-diaphragm is fully open, the screen is found to exhibit a colour much less saturated than that of the light which finds entry through the window. The observer then proceeds to close down the iris step by step, and views the screen and window alternately. The difference in their hues then becomes more and more conspicuous. Whereas the colour of the light entering at the window remains the same throughout, the colour of the screen becomes paler and paler until finally, it can only be recognised with difficulty, if at all.

The advantage of the second technique is that the colour-luminosity relationship can be followed over a greater range of brightness. It also allows the use of colour filters without any restriction. In other words, the phenomena under consideration are observed even when the light is not monochromatic in the strict sense of the term. It is worthy of remark that the effect is noticed in all cases, *viz.*, whether the colour of the light which passes the filter is red, orange, yellow, green, blue or violet.

The colour-luminosity relationship which emerges from the studies described above enables us readily to understand various well-known facts in the field of observational astronomy. The stars seen in the sky at night appear to the naked eye as mere specks of light, no colour being recognisable except in the case of the very brightest stars, *e.g.*, Sirius which exhibits a distinctly bluish tinge, and Betelgeuse and Antares which exhibit reddish hues. Sirius which is the brightest of them all belongs to the spectral class AI, while its apparent visual and photographic magnitudes do not differ, being both — 1·43. Betelgeuse and Antares belong to the spectral classes MII and MI respectively, and in both cases, the apparent visual and photographic magnitudes differ very considerably, those of Betelgeuse being 0·7 and 2·6, and those of Antares 0·98 and 2·78. If the surface-temperature of a star and the spectral class to which it belongs were the sole determining factors, we should expect a great many stars, especially those with very high or very low surface temperatures, to exhibit a recognisable colour. That they do not is a clear indication that for the visibility of colour, it is necessary that the star should be exceptionally bright.

The same considerations indicate that it should be much easier to recognise the colours of stars and especially the colour-differences between the stars if they are observed through telescopes of adequate power and hence appear much brighter. Indeed, it is well known that the colour difference between the components of a double star may be readily recognised if a telescope of adequate power is employed to observe them.

Finally, we come to the case of the so-called emission nebulae which emit light as the result of the optical excitation of the atoms of the gases of which they consist by the ultra-violet radiation from very hot stars in their neighbourhood. The gaseous nebulae which emit such light are in many cases spread over great volumes and have a low density. Even so, we should expect them to exhibit brilliant colours. Actually, however, when observed through telescopes of modest light-gathering power, they appear as patches of luminosity with scarcely any visible colour. We may here mention as examples, the Great Nebula in Orion, and the Ring Nebula in Lyra, both of which are objects visible in small telescopes.

Plate IV

The Ring Nebula in Lyra
as seen in large telescopes

But when the light-gathering power of large telescopes is made use of, those objects do present striking colours which can be seen by the observer. Many years ago, the author had the privilege of observing these two nebulae with the great reflecting telescopes at Mount Wilson and was immensely impressed by the colourful appearance they presented (Plate IV).

CHAPTER V

FLUCTUATIONS OF LUMINOSITY IN VISUAL FIELDS

THE phenomenon which forms the subject of the present chapter was observed and described by the author in a publication in which its origin was also discussed (*Current Science*, Vol. 33, 1964, page 65). As was there stated, the phenomenon is a striking demonstration of the part played by the corpuscular nature of light in its visual perception. It also plays a basic role in a subject of great importance, *viz.*, the acuity of vision and its variations. The latter topic will be dealt with in a subsequent chapter, while the phenomenon itself will be considered here.

The experimental set-up needed for the study is quite simple. A white screen which has a uniform texture and a smooth surface is the principal requisite. It should be capable of diffusing the light which falls upon it uniformly over a wide range of angles. These requirements are admirably satisfied by a sheet of milk-white plastic which is a few millimetres thick and has a polished surface. A screen of this material 150 cm. × 100 cm. in area which is held vertically on a wooden stand and can be readily moved about is very suitable for the observations. The screen is illuminated by a source of light placed at some distance from it and is viewed by an observer who can take up any chosen position in the room, moving nearer to the screen or further away from it as desired. The source of light should be completely covered up except on the side facing the screen, an aperture being provided on that side for the emergence of light. These arrangements ensure that no stray light falls on the screen. It is desirable also to provide for the illumination of the screen being varied over a wide range of values. This is most conveniently secured by the use of an iris-diaphragm to cover the aperture through which the light emerges. A sheet of ground-glass interposed between the light-source and the iris-diaphragm is a useful adjunct as it helps to diffuse the light uniformly over the aperture of the iris. A maximum opening of 10 centimetres and a minimum of 2 millimetres for the iris enables the illumination to be varied by a large factor as may be needed.

The observations should be made in a completely darkened room, and it is desirable that they are commenced only after some time has been allowed for the disappearance of the after-effects of any previous exposure of the eyes of the observer to bright light. A sodium-vapour lamp or a mercury-vapour lamp with appropriate colour filters may be used for observations with monochromatic light, while an ordinary tungsten filament lamp suffices for observations with white light. Colour filters may be inserted in front of the iris, if it is desired to isolate a particular part of the spectrum of white light.

A screen which is uniformly illuminated and which diffuses the light falling on it through a wide range of angles should appear to a distant observer as a continuous area of light which does not exhibit any variations. It is a surprising fact that this anticipation is not realised and that the screen actually exhibits over its entire area a display of varying luminosity which alters from instant to instant in a chaotic fashion. The nature of the patterns of variation of brightness over the area and the manner they change with time is found to depend greatly on the strength of illumination of the screen, as also on the distance from which it is viewed by the observer. The spectral character of the illumination has also a noticeable influence on these features.

That the phenomenon is a consequence of the corpuscular nature of light is *prima facie* inferable from its observed features. This inference is confirmed when we proceed to consider in detail the consequences which would follow from the recognition that our visual sensations represent the conjoint effect of a great many individual light-corpuscles which reach the observer's eye and are there actually perceived.

The number of individual light-corpuscles sent out by a source and reaching the screen under observation in any given time-interval would, of course, be very large. The number is proportional to the light-flux incident on the screen. But if we consider only a small element of the area of the screen, the number is reduced in proportion to the area of the element. Then, again, only a very small fraction of this number can reach the eye of the observer. For, the screen diffuses the light over a wide range of angles and if the distance of the observer from the screen is large, the number actually finding entry into the pupil of his eye would be but a minute fraction of the whole. We have also to recollect that of the light-corpuscles reaching the retina, only a small fraction would actually be absorbed and be effective in perception. When all these considerations are taken into account, and it is also remembered that the eye can, in appropriate circumstances, take note of rapid variations in the perceived luminosities, the possibility of fluctuations of luminosity being perceived at various points on the area of the illuminated screen becomes evident.

A significant fact of observation is that the patterns of fluctuating luminosity seen on the screen are on a larger scale, in other words, appear to consist of larger individual areas, when the illumination of the screen is at a low level. *Per contra*, if the screen is more brightly illuminated, the patterns of varying intensity are on a much finer scale. A second fact of observation is that the patterns of varying luminosity are on a much larger scale when the observer is far removed from the screen than when he is close to it. Finally also, it may be remarked that if the illumination of the screen is at a high level and the observer is also close to the screen, the patterns of varying brightness are on an extremely fine scale and need attentive observation to enable them to be discerned. All these facts agree with what we should expect on the basis of the considerations set forth above.

The observed dependence of the fluctuations of luminosity on the spectral character of the light falling on the screen is a further confirmation of the origins of the phenomenon. The simplest way of exhibiting this dependence is for the observer to view a white plastic screen placed in a darkened room and facing a window through which skylight is admitted, its illumination being controlled by opening or closing an iris-diaphragm which covers the window. The illumination is first adjusted to be at such a level that the fluctuations are visible on the screen but on a fine scale and are not very conspicuous. On placing a filter of blue glass before the observer's eye, it is found that they become far more conspicuous and are also on a larger scale. This is the result to be expected. For, the blue-violet end of the spectrum is the least luminous part of it, thereby indicating that a much smaller proportion of the energy appearing in that part of the spectrum is actually perceived as light. Further, the energy of an individual corpuscle is also greater in that region. Hence, the number of corpuscles actually effective in vision is relatively much smaller than for other parts of the spectrum. The more pronounced character of the fluctuations of luminosity which are observed thus becomes intelligible.

Introduction of a red filter before the observer's eye has a less striking influence on the fluctuations of luminosity visible on the screen than in the case of a blue filter. Why this is the case hardly needs to be elaborated in view of the remarks already made. But it should be mentioned that the fluctuations visible through a red filter are more conspicuous than when viewed without the filter, if the level of illumination of the screen is so low that the sensory impression produced by red light itself becomes extremely weak. The effects then seen are comparable with those observed through a blue filter.

CHAPTER VI

COLOUR AND LUMINOSITY IN THE SPECTRUM

The ability to perceive and recognise colour is a characteristic feature of human vision. It follows that the elucidation of the origins of colour is a highly important part of the science of vision. Already, in the earlier chapters, we have encountered certain aspects of the subject and we now proceed to concern ourselves with it in greater detail.

When white light emitted by a solid body at a high temperature is examined through a spectroscope, we observe a band exhibiting varied colours which is referred to as its spectrum. An essential feature of this spectrum is that the colours observed in it form a continuous sequence. The number of colours which can be distinguished from each other is fairly large. If, for example, the spectrum is divided up into fifty strips in the manner already described and illustrated in an earlier chapter, each of these strips exhibits a colour visibly different from those of the adjoining strips. Such a sub-division of the spectrum also represents a partition of it into sections in which the energy of the light-corpuscles which give rise to the observed colour alters by equal increments. It is thus evident that the perception of colour depends upon and is linked in the closest fashion with the corpuscular light-energy.

It follows from the foregoing remarks that the subject of colour falls naturally into two distinct divisions. The first division concerns itself with the pure spectral colours, in other words with the sensations excited by light in which the corpuscles all possess the same energy. The second division concerns itself with the colours of composite light, in other words with the hues exhibited by light in which the corpuscular light-energies are not all the same but differ widely. It is obvious that this second part of the subject needs to be dealt with separately. It is a more complex field of enquiry than the first and it would be both illogical and fruitless to attempt to deal with it until the subject of the pure spectral colours has been fully explored and elucidated. Accordingly, in the present chapter and in the succeeding one, we shall limit ourselves to the pure spectral colours which, as we shall see, themselves present a wide field of investigation. What the colours of composite light are and how they are generated will be dealt with in later chapters.

Highly remarkable and significant changes are observed in the spectrum of white light when the level of brightness at which it is viewed is progressively lowered. We shall first describe these changes and later proceed to make some comments regarding their significance.

The technique of observation adopted is quite simple. A source of light which is useful in such work is a tungsten filament lamp of the kind employed in projection lanterns. The lamp contains a group of coiled-coil filaments placed side by side which together make an extremely powerful source of white light of small area. The lamp is kept cool by a fan and may be brought quite close to the slit of a wave-length spectrometer of the well-known type. The resulting spectrum may be viewed directly on the ground-glass screen usually provided with the instrument for focussing the spectrum. As the dispersion of the instrument is adequate, it is possible to open its slit to a width of one millimetre without appreciably affecting the purity of the spectrum. In these circumstances, it appears extremely brilliant on the screen. The brightness may be reduced by adopting one or another of three devices, either together or separately. The first is to move the lamp away from the slit of the spectrometer to a considerable distance up to say two metres. The second is to narrow the slit of the spectrograph down to a tenth of a millimetre. The third device is to insert a piece of ground-glass in an appropriate position between the slit and the lamp when these are sufficiently far apart. When all these devices are simultaneously made use of, the spectrum seen on the ground-glass is of greatly reduced brightness. Nevertheless, if the room has been darkened, and the observer uses a hood of black cloth to keep out stray light, there is no difficulty whatever in his viewing the spectrum and taking note of its features. We shall describe the spectrum as seen at five different levels of brightness, beginning at the highest and ending with the lowest.

At its most brilliant level, the spectrum exhibits its maximum extension at both ends. The features noticed at this stage which are of particular interest and importance are the following: By far the brightest part of the spectrum is the region which is yellow in colour. This region covers an appreciable width of the spectrum. An orange-yellow strip on one side and a greenish-yellow strip on the other side are also conspicuous. Beyond these areas, the red and green sectors appear. The rest of the spectrum consists of regions which exhibit three distinct colours: the first region is a bright blue, the second is a dark blue which may be termed as indigo, while the third region is of a violet colour. The three regions are of progressively diminishing intensity, but between the blue and indigo regions, a fall of intensity is very clearly noticeable, while a second fall of intensity is also noticeable between the indigo and violet regions.

At the second stage in the order of diminishing intensity of the spectrum, it exhibits a visible contraction at its red end. The yellow of the spectrum is still the brightest part of it, but it is not now so conspicuous. The orange-yellow and greenish-yellow parts are still observable, but they have definitely contracted. A particularly noteworthy feature is that the blue part of the spectrum has visibly contracted, its place being taken by the indigo and violet parts moving inwards. The falls of intensity between the blue and the indigo, and between the indigo and the violet are however still noticeable.

At the third stage of diminishing intensity, a further contraction of the spectrum at its red end is noticed. The yellow of the spectrum is still seen, but it does not appear as more brilliant than the red and the green on its two sides. These two colours appear redder and greener respectively than in the spectra at the earlier stages. The bright blue of the spectrum has disappeared completely and the regions beyond the green which are now of diminished intensity exhibit only the dark blue and violet colours.

At the fourth stage of diminishing intensity, the red of the spectrum has contracted further, and the yellow is barely discernible. Both the red and the green appear of a richer colour than previously and are of comparable intensities. The spectrum beyond the green is very weak and appears of a violet colour throughout. The falls of intensity noticed in the earlier stages in these regions are no longer visible.

In the fifth stage of the series which is the lowest in respect of intensity, the red of the spectrum continues to be visible, but it is much shortened and of greatly reduced intensity. The yellow of the spectrum has disappeared. But the green continues to be visible and is now the brightest part of the spectrum. The part of the spectrum which follows it is of low intensity and its colour is barely noticeable. This region is also of visibly diminished extension.

Another technique which has also been successfully employed in these studies makes use of a tubular lamp 25 centimetres in length carrying a luminous tungsten filament stretched along its axis. The observer holds a replica-grating before his eye and views the diffraction-spectra of various orders seen on either side of the glowing filament. The brightness of the spectra can be altered over a great range by varying the electric current which heats the luminous filament. The brightness of the spectra as actually perceived can also be diminished considerably by the observer with the grating held before his eye moving away to a great distance from the filament. *Vice versa*, by coming close to it, the brightness can be greatly enhanced. The visual comparison of the colours seen in the spectra of different orders is also found to be extremely useful. For, they differ greatly in their brightness.

A particularly interesting case is that in which the filament is at a low temperature and emits a weak glow of red colour. The spectra of the first order then exhibit only the green region, the rest of the spectrum having gone completely out of sight. The progressive weakening and ultimate disappearance from sight of the red part of the spectrum as the level of illumination is lowered can be followed by diminishing the heating current through the filament step by step until the green of the spectrum is its only surviving part. The second-order spectra being much weaker than those of the first order exhibit these changes at an earlier stage.

The very striking changes in the intensity of the yellow sector of the spectrum as we pass from the highest levels of brightness down to lower levels are impressively exhibited by the same technique. Beginning with the filament at the highest temperature which it can withstand, the observer also being close to the lamp, the yellow is observed to be the dominant feature in the spectrum. Besides being extremely bright, it is observed to modify the colour of the regions of the spectrum on either side to a notable extent. As the filament current is diminished, or if the observer moves away from the lamp, the dominance of the yellow becomes much less evident. Later, a stage is reached at which the yellow is barely visible as a thin strip separating the red and green regions of the spectrum, these now exhibiting hues which appear highly saturated. Finally the yellow disappears completely. At still lower levels of brightness, the red also becomes weaker and finally disappears, as already stated.

Observations by the same technique confirm the remarkable finding that the colours observed in the short-wave range of the spectrum may be either blue or indigo or violet according to the circumstances of the case, the violet replacing both indigo and blue when the intensity is low, and finally itself becoming almost colourless. These effects can be followed by varying the heating current through the filament. They are also manifest when the colours of the first and the second-order spectra are compared with each other. The observations also confirm the appearance of two distinct falls of intensity which appear respectively between the blue and the indigo and between the indigo and violet when the spectrum is sufficiently bright for these colours to be distinguishable.

Finally, it may be remarked that the general weakening of all colour sensations which goes hand in hand with diminishing brightness is strikingly manifest when we compare the spectra of the different orders with each other.

It appears appropriate to conclude the present chapter with some comments on the trichromatic theory of colour-perception. As has already been remarked, the colours perceived in the spectrum stand in the closest relationship with the corpuscular energy. Hence, every colour which can be perceived in the spectrum of white light must necessarily be regarded as distinct from every other, and the total number of independent colour sensations is therefore limited only by our ability to perceive them as distinct. Hence, to postulate that there are only three independent colour sensations from which all other colour sensations can be derived by superposition is clearly an arbitrary and unjustifiable hypothesis.

The falsity of the trichromatic theory becomes manifest when we consider the region of the spectrum which appears to us as yellow in colour. According to the trichromatic hypothesis, yellow is not an independent sensation and is derived by a superposition of the red and green sensations. We have only to compare this assumption with the actual facts of the case as they emerge from the observations described in the present chapter. We have seen that in brilliant light, the yellow is the most luminous part of the spectrum. far brighter than either the red or the green in it. Indeed, it is possible to go further and view the spectrum of white light at extremely high levels of intensity, as, for example, by observing a tungsten filament glowing at a white heat through a replica diffraction grating held before the eye. The spectrum is then seen as a brilliant band of yellow colour over its whole length with relatively feeble terminations of red and blue at its ends. *Per contra*, as we have seen, at low levels of illumination, the yellow is barely observable in the spectrum, while the green and the red are still to be seen exhibiting their characteristic hues. These facts of observation demonstrate the fallacy of describing the yellow of the spectrum as a secondary or derivative sensation.

CHAPTER VII

THE COLOURS OF INTERFERENCE

THE role of outstanding importance in vision played by the yellow sector of the spectrum is strikingly illustrated by a study of the interference patterns of the kind described earlier and illustrated in Chapter II when observed in white light. The colours exhibited by such patterns are a familiar phenomenon, but surprisingly enough, though they have been known for three centuries, attention does not appear to have been drawn to the special features which characterise these patterns and the recognition of which is necessary for their real nature to be understood.

In a well-known form of the experiment, the air-film is that enclosed between two surfaces, of which one is plane and the other spherical with a large radius of curvature. In these circumstances, the interferences take the form of rings which are concentric around the region of actual contact of the two surfaces where the film has zero thickness. This central region appears black in the pattern. Sir Isaac Newton devoted the second book of his classical treatise on optics to a description of these rings and hence they are usually known by his name. But neither Newton nor any of the numerous other observers who have described and discussed the effects observed in the experiment make any reference to the major feature of the phenomenon, *viz.*, the manifestation of a series of maxima and minima of luminosity in the field covered by the pattern. These alternations of luminosity determine the characters of the interference pattern and the alternations of colour observed are related to the alternations of luminosity in a manner which clearly indicates that the latter constitute the basic phenomenon and that the colour differences are only incidental consequences.

The diameter of the interference rings and the area over which they can be perceived in white light depend on the difference in curvature of the surfaces enclosing the air-film. The pattern and the rings may be so small that they can only be seen through a magnifier. On the other hand, the pattern and the rings may be on such a large scale that they can be seen and examined without any optical aid. The author has found that by merely holding together two pieces of thick plate glass in contact at the correct relative orientation, it is possible to obtain circular ring patterns on a very large scale. This is a consequence of the surface of the plates being cylinders of large radius which when held in crossed positions enclose between them an air-film of thickness depending only on the radial distance from the point of contact. This arrangement is found to be particularly useful for the studies presently to be described.

A surprising fact is that when the interference rings are on a small scale and are viewed by an observer from the usual distance of distinct vision, they are seen by him as a succession of bright and dark rings, five or six in number, but not exhibiting any visible colour. But when the same pattern is held close to the eye and viewed through a magnifier, the colours spring into view. What these observations signify is that the interferences as seen with white light are essentially a pattern of varying intensity of illumination analogous to those observed with monochromatic light but with the difference that the successive rings, instead of all being equally conspicuous, progressively diminish in visibility, thereby limiting the number that can be seen and counted.

Inspection of the interference patterns exhibited by air-films of varying thickness reveals in all cases that, following the region of actual contact where the film does not reflect light, we have four or five alternations of the brightness or intensity of the reflected light. Very conspicuous is the first minimum of intensity which is nearly but not quite black. Following this again, there are three other minima of intensity which are progressively less conspicuous but of which the positions can be determined with precision. A fifth minimum of brightness can be recognised but with some difficulty.

The manifestations of colour in the patterns observed with white light are very clearly related to the variations of luminosity in the field. What we may describe as a cycle of colours begins at each minimum of luminosity and ends at the next minimum, where a fresh cycle commences and proceeds to the next and so on. At least six such cycles are clearly recognisable, beyond which a few more can be glimpsed. The characters of the cycle of colours show a change as we proceed from the first to the second and then to the third, while the subsequent cycles resemble each other pretty closely. In the first three cycles, the yellow colour at the place of maximum luminosity is evident. At each minimum, we begin with a blue or bluish-green and pass on to the yellow, and then through orange to red at the next minimum where the cycle terminates. In the later cycles the yellow is not visibly manifested and we observe only an abrupt change of the colour from green to red.

The relationship between the interference pattern as seen by white light and as observed in monochromatic yellow light is made strikingly evident when arrangements are made by which the interferences as observed with white light and with monochromatic light are brought into juxtaposition so that a direct visual comparison between the two is made possible. It is desirable that the interferences should be on a fairly large scale so that they can be seen without any optical aid. Interferences of the type illustrated in Fig. 1 (A) and (B) of Chapter II are suitable and convenient for the purpose in view. One half of the pattern under study is illuminated by the diffuse white light from a tungsten filament lamp and the other half by the yellow light from a sodium vapour lamp, the two halves meeting sharply along the dividing line between them. At least four successive orders of interference in the white light patterns show recognisable minima of illumination, and with the arrangements described, it is found that they are completely coincident with the four corresponding dark lines in the patterns as seen with the sodium light, no break or shift appearing as we move from one part of the pattern to the other. In other words, white light behaves as if we could assign to it a specific wavelength located in the yellow sector of the spectrum.

These findings are confirmed by precise measurements of the positions of the minima of illumination in the white light patterns and comparing them with the minima as observed with monochromatic light of various wavelengths. For this purpose, the selected radiations are, besides the yellow of sodium vapour, the yellow and green radiations of a mercury vapour lamp, these being separated from each other by the use of a monochromator. The pattern which has been measured is the Newtonian ring-system which surrounds the point of contact between two lenses having curved surfaces. This pattern is on a sufficiently small scale to be suitable for exact measurements being made on it with a Hilger micrometer. The results are shown below in the Table.

TABLE I

Diameter in millimetres

Dark Ring	White Light	λ 5893	λ 5780	λ 5461
No. 1 ..	3·357	3·346	3·315	3·229
No. 2 ..	4·651	4·639	4·604	4·489
No. 3 ..	5·590	5·574	5·538	5·389
No. 4 ..	6·490	6·398	6·358	6·176

It will be seen from the data exhibited in Table I that the positions of the minima of illumination as observed with the sodium light and with white light agree fairly well. The agreement is not so good with the yellow light of a mercury lamp, while they diverge widely from the positions of the minima as observed with the green λ 5461 radiation.

CHAPTER VIII

THE DISCRIMINATION OF COLOUR

WE shall concern ourselves in the present chapter with the following questions. How sensitive are our eyes to differences in colour? What are the factors which determine or limit this sensitivity? It is obvious that these questions can only be answered by systematic observational studies, though it is possible to venture on some general considerations based on pure theory.

So long as we restrict ourselves to the pure spectral colours, we can base ourselves on the fact of observation that the progression of colour in the spectrum corresponds to a progression in the energy of the corpuscles of light which are perceived, in other words that there is a one-to-one correspondence between the perceived colour and the energy of the corpuscles which are absorbed by the retina and excite the sensation of light. This being the case, any lack of precision that is noticeable in the perception or discrimination of colour may reasonably be attributed to a corresponding lack of precision in the energy-transformation which results in the observed visual sensation. The absorption of light by the molecules of a pigment present in the retina may be assumed to precede such transformation of energy. A factor which is inevitably present is the energy of the thermal agitation of the molecules of the absorbing material. Hence, we must be prepared to find that the energy of the incident corpuscle of light is either added to or diminished by the energy of such thermal agitation in the act of absorption. The situation may be expressed by the formula:

$$h\nu^* = h\nu \pm k\mathrm{T}$$

Here ν is the frequency of the incident light, ν^* is the frequency of the light as actually perceived, k is the Boltzmann constant and T is the absolute temperature of the retina. Dividing out both sides of the equation by Planck's constant h, we obtain

$$\nu^* - \nu = \pm kT/h$$

Expressing the quantities on both sides of the equation in terms of wave-numbers, we find from the equation that our perception of colour in the spectrum is liable to an uncertainty due to the thermal agitation existing in the retina of the order of $\pm$ 215 wave-numbers. If expressed in wave-lengths, the magnitude of this uncertainty would increase progressively as we proceed from the violet towards the red end of the spectrum. At both of these ends, the luminosity of the spectrum is very low, and this is especially the case near the violet end. Taking 4200 angstroms and 6500 angstroms respectively as the limits within which a critical study of colour discrimination is possible, the uncertainty of $\pm$ 215 wave-numbers would be equivalent to $\pm$ 38 angstroms at the violet end of this region and of $\pm$ 89 angstroms at the red end, with intermediate values elsewhere.

We may also state the same result in a different way. By dividing the entire spectrum into a series of strips of which the separation is 215 wave-numbers, we obtain 50 strips in all. The argument set forth indicates that an observer viewing the spectrum thus divided would find each strip differing visibly in colour from the strips on either side of it. An observational test of this statement is readily possible by making use of the optical device described and illustrated in Chapter II which enables the spectrum to be transformed into a succession of bands following each other at a constant wave-number separation. This separation can be altered at will. We can therefore proceed step by step and compare the colour of each band with those of the bands on either side of it. So long as the number of bands in the spectrum is not too great, a perceptible difference of colour is then actually observed. This is definitely the case when the number of bands which can be counted in the spectrum is as large as 50, which corresponds to the wave-number separation of 215.

The argument set forth above assumes that the absorption of light at all points of the spectrum would be influenced by the thermal agitation of the molecules to the same extent everywhere. That this would actually be the case is however most unlikely. For, the absorption of light in the visible spectrum would primarily be the result of a change in the electronic energy levels of the absorbing molecules. Such change need not necessarily be accompanied by a change in the energy of their internal vibration or of their translatory movements. The energy taken up from the incident light would then be fully available for its perception, and a high degree of accuracy in the recognition of colour differences could be expected. On the other hand, if the absorption of light involves also changes in the energy of internal vibration and of translatory movement, the same measure of precision cannot be expected. We are thus led to infer that the estimate of $\pm$ 215 wave-numbers should be regarded as an upper limit and not as a definitive value for all parts of the spectrum. We may expect a much better performance in respect of the accuracy of colour perception in the regions of the spectrum which correspond to the changes of the electronic energy levels alone and a lesser degree of accuracy in the regions of the spectrum remote therefrom. Especially at and near the extremities of the spectrum where the luminosity is low, in other words where the absorbing power is weak, we may reasonably expect a close approach to the upper limit of $\pm$ 215 wave-numbers in the uncertainty of colour perception.

The considerations set forth above indicate that a quantitative study of the power of colour discrimination over the entire range of the visible spectrum would throw much-needed light on the absorptive properties of the visual pigments present in the retina and may even assist in their identification. The optical technique of study making use of a banded spectrum, though useful for a qualitative survey of colour perception, cannot serve for a precise quantitative study. Accordingly, two other methods have been devised and adopted and will presently be described.

The first of the two techniques adopted is perhaps the simplest that could be thought of. It depends on the presentation to the eye of the observer of a limited part of the spectrum and then very quickly afterwards an adjoining region of the spectrum. He has then to decide whether or not he perceives a change of colour. The observations are made with a spectrometer having a calibrated wavelength drum. A slit of adjustable width is placed in the focal plane of the observing telescope. This admits a narrow strip of the spectrum which is viewed by the observer through the eye-piece of the instrument. A rotation of the wavelength drum in one direction or the other enables the smallest change of wavelength which produces a detectable change of colour to be read off. By taking the average of several readings, fairly reliable values can be obtained. The width of the slit most suitable for the observations is something in the nature of a compromise. If it is too narrow, not enough light comes through, and if it is too broad, it admits light over a range of wavelengths comparable with the quantities sought to be measured. Despite this source of uncertainty, the technique is found to be capable of yielding useful results.

The results of a set of measurements made in the manner explained are exhibited in Fig. 5. The ordinates in the graph show the wavelength shifts required to produce an observable change of colour, while the abscissae indicate the part of the spectrum under observation. The readings were taken at intervals of 100 angstroms. The noteworthy features in the graph are the very conspicuous dips in the wavelength region between 4900 and 5000 angstroms and in the yellow of the spectrum around 5800 angstroms. Higher elevations appear elsewhere and especially in the parts of the spectrum near its two terminations. The lesser dips in the curve at 4300 angstroms in the short-wave region and at 6300 angstroms in the long-wave region correspond to points in the spectrum at which fairly rapid changes in colour are visually noticeable.

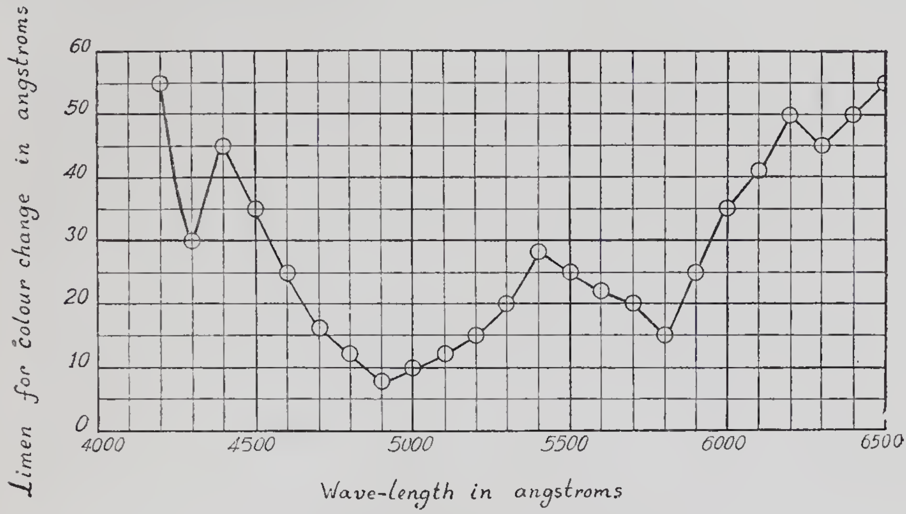


FIG. 5. Discrimination of Colour in the Spectrum.

The ideal arrangement for determining the sensitivity of the eye to the colour differences which present themselves in the spectrum is to compare light of each wavelength with light of an adjacent wavelength by presenting both side by side with a sharp dividing line of separation, as in ordinary photometric practice. It is necessary that the intensities of the lights under comparison should first be equalised to ensure that differences in luminosity are not mistaken for differences in colour. Two monochromators have been used for a study of this kind, one being a quartz monochromator of large aperture by the firm of Hilger and the other a double-monochromator with glass prisms supplied by Kipp and Zonen. The instruments were so placed that the monochromatic pencils emerged from them in perpendicular directions. This enabled the comparisons between them to be made using a Lummer-Brodhun cube as the photometric device. The field of view under observation then appears as a circular area surrounded by a circular ring. The original light-sources used with both instruments were of the same kind, *viz.*, tungsten-filament lamps emitting white light of great intensity. The equalisation of the intensities of the light appearing in the two parts of the field was effected by varying the widths of the entrance-slits of the two instruments. It was checked at each stage by direct observation of the field of view when the wavelengths were the same. The light issuing from the Hilger monochromator could be shifted by steps of 100 angstroms at a time and was made the standard of reference. The wavelength of the light issuing from the Kipp and Zonen instrument could be varied by rotating the drum provided for the purpose. The smallest wavelength shift producing an observable difference in colour was determined, six successive settings being made at greater wavelengths and six at smaller wavelengths. A systematic series of observations was thus made, covering the spectrum from end to end. This was repeated a second time to check the reliability of the determinations.

FIG. 6. Discrimination of Colour in the Spectrum.

The results obtained in the manner set forth above are shown as a graph in Fig. 6. A comparison with those shown earlier in Fig. 5 shows a gratifying measure of agreement. In both figures, the wavelengths at which the eye perceives the most rapid changes of colour are the same, *viz.*, at 4900 angstroms and at 5800 angstroms. At 5400 angstroms, both curves exhibit a turning point where the colour changes but slowly. Dips of a minor character appear at 4300 angstroms and 6300 angstroms in both figures. In both figures also, the curve rises steeply on the two sides of the dip at 5800 angstroms and somewhat less steeply on the two sides of the dip at 4900 angstroms. The asymmetrical shape of the graph on either side of the wavelength of 4900 angstroms is also clearly exhibited in both figures.

The two graphs differ from each other in respect of some minor details. But this is not surprising, since the techniques of observation employed were not the same. Further, the levels of illumination at which the determinations were made were not identical. With the more elaborate technique using two monochromators, the illumination of the field under observation is at a distinctly lower level than when a strip of the spectrum is viewed directly through a slit. As was already been noticed in an earlier chapter, the absolute luminosity of the spectrum has a notable influence on the colour sequence observed in it.

From the data exhibited graphically in Fig. 6, Table II has been prepared to exhibit the points in the spectrum at which the graph exhibits noteworthy features, *viz.*, a maximum or a minimum. The wavelength has been shown as also the corresponding wave-number. Figure 6 shows the data in terms of wavelengths and wavelength differences. But in Table II, the wave-number, wave-number differences and their percentages have been shown as they are more significant.

It will be seen that all the figures in the fourth column except the last are much less than the wave-number difference of 215 to be expected if the thermal agitation of the retina exercises its maximum effect on colour perception.

We now proceed to sum up the results which have emerged in this chapter. The progression of colour in the spectrum of white light is the sensory perception of the progressive increase in the energy of the corpuscles of light

TABLE II

Colour Sensitivity of the Eye

Colour	Wave-length	Wave-number	Detectable Wave-number difference	Percentage difference
Red ..	6300 Å	15873	± 88	0·6%
Yellow ..	5800 Å	17242	± 39	0·2%
Green ..	5400 Å	18519	±174	0·7%
Blue ..	4900 Å	20408	± 71	0 35%
Violet ..	4300 Å	23256	±216	0·9%

as we pass from the red to the violet. It may be inferred that the precision exhibited by the colour sense is also a measure of the precision with which the energy of the light-corpuscles becomes available for the perception of light without diminution or addition. The only limiting factor which may lead to uncertainty and needs to be considered in this context is the thermal energy of the molecules which absorb the light and enable it to be perceived. Calculations show that the uncertainty due to this factor is more than sufficient to account for the observed lack of precision of the colour sense at all points in the spectrum. It may be inferred from this that the graph exhibiting the varying power of colour discrimination over the spectrum exhibits the extent to which the absorptive processes resulting in the perception of light are actually affected by the thermal agitation in the retina. The variations in the power of colour discrimination over the range of the visible spectrum are thus indicative of the spectral behaviour of the visual pigments in the retina and can assist us in their identification.

We may appropriately conclude this chapter with some comments on the photochemical theories of colour perception which have in the past found a place in the literature of the subject. These theories contemplate that the incidence of light on the retina results in a photochemical break-up of the material contained in it and that such break-up is the primary process which enables light to be perceived. One need not question the possibility of such photochemical reactions taking place in the retina and of the subsequent regeneration of the materials thus decomposed. But what should be called into question is the assumption that such chemical changes play the primary role in the visual perception of light and that the material undergoing such modifications is itself the "visual pigment" which plays an active role in such perception. That these assumptions are unnecessary and indeed untenable is indicated by various considerations. It will suffice here to point out that if what has been set forth in the preceding paragraph regarding the perception and discrimination of colour is valid and acceptable, *ipso facto*, all photochemical theories of vision must stand rejected. For, any chemical reaction excited by light would necessarily take up a proportion of the energy of the incident light-corpuscles and this proportion would depend on the nature of the reaction and on the part of the spectrum in which the incident light appears. In such circumstances, the continuous progression of colour in the spectrum and the high degree of precision exhibited by the colour sense would remain unexplained.

CHAPTER IX

THE PERCEPTION OF POLARISED LIGHT

One of the most remarkable of our visual faculties is the ability to recognise polarised light and to locate its plane of polarisation. It is the foveal region of the retina that exhibits this power which, it may be remarked, is limited to light appearing in the blue sector of the spectrum. The fovea is the most useful part of the retina and the spectral region manifesting this property is also distinguished by its being the most colourful and yet the least luminous part of the entire spectrum. Clearly, therefore, the process by which the fovea is enabled to recognise the presence of polarisation in light appearing in a restricted range of wavelengths and is unable to achieve the same results in other parts of the spectrum is of great significance. The investigation of which the results will be set forth in the present chapter has revealed that the perception of polarisation is effected by a physiological process which stands in the closest relationship to the perception of colour and luminosity in the same spectral region.

Haidinger's Brushes.—The blue colour of the sunlit sky has its origin in the scattering of sunlight by the molecules of the earth's atmosphere. Skylight accordingly exhibits a high degree of polarisation when observed in a direction transverse to the rays of the sun. As a consequence, observation of the parts of the sky which exhibit the maximum degree of polarisation should enable us to demonstrate the ability of our eyes to perceive and determine the state of such polarisation. The effects thus arising are best looked for in the forenoon of any bright clear morning when the sun is well up above the horizon. The observer should stand with his back to the sun and view the regions of the sky where the maximum of polarisation is to be expected. These regions would evidently lie along the arc of a great circle which runs at a slant across the sky. Scanning this circle rapidly with his eyes, the observer will notice a band along the circle which appears bluer than the rest of the sky and which is bordered on both sides by bands of the same width exhibiting a distinctly yellowish hue. On fixing his attention at a particular part of the circle to his left, it will be found that the colours seen in that region soon fade away from sight. The observer should then turn quickly and fix his attention on the part of the great circle to his right which is ninety degrees away from the original point of fixation on the left. He will then notice in this region a very striking phenomenon, *viz.*, a dumbell-shaped blue brush of light having its axis on the great circle of maximum polarisation of skylight and crossing this brush a yellow brush of light of similar shape with its axis transverse to that circle. These brushes are conspicuous when first seen, but when the observer continues to gaze at them, they fade away from sight. He should then again turn quickly to the region on the circle previously viewed. He will then notice in that region a similar conspicuous manifestation of the blue and yellow brushes crossing each other. This alternation between the left and the right can be repeated as often as desired.

Studied in the manner described, the nature and origin of the phenomena become clear. What the observer perceives is an enormously enlarged picture of the foveal region in the retinae of his own eyes projected on the sky and manifesting itself by reason of the visual response of the fovea to the light incident on it. The spectral character of that light, its state of polarisation and the orientation of the plane of polarisati n in relation to the fovea are the factors which determine the nature of the picture perceived. The circumstances in which it is observed indicate that the conditioning of the eye by an earlier exposure to polarised light also plays a highly important role. The entire light of the spectrum is polarised, but the part of the spectrum not included in the range of wavelengths between 400 mμ and 500 mμ behaves quite differently from the part which is included in that range. It is the latter part of the spectrum that evokes a powerful visual sensation in the two sectors of the fovea of which the axis is parallel to the direction of vibration in the incident light. The two other sectors of which the axis is perpendicular to that direction are not thus excited. Since these differences appear only in the blue-violet sector of the spectrum, the visual sensation in the former case manifests itself as a brush of a bright blue colour. In the latter case, the absence of any sensation in the blue region of the spectrum results in only the rest of the spectrum being perceived. The manifestation of a yellow brush crossing the blue brush is thus accounted for.

The blue and yellow brushes and the regions in the fovea which they represent interchange positions when the observer shifts his vision from the part of the sky on his left to another on his right located ninety degrees away from it. The regions of the fovea which are not excited in one case are those excited in the second case and *vice versa*. The sectors are thus conditioned by the first exposure respectively to respond and not to respond to the second exposure. Accordingly, the blue brush and the yellow brush both turn round through a right angle and manifest themselves conspicuously to the observer's vision.

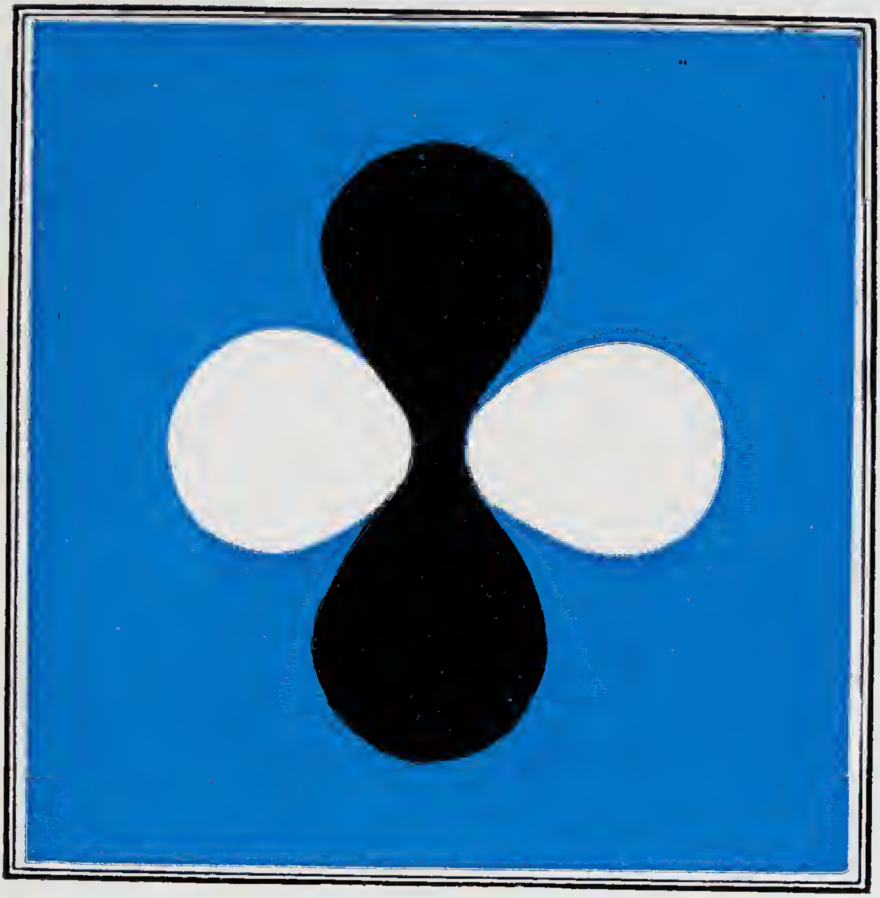
The Spectral Characteristics.—As stated above, the ability of the fovea to perceive polarisation is restricted to the blue-violet part of the spectrum. In other words, polarisation is detectable throughout the spectral range between 400 mμ and 500 mμ but is unobservable in the region of greater wavelengths. A simple technique by which these facts can be demonstrated has been devised by the author. A brilliantly illuminated part of the sky (close to the sun) is viewed through the long slit-shaped opening between the two shutters of a window by the observer who takes up a position at a suitable distance from the opening. Holding a diffraction grating before his eye, the observer can view the first-order spectrum produced by it and can direct his vision to any particular part of the spectrum and scan the entire spectrum from end to end. Insertion of a polaroid before the grating results in polarising the light appearing in the spectrum. Two brushes are then seen crossing each other, one of them being a bright brush and the other a dark brush. When the polaroid is rotated, both the brushes rotate together in the same direction as the polaroid. The brushes can be very clearly seen in the blue-violet sector of the spectrum, but not elsewhere in the other sectors of greater wavelengths.

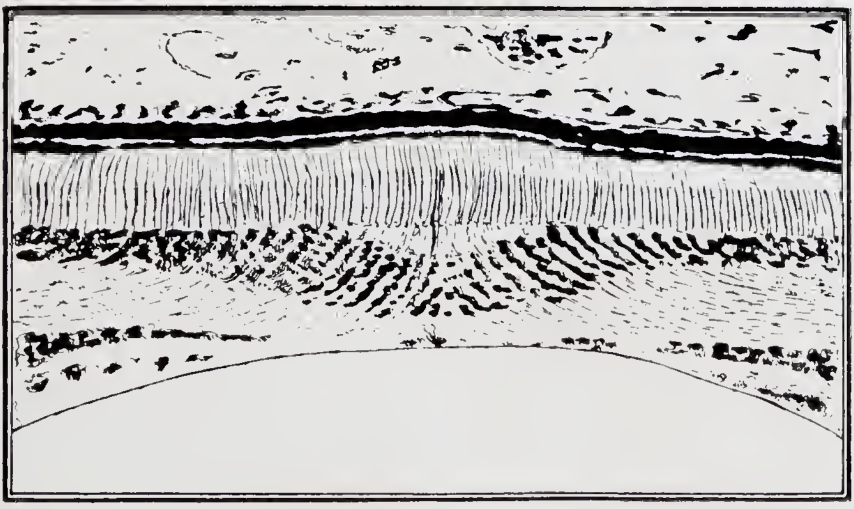
That the polarisation of light is undetectable by the unaided vision if the wavelength of the light exceeds 500 mμ also becomes evident when the observer makes use of a colour filter which completely cuts off all wavelengths less than 500 mμ while freely transmitting greater wavelengths. Glass filters having such a spectral behaviour are commercially available and they appear of a golden-yellow colour by transmitted light. Viewing an extended source of light through such a filter with a polaroid placed in front which can be turned round in its own plane, critical examination fails to reveal any observable brushes in the field of view. *Per contra*, the use of a colour-filter that cuts out all wavelengths greater than 500 mμ and transmits shorter wavelengths enormously facilitates the observation of the brushes. Instead of a blue brush crossed by an yellow brush, we have then a bright brush crossed by a dark brush, both appearing in a field exhibiting the colour of the transmitted light. The contrasts in respect of luminosity then manifested make the whole phenomenon very conspicuous. The axis of the bright brush is parallel to the direction of vibration in the polarised light, while the axis of the dark brush is transverse to that direction.

Techniques of Observation.—The use of a colour filter to eliminate the unwanted parts of the spectrum and of a polaroid to secure complete polarisation of the light in any desired azimuth makes further critical studies possible. Observations can then be made under controlled laboratory conditions and artificial light sources having the desired spectral characters can also be utilized. By such studies it can be established that, though restricted to the blue-violet sector of the spectrum, the ability to detect polarisation belongs to the same category of visual phenomena as the perception of light, form and colour and that it stands in the closest relationship with these perceptions. The difficulty which presents itself in the evanescent character of the phenomenon can be overcome by the adoption of a suitable technique. Holding the colour filter together with the polaroid in front of his eye, the observer should view an extended source of light. The polaroid should be held at first in a particular orientation and then smartly turned round in its own plane through a right angle. It should then be held in the new position for a little while and later turned back again to the original position. These movements may be repeated as often as desired. Immediately after the polaroid is turned into a new orientation, the brushes are seen at their best, a bright brush along the direction of vibration in the transmitted light and a dark brush in the transverse direction. The brushes fade away soon, but they reappear in full strength in the new position when the polaroid is turned again through a right angle.

The extended sources of light needed for the study are most conveniently accessible out-of-doors, sunlit clouds being the most luminous. Next in order comes skylight, the brightness of which varies enormously with the part of the sky under observation, as also with the time of the day. In the vicinity of the sun, especially when it is covered by a thin haze, skylight can be extremely brilliant. Further away from the sun, the luminosity falls off rapidly. It also becomes very weak in the twilight hours. Indoor observations may also be made using screens which receive their light from open windows. If the screen employed is of the type used for projection work, consisting of a great number of tiny glass-balls embedded in a plastic sheet, a fairly high luminosity may be achieved. Other screens are, of course, less satisfactory. It should be remembered that the combination of a blue filter with a polaroid transmits only a very small part of

Plate V





Perception of Polarised Light
and the
Structure of the Fovea

white light. The need for a high intrinsic luminosity when an extended source of light is viewed through such a combination is obvious.

For observations indoors with monochromatic light the most suitable source is a powerful mercury arc lamp of the type used in street lighting. This should be enclosed in a box of suitable size which is provided with an exit window of sufficient area for the emergence of the light. A glass cell containing cuprammonium solution which covers the exit aperture makes an effective filter. It transmits the λ 4358 radiations and cuts out all longer wavelengths. The light emerging through the filter may be received on a ground-glass screen, the observations being made on the light emerging through it. Alternatively, the light may be received on an opaque diffusing screen, the surface of the latter being viewed by the observer at any convenient angle. This, of course, is a much less efficient source of light than the ground-glass screen which operates by transmission. No colour filter is necessary in either case, only the polaroid being held by the observer before his eye. By varying the distance of the ground-glass sheet or of the diffusing screen from the exit-aperture of the source, a very wide range of strength of the illumination may be obtained.

When the techniques of observation described above are made use of, it becomes immediately apparent that the perception of polarisation is only possible when the source under observation has a fairly high luminosity and that it becomes more and more difficult as the luminosity of the source is progressively diminished. Finally, a limit is reached below which the phenomenon cannot be perceived. These facts of observation make it evident that the perception of the brushes with polarised light is a phenomenon of a physiological nature. Its complete parallelism with the other aspects of the perception of light may be demonstrated with the aid of an ophthalmic chart of the usual kind consisting of rows and columns of letters of various sizes printed in black on white cardboard. Viewed by the observer through a blue filter and a polaroid at the same levels of illumination, the visibility of the letters falls off in the same fashion.

Further striking evidence that the perception of polarised light is a physiological process is furnished by the following experiment. The observer should hold a blue filter and a polaroid before his eye and view a luminous field of adequate luminosity for a sufficient interval of time to allow the brushes seen at first completely to fade away. He should then suddenly remove the polaroid but allow the blue filter to remain in place. He will then see the brushes once again, but turned through a right angle. In other words, the fovea then perceives with enhanced brightness that part of the incident light which was cut off by the polaroid when it was in place before the observer's eye.

The Origin of the Haidinger Brushes.—We may here comment upon the explanation of the brushes observed with polarised light which was long ago suggested by Helmholtz and received general acceptance, *viz.*, that it is an effect arising from the dichroism of the material contained in the macular region of the retina. This explanation, if correct, would make the brushes a physical curiosity having no physiological significance. It is therefore appropriate here to point out that the explanation given by Helmholtz is wholly untenable. This becomes evident when we examine the assumptions on which that explanation is based and also when we compare its consequences with the actual facts of the case.

As has already been stressed, special techniques are necessary for the visual perception of polarised light to manifest itself in an impressive fashion. One of the essentials is the use of a colour filter which cuts out all light having a wavelength greater than 500 mμ and transmits freely the region of the spectrum having shorter wavelengths. The luminosity of the field as seen through such a filter combined with a polaroid should also be adequate. When these requirements are satisfied, the field exhibits a bright brush running *parallel* to the direction of vibration of the light and a dark brush *transverse* to the direction of vibration.

Employing the proper technique, we observe that the brush running transverse to the direction of vibration is completely dark.

If the facts of observation indicated above are to be explained on the assumption that the material of the retina in its foveal region has a radially symmetric structure which exhibits dichroism, it would be necessary for the absorption of light by the material to be effective and indeed *total* for optical vibrations along directions *transverse* to the radii of the structure and over the entire wavelength range between 400 mμ and 500 mμ. Further, there should be no absorption at all for directions parallel to the radii of the structure. These assumptions are inadmissible for the following reasons. In the first place, the retina being a thin membrane and especially thin in the region of the fovea, the presence in it of sufficient absorbing material completely to block out the entire spectrum between 400 mμ and 500 mμ is scarcely possible. Indeed, our eyes would then be unable to perceive the blue light of the spectrum. Another cogent objection is the known behaviour of fibrous materials dyed with organic dye-stuffs. In numerous cases where the dye-stuffs have elongated molecules, the dyed fibres do indeed display marked dichroism. But in all such cases, the strong absorption is manifested for directions of vibration *parallel* to the length of the fibres and not for directions *transverse* to them. It follows that the explanation suggested by Helmholtz for the appearance of the brushes is entirely mistaken.

It is well known that the retina exhibits a radially symmetric structure around the deepest part of the depression in it which is the fovea. The layers in the retina which elsewhere run parallel to its surface are tilted within the depression. As a consequence, the nerve fibres leading away from the bacillary layer run at an angle to the surface. These features appear as we move away from the centre of the fovea but are not noticeable outside the foveal depression. That the brushes observed with polarised light are a consequence of these features in the structure of the fovea is scarcely to be doubted.

That the brushes observed with polarised light are seen only within the limited spectral range in which the colour perceived is blue may be regarded as a demonstration that the material present in the retina which enables us to perceive light and colour in that spectral region is also responsible for the effects observed with polarised light. These effects accordingly enable us to infer some of the characteristics of that material. In the first place, its absorption of light should be limited to the blue sector of the spectrum. Then again, its molecules should possess an elongated structure and the absorption by them should be limited to directions parallel to the length of the molecules and relatively negligible in perpendicular directions. Further, these molecules should be disposed with radial symmetry in the fovea around its centre and should lie with their longest dimensions parallel to its radii, in other words, along the nerve-fibres which run at an angle to the surface (*see* Plate V).

From the considerations set forth above, it would follow that except in regions close to the centre of the fovea, polarised light would be most strongly absorbed in the foveal region if its vibration direction is parallel to the radii of the structure and not absorbed at all if the vibration direction is perpendicular to the radii. Since perception of light is only possible as a consequence of the absorption of light by the materials present in the retina, it follows that with polarised light, we should observe a bright brush along its vibration direction and a dark brush running transversely to that direction. This, indeed, is what is actually observed.

It is thus evident that that the brushes observed with polarised light furnish information of great value in regard to the identification of the material present in the retina, which enables us to perceive light and colour in the blue sector of the spectrum, and also in regard to the manner in which that material is distributed in the foveal region. We shall return to this topic in a later chapter.

CHAPTER X

VISUAL ACUITY AND ITS VARIATIONS

We may begin by briefly recalling the facts of observation set out in Chapter V under the heading "Fluctuations of Luminosity in Visual Fields". It was there stated that a diffusing screen which is uniform and is uniformly illuminated nevertheless appears to the observer viewing it from a distance to exhibit variations of luminosity over its area which alter from instant to instant and are seen to move about in a chaotic fashion. These variations of luminosity, however, exhibit certain recognisable characteristics which are different in different circumstances. They depend on the strength of the illumination and also on the distance of the observer from the screen. The spectral character of the light which illuminates the screen is also observed to play an important role in determining the characters of the observed phenomena.

It is evident that such fluctuations of luminosity would interfere with our perception of the details of any objects depicted on the screen which are recognisable by reason of differences in brightness or colour exhibited over their area. The extent of such interference with the visibility of the objects may also be expected to be influenced by the same circumstances as those which determine the characters of the fluctuations of luminosity. Observations show that these anticipations are completely in accord with the actual facts of the case.

For the study of visual acuity and its variations, the well-known Snellen test-charts of the type used by oculists are very convenient. Letters of various sizes printed in black on white card and arranged in rows and columns appear in these charts. The letters are of large size and few in number in the top rows and progressively diminish in size and increase in their number in the following rows. The sizes of the letters in the chart are such that when it is placed at a distance of eight metres from an observer with normal vision in a well-lighted room, he can read all the letters without difficulty or hesitation.

To exhibit the dependence of visual acuity on luminosity, the observations may be made in a chamber the admission of light into which can be controlled and varied over a great range with the aid of an iris-diaphragm covering a circular opening in a window which faces the sky. The test-chart should be placed as far away as possible from this opening, but facing it so that it is uniformly illuminated. The observer should also face the chart and can view it from any desired distance, commencing from the maximum permitted by the size of the room.

When the iris is fully open and the chart is therefore brightly illuminated, all the eight rows of letters on the chart can be read by the observer provided that he is not too far away from it. If the observer remains in a fixed position and the iris is then progressively closed down, the successive rows of letters disappear from sight one after another, commencing from the last row containing the smallest letters and proceeding upwards. Finally, when the opening of the iris is a minimum and the illumination of the chart is very feeble, even the rows at the top containing letters of large size are scarcely visible or recognisable. If at this stage, the observer moves towards the chart and comes closer to it, the sequence of changes is again observed, but in the reverse order. In other words, the rows of letters become visible one after another commencing from the rows of the larger letters at the top and moving downwards to the rows of smaller letters. Finally, when the observer is close to the chart, he can read all the letters, despite the weakness of the illumination.

Fluctuations and Visual Acuity.—Attentive observation of the individual letters at various stages of the foregoing experiment reveals a phenomenon which may be described as a disintegration or break-up of the lines or curves which together make up a complete letter. In other words, only a part of the complete letter is visible and the other parts are not. At intervals, even the complete letter vanishes from sight and later reappears. These changes make it difficult to recognise and read the letters, and when they have proceeded far enough result in their obliteration. The lower the level of the illumination, the larger are the areas which pass out of sight. It is readily understood why in these circumstances, it is the smallest letters which first cease to be legible as the illumination is diminished and that they are followed later by the larger letters. Likewise, it is noticeable that the distance of the observer from the chart determines the size of the regions of disturbance. The closer he approaches to the chart, the smaller they become. When the regions are small enough, even the smallest letters on the chart become legible.

These facts are intelligible in the light of the opening remarks in this chapter. The ability to observe and recognise the details of any object under view depends on the existence of visible differences between the contiguous areas of the object in respect of brightness or other features, as also a reasonable measure of constancy in time of these differences. The observations set forth above demonstrate that the falling away of visual acuity with diminishing illumination is a consequence of the lack of such constancy. In other words, the perception of light is not continuous but is a fluctuating phenomenon, the magnitude and character of these fluctuations varying with the strength of the illumination and the distance of the observer from the object under view.

That the fluctuations of luminosity of the same nature as those described in Chapter V are the effective cause of the diminishing acuity of vision with decreasing illumination becomes even more clearly evident when we set the test-chart side by side with a simple white screen so that they are illuminated similarly and observed from the same distance. It is then noticed that the parts of the chart in which the letters cannot be recognised exhibit the fluctuations of brightness much in the same manner as the smooth white screen. Further, even in the part of the chart where the letters can be read, local variations of brightness of the same nature and of the same magnitude as in the white screen are noticeable. In every case, the size of the patches of varying luminosity is comparable with the size of the letters which are just on the limit of visibility.

Instead of the Snellen charts, a white card on which rows of letters of different sizes following each other are printed may be used. The card may be held in the hand by the observer and read from the usual distance of distinct vision. We may, for example, have a card with ten rows in each of which all letters of the alphabet appear, the first row being 15 centimetres in length and the last only 3 centimetres long, the types being of correspondingly smaller sizes. In a brightly lit room, all the letters on the card are legible. But as the illumination is progressively reduced, the successive rows of letters commencing from the last go out of sight one after another, until finally even the first row becomes illegible. Simultaneously, it will be noticed that in the blank white spaces on either side of the region occupied by the letters, the card exhibits a fluctuating luminosity, the character of these fluctuations altering progressively as the illumination is reduced.

It is easy to demonstrate that the finer the detail which we wish to observe and recognise by our unaided vision, the stronger should be the illumination of the object under view. If, for example, we endeavour to read a page of ordinary print which has been miniaturised and reduced in size to a third or one-fourth of its normal dimensions, the lines of print on it will be found to be illegible even in a brightly-lighted room. But it is found that such a page when held in bright sunlight can be read easily enough.

Visual Acuity and Brightness Contrast.—The visibility of details in any object viewed by an observer is a consequence of the brightness or the colour of the object being different at different points in his field of view. The greater these differences are, the easier it is to recognise their existence, and it is a familiar experience that the closeness of the observer to the object and an increase in the strength of its illumination are both favourable to such recognition. Here again, we have another illustration of the role played by fluctuations of luminosity in the functioning of our visual perceptions. The effect of these fluctuations on the visibility of detail in the objects under view would evidently be greater, if the contrasts which permit of such visibility are relatively feeble. By increasing the strength of the illumination or by the observer approaching closer to the object, the fluctuations are rendered less effective and the visibility of the detail is thereby improved.

By way of illustrating the foregoing remarks and to reinforce them by actual observations, a Snellen test-chart was specially prepared which was similar to those ordinarily made use of, but the letters, instead of being printed in black type, were filled up by hand using an ordinary graphite pencil. The letters then appear of a grey colour, the contrast between them and the white surface of the card being then much less than that exhibited by letters printed in black on white ground. When a Snellen chart thus prepared is set side by side with one of the usual kind, and the illumination of both is progressively reduced, they display a strikingly different behaviour. The chart with the grey lines becomes totally illegible at a level of illumination at which the black lines on the other chart can all be seen and the letters of the first four or five rows are quite distinctly readable. The fluctuations of luminosity are visible on both charts and their effectiveness in suppressing the visibility of the grey letters is recognisably the result of the low contrast between them and the background on which they have been placed.

Colour and the Acuity of Vision.—A remarkable and highly significant relationship between the ability to perceive colour and the ability to perceive fine detail in a visual field emerges when the observations set out in the preceding paragraphs are made with monochromatic light instead of with ordinary daylight. Such observations demonstrate that, as in the case of white light, so also with monochromatic light, the fluctuations of luminosity in the visual field are effectively the origin of the observed dependence of visual acuity on the strength of the illumination. But they also show that *pari passu* with the fall in visual acuity as the strength of the illumination diminishes, there is a progressive falling off of the colour sensation excited by monochromatic light. The latter effect and its explanation have already been set out in Chapter IV on "The Basic Visual Sensations". But what now emerges is that the perception of colour and visual acuity stand in the closest relationship to each other. As the sensation of colour becomes more pronounced, the acuity of vision is enhanced. *Vice-versa*, when the perception of colour becomes weaker, visual acuity also falls off. Finally, when the colour sensation ceases to be perceived, the visual acuity has also vanished.

An impressive demonstration of the statements made above may be given, using appropriate arrangements of the nature already described. A test-chart containing a series of rows of printed letters of progressively diminishing size is held by the observer in his hand and moved away from an area strongly illuminated by monochromatic light to a region in which the chart is much less strongly lit up. Viewing the chart in these circumstances, it is noticed that the successive rows of letters become illegible, commencing from those of smallest size and followed by those of larger size. Simultaneously, the colour of the illuminated chart exhibits a rapid change, beginning from a rich hue resembling that of the light-source as viewed directly and falling off to a much paler hue and progressively approaching an achromatic sensation. The experiment may be made with monochromatic light of various colours, *viz.*, the yellow light of a sodium vapour-lamp, the green and the blue radiations of mercury-vapour isolated by appropriate colour-filters, and also with the light from a tungsten filament lamp covered by a deep red filter. The rapid weakening of the colour sensation which accompanies the rapid diminution of visual acuity is noticeable in all cases. But the effect is particularly striking as exhibited by the blue-violet λ 4358 radiations of the mercury vapour-lamp.

That the variations of visual acuity with the strength of illumination over its entire range have their origin in the fluctuations of luminosity observed in the field of vision is readily established with the aid of monochromatic light-sources. The fluctuations are then distinctly more conspicuous than those observed with white light and are noticeable even at fairly high levels of intensity. The regions of the spectrum for which the visual acuity is low, including especially the blue, exhibit the fluctuations more conspicuously than those for which the visual acuity is high.

Binocular Vision.—The fluctuations of luminosity on a uniformly illuminated screen are more conspicuous when viewed with only one eye of the observer open (the other being closed), or *vice-versa*. This observation indicates that the fluctuations of luminosity as seen by the retinae of the two eyes are independent and the effect of binocular superposition is therefore to diminish their visibility. In the circumstances, it is not surprising to find that when a test-chart is viewed under reduced illumination, the visibility of the letters is noticeably improved by using both eyes instead of only one or the other.

Scintillating Charts.—Instead of letters of various sizes printed in black on a white background, we may employ charts in which the objects depicted are all similar and are arranged in regular geometric order. We may, for example, use charts exhibiting a pattern of white squares arranged in parallel rows and columns on a black background. It is useful to have a set of such charts in which the squares are of different sizes. They may be viewed by the observer from various distances and illuminated at different levels of brightness, and the visibility of the squares on the different charts may be compared with each other, and some quantitative results may be obtained. Some particularly interesting effects are noticed with the charts containing squares of rather small size, *e.g.*, 5 millimetres, when they are illuminated with the light of a sodium vapour lamp at a fairly low level of brightness and viewed from such a distance that the squares can still be distinguished as separate entities. They are then observed to scintillate, showing large variations in intensity, the patterns of such luminosity moving over the chart from instant to instant. The charts containing the larger squares exhibit in similar circumstances some very curious phenomena, the individual squares changing their shape from instant to instant and showing irregular patterns of light and shade within their respective areas.

Visibility of Fine Detail.—Of particular interest is the question, what is it that sets a limit to the ability of our eyes to perceive fine detail in any object? In considering this question, we have also to take into account the nature of the object. Earlier in this chapter, we have already dealt with some particular cases, *e.g.*, small letters in black type printed on white paper. The observations showed that an adequate strength of illumination is essential for their legibility. A somewhat similar case presents itself when we examine half-tone illustrations printed in black and white. It is the intention that the illustrations should present only gradations of light and shade to the eye of the observer. But when adequately illuminated, *e.g.*, by direct sunlight, the mesh of even the finest half-tone screens is readily visible in the printed illustrations.

A slightly different situation arises when the object under examination is a transparency. We may take the typical example of screens woven with fine metallic wires interlacing each other. Such screens are commercially available and exhibit a remarkable uniformity in the diameters of the wires and in their spacing. Five such screens have been examined by the author, the spacing of the wire-mesh being respectively 0·85 mm., 0·52 mm., 0·26 mm., 0·22 mm. and 0·18 mm. When held at the usual distance of distinct vision and viewed against the bright sky, the two most widely spaced meshes are quite clearly visible. But the visibility is much less with the other three, the last of the series being particularly difficult. In every case, the visibility falls off as the screen is moved further away from the observer, the maximum distance beyond which the visibility vanishes being the greatest for the first of the series and progressively less for the others. It is found also that the visibility depends notably on the illumination of the background against which the mesh is viewed, the minimum necessary increasing as the spacing of the wires is smaller. Even the coarsest mesh of the five ceases to be visible when held at the usual distance of distinct vision, if the background illumination is below a certain limit.

A rather searching test of visual acuity is provided by the "BMC Fine mesh" made by the firm Buckbee Mears of Saint Paul, Minnesota. This is a thin film which exhibits under a magnifying lens a network of dark lines spaced a tenth of a millimetre apart and crossing each other at right angles. For the mesh to be visible to the unaided eye, it is found necessary to hold it against a brilliantly illuminated background.

CHAPTER XI

VISION IN DIM LIGHT

There is an immense disparity between the illumination which reaches the Earth in daytime from the Sun and the light received from various sources in the sky on a clear but moonless night. The former is roughly about a thousand million times brighter than the latter. Between these extremes is the light of the full moon which may be put as roughly half-a-millionth part of the light of the noonday sun. Twilight, the duration of which in the tropics is about an hour, permits of a comfortable transition from the brilliance of sunlight to the dimness of starlight, in other words allows human vision to adjust itself naturally to the enormously reduced intensity. It also permits of a leisurely observation of the changes in the characters of the visual perception of light which accompany this reduction.

Very readily noticeable changes appear in our visual perceptions in dim light; firstly, the very low visual acuity and secondly, the weakness or even total disappearance of the sense of colour. These changes are essentially progressive in their nature, becoming more and more obvious as the level of illumination falls off. In the earlier chapters of this book, it has been shown that such changes are necessary consequences of the corpuscular nature of light. No special hypotheses or assumptions are needed to account for them.

The idea that human vision is of two kinds designated respectively as photopic vision and scotopic vision arose originally as an explanation of the disease or abnormal condition known as night-blindness. It gained strength from the anatomical finding that there are two kinds of structures in the retina, now known familiarly as the rods and the cones which were identified as the visual receptors. It was an easy step to recognise the rods as the receptors for dim light and the cones as the receptors for bright light. A further step was to assume that the rods enable us to perceive light but without colour, whereas the cones enable us to perceive both light and colour.

We shall later in this book have occasion to comment on these and other aspects of the duplicity theory of vision. In the present chapter, we shall confine ourselves to setting out the observational evidence that points to the conclusion that human vision is of one kind only at all levels of illumination.

As has been remarked above, the differences between vision in bright light and vision in dim light are of a progressive nature and it is not possible to set definite limits which would require us to recognise two different categories of perception. This is particularly evident from the studies of visual acuity and its variations described in the preceding chapter. The strength of illumination needed for any particular visual task is determined by the nature of the task. If the task is particularly difficult, brilliant light is needed. If the task is easy, much less illumination is sufficient. Hence, the differences in visual acuity cannot possibly furnish any support for the idea that vision is of two different kinds.

The position is very similar in regard to the perception of colour. We have indeed remarked upon the remarkable parallelism which exists between the variations in visual acuity and in colour perception produced by lowering or raising the level of illumination. Colour is vividly perceived in bright light and it fades away quite gradually as the light becomes feebler. Here again, there is no basis for the assumption that we have two kinds of vision, one in which we have both light and colour and another in which we have light but no colour.

The credence which the duplicity theory of vision obtained is largely based on the supposition that the rods and cones correspond to two different kinds of perception. As against this, we have only to point out that in the foveal region of the retina, the anatomist finds only cones and no rods. Nevertheless, the characteristic differences between vision in bright light and vision in dim light, *viz.*, the lowered visual acuity and the enfeebled perception of colour are very clearly manifested in foveal vision. From this, it may properly be inferred that the rod-cone dualism is altogether irrelevant in this context.

The clearest proof that we are concerned with only one kind of vision at all levels of illumination is forthcoming from a study of the spectrum of white light commencing from ordinary or daylight levels and carried down to the lowest levels of illumination at which it is possible for vision to function. There are indeed noteworthy changes in the observed features of the spectrum as has already been remarked in Chapter VI. But there is a feature common to all levels, namely the role played by the green sector of the spectrum, the limits of which may be put as between 500 millimicrons and 560 millimicrons in wavelength. This sector may properly be described as the principal feature in the spectrum of white light. It is a region in which the luminous efficiency is high. As we pass from bright light to dim light, the parts of the spectrum which are of both greater and lesser wavelengths, *viz.*, the red, orange and yellow on one side and the violet, indigo and blue on the other fall off in their luminous efficiency and ultimately disappear from sight. But the green sector survives even in the dimmest light and is indeed the only part of the spectrum which then functions in vision. It is thereby made evident that a differentiation between photopic and scotopic vision is wholly unjustified.

There are several different techniques which may be adopted to enable us to observe the changes in the spectrum of white light as the level of its brightness is progressively reduced to the minimum. They all yield the same result. We shall describe them in the order of their simplicity, beginning with that which is the least sophisticated and ending up with that which makes use of instruments and artificial light sources.

Observations with Colour-Filters.—The observer takes a seat in a completely darkened room at a distance of about five metres from a white screen which he faces. The light of the sky enters the room and falls on the screen through an aperture covered by an iris diaphragm the diameter of which can be varied over a great range of values from twenty centimetres down to a few millimetres. The screen of which the illumination is thus controlled is viewed by the observer through one or another of a set of suitably chosen colour-filters placed before his eye. The observations are made at a series of levels of brightness commencing from the lowest possible at which the illumination of the screen is so feeble that it remains invisible to the observer until after a prolonged stay by him in complete darkness. The results of the observations are quite different for the different colour-filters and indicate how the luminous efficiency of the spectrum in its various regions alters with the level of the illumination of the screen.

With the illumination of the screen at its lowest level, the difference between the effects observed with colour-filters which transmit the green sector of the spectrum and with those which do not is extremely striking. The screen remains invisible when viewed through filters which transmit only the red or the blue sectors of the spectrum and are opaque to the green sector. Likewise, a colour-filter of gelatine dyed with magenta which transmits both red and blue light freely but cuts out the green appears completely opaque. On the other hand, a yellow filter which cuts out the blue but freely transmits green and the rest of the spectrum appears quite transparent and does not observably diminish the brightness of the screen. The measure of the transparency of a filter to green light is also a measure of the brightness of the screen as seen through it.

What has been stated above represents also what is observed at levels of illumination considerably higher than the lowest. Step by step, however, as the iris diaphragm is opened and more light falls on the screen, the complete extinction of the parts of the spectrum other than the green is replaced by a weak transmission. But at all stages, the green sector continues to exhibit a luminous efficiency far greater than those of the other regions of the spectrum. It is also notably superior to them in respect of the acuity of vision.

The Spectrum of Twilight.—The light of the sky in daytime owes its origin to the scattering or diffusion of the rays of the sun by the atmosphere and the dust or other small particles present in it. As is to be expected in the circumstances, the brightness of skylight depends greatly on the time of the day and on the part of the sky under observation. Skylight is, in general, extremely brilliant in the immediate vicinity of the sun and much weaker in directions remote therefrom. These differences manifest themselves very clearly in the spectrum of skylight as viewed through a pocket spectroscope. Great brilliancy is accompanied by an increase of the visible length of the spectrum at both ends, as also by an increased prominence of the yellow sector. *Per contra*, a readily visible contraction of the spectrum at both ends and a noticeable weakening of the yellow are observed when the skylight is of diminished brightness.

As the sun moves down towards the horizon before it sets, its light has to traverse increasingly greater distances through the atmosphere and is much reduced in its brightness by diffusion. The light of the sky above the observer is much enfeebled as the result. When the sun goes below the horizon, the shadow of the earth moves upwards and only the upper layers of the atmosphere receive the light of the sun directly. Since these layers fall off in density with increasing height, there is a rapid diminution of the strength of skylight. The effect of this can be readily followed by observations of various parts of the sky through a pocket spectroscope. The red, orange and yellow disappear completely from the spectrum, while the colours at the other end are also much enfeebled. But the green survives and continues to be seen until twilight has itself disappeared.

A more satisfactory procedure for the study of the spectrum of twilight will now be described. The observer sits in his room two metres away from a window which faces north or east and is provided with wooden shutters. These shutters when fully open allow a clear view of the sky. But only a vertical slit a few millimetres wide is allowed to remain open between them, while the shutters of all the other windows are closed, thereby making the room completely dark. The observer views the slit through a replica-grating held before his eye, fixing his attention on its first-order diffraction spectrum. Since the spectrum is an image of the slit formed by diffraction, it has the full length of the slit which may be a metre or more. A spectrum of this length is seen running through the field of view from end to end. It thereby becomes possible to study the spectrum as seen both by foveal vision and by peripheral vision over a wide range of visual angles.

The observations are best made when the sky is quite clear and there is no moon, so that when twilight has ended, the sky is as dark as it can be. There is a large progressive fall during this period in the intensity of the light which finds entry through the slit and of the resulting diffraction spectrum. But since the room is completely dark, the sensitivity of the observer's eye to faint light improves greatly during the same period. He therefore finds no difficulty in watching the spectrum and the changes which appear in it until it becomes extremely weak. It is found useful for the observer to have at his disposal three colour-filters, respectively red, blue and yellow, which can be quickly inserted between the eye and the diffraction grating as and when desired and which can also be used for a direct observation of the slit through the filter at intervals during the series of observations.

At the start of the observations, the spectrum presents much the same appearance as in daytime. At the end of the sequence, all that is seen of the spectrum is a long strip of light with no recognisable colour but in the same position as the green sector of the spectrum seen at the beginning. That all other parts of the spectrum have ceased to be observable is readily established with the aid of the red and blue filters. Either of these filters when inserted before the eye (with or without the diffraction-grating) results in a complete cut-off of all visible light. On the other hand, the insertion of the yellow filter which has no sensible absorption in the green sector has no effect. In other words, what is actually visible is only the green of the spectrum.

The technique of study described above has some valuable features. The brilliance of the spectrum produced by the replica-grating and the adequate resolution and dispersion which it provides enables the spectrum to be carefully examined and the entire sequence of changes in colour and luminosity to be followed continuously over a great range of brightness. As these changes have, for the most part, been described earlier in detail using other methods of observation, it is not necessary here to traverse the same ground. The specially noteworthy feature at the lower levels of illumination is the progressive contraction and final disappearance of the short-wave region of the spectrum which normally exhibits the colour sequence of blue, indigo and violet. Another useful feature of the technique is that it enables the spectrum as it manifests itself to the peripheral regions of the retina to be examined over the same extended range of luminosity as foveal vision. No noticeable difference has been observed.

The Faintest Observable Spectrum.—A simple technique has already been described in Chapter VI which enables the spectrum of a source of white light to be viewed at various levels of brightness, ranging from one of great brilliance in which the yellow sector is the dominant feature in the spectrum down to levels at which all other regions of the spectrum appear much enfeebled in comparison with the middle or green sector which is then its most conspicuous part. A few simple modifications of the same technique enable the observations to be carried down to the lowest levels of brightness at which the spectrum itself ceases to be visible. The two modifications necessary are, firstly an arrangement by which the flux of light finding entry into the slit of the spectrograph can be progressively reduced to the extent necessary, and secondly, an arrangement which secures that the observer viewing the spectrum on the ground-glass-screen of the instrument remains in complete darkness so that his vision functions with the maximum sensitivity.

The source of light employed is the same as before, *viz.*, a coiled-coiled tungsten-filament-lamp kept cool by a fan blowing air on it and emitting a brilliant white light. This is placed in an annexe separate from the completely darkened room in which the spectrograph and the observer are located, and at a distance of five metres from the instrument. The collimator is directed towards the source of light and a screen prevents the entry of light into the observing room except through an aperture five centimetres in diameter covered by a ground-glass sheet which diffuses the light forwards. The distance between this sheet and the slit of the spectrograph being four metres, the diffusion results in the flux of light entering the instrument being greatly diminished. A further diminution is effected by an iris-diaphragm which covers the aperture and enables it to be reduced from a maximum diameter of five centimetres down to three millimetres. The slit-width of the spectrometer can also be varied from one millimetre down to a few hundredths of a millimetre.

With these arrangements and a dark hood screening his eyes from stray light, the observer can watch the whole sequences of changes produced by closing down the iris-diaphragm when the slit-width is at a minimum. He then observes that the only part of the spectrum which survives till the last and then passes out of sight is the green sector of the spectrum, the wavelength limits of which can be put as 500 mμ and 560 mμ.

Observations with Mercury Lamps.—A very instructive modification of the arrangements described above is to replace the tungsten-filament lamp by a mercury-vapour lamp enclosed in a bulb of the type which is commercially available. With such a lamp at a distance of five metres from the slit of the collimator and with the slit-width set at a tenth of a millimetre, all the strong lines of the mercury arc appear on the ground-glass screen of the spectrograph and can be viewed through a magnifier. It is noteworthy that the two so-called yellow lines λ 5790 and λ 5770 are recognisably different in their colour, the former being distinctly orange-yellow and the latter distinctly greenish-yellow. When a plate of ground-glass is put in and covers the aperture through which the light of the mercury lamp has to pass before it reaches the spectrograph, there is a great diminution in the brightness of the spectrum. The lines λ 4358 and λ 4046, and the faint continuous spectrum disappear, while the yellow lines λ 5790–5770 become much weaker than the green λ 5461. The weak λ 4916 also ceases to be visible. When the iris-diaphragm covering the aperture is progressively closed down, further changes appear in the spectrum. The yellow lines become fainter and fainter and finally disappear. But the green line λ 5461 continues to be visible as the sole surviving feature of the spectrum till the very end.

Very useful also are the observations made with a mercury-vapour lamp of the same kind but which exhibits a strong continuous spectrum extending over the entire range from the red to the violet and overlying it also the lines of the mercury arc spectrum. With this lamp, the changes in the continuous spectrum can be followed, besides those of the bright lines in the spectrum. The red part of the continuous spectrum as well as its blue part disappear along with the lines λ 4916, λ 4358 and λ 4046 when the ground-glass plate is put in to cover the light of the lamp as it emerges from the aperture before it can reach the spectrograph. What then remains are the two yellow lines λ 5790–5770, the green line λ 5461, and the part of the continuum appearing in the green sector of the spectrum. As the aperture through which the light emerges is progressively closed down, the yellow lines rapidly become weaker and disappear. But the green line λ 5461 and the continuum which accompanies it continue to be visible as the sole surviving parts of the spectrum.

CHAPTER XII

THE NIGHT-SKY

THE spectacle presented to us every clear night of the dome of the sky studded with stars has been the inspiration for the systematic explorations of space with the aid of powerful telescopes which have revealed to science the immensity of the cosmos. What we perceive of the Universe without such instrumental aid is evidently but a small part of the gigantic whole. Nevertheless, the role played by our visual faculties in enabling us to perceive at least what lies nearest to us in the vast expanses of space is of the highest interest and significance. It is clearly worthy of the closest study.

The investigations on vision in dim light described in the preceding chapter suggested to the author that a simple visual examination of the sky at night through various colour-filters might yield results of interest. This has indeed proved to be the case. The very striking fact has emerged from such observations that the night-sky as viewed through a colour-filter which transmits the green part of the spectrum freely does not differ noticeably in its appearance from what is seen without a filter, even though the filter cuts out the rest of the spectrum. *Per contra*, a filter which absorbs the green of the spectrum but freely transmits all the rest obscures the view of the night-sky more or less completely when held by the observer before his eyes. A filter of the first kind is provided by a gelatine film on glass dyed with lissamine green. It cuts out the red, orange and yellow and much weakens the blue in the spectrum. A filter of the second kind is provided by a gelatine film on glass heavily dyed with magenta. This cuts out the green completely but transmits the red and the blue regions of the spectrum. What these observations signify is that at the low levels of illumination presented by the night-sky, the green of the spectrum is the only part of it which has a luminous efficiency of significant magnitude, while the rest of the spectrum is, by comparison, of negligible importance.

It follows from what has been stated that the light received at ground level from the night-sky and which illuminates the landscape would exhibit the same characteristics, in other words, that the only significant part of it is that comprised in the green sector of the spectrum. This inference is confirmed by viewing the landscape in such circumstances through various colour-filters. We may describe the situation in the following manner. If an observer is walking along a path having only the dim light from the star-studded sky to guide his footsteps, he would have no difficulty whatever in keeping to the path if he wears green or yellow spectacles. But if he wears glasses of any colour, such as red or blue which excludes the green part of the spectrum, he would find himself walking in darkness. Such an experience would help him to realise that vision in bright light and in dim light are not essentially of a different nature.

The light of the night-sky belongs to two distinct categories, namely that derived respectively from terrestrial and extra-terrestrial sources. To the latter class belong the individual stars which are perceived by an observer as points of light, ranging in brightness from the most luminous to those which are so faint as to be barely visible. We have also light from the immense numbers of stars present in the Galaxy which the eye is unable to perceive as individual sources of light but which are revealed by the diffuse luminosity of the sky which they produce. The familiar manifestation known as the Milky way is the most conspicuous exhibition of the luminosity thus arising, and can be seen as a great belt running round the sky. The zodiacal light which is conspicuous in certain regions of the sky and at certain times also makes an important contribution to the light of the night-sky. Amongst the sources of terrestrial origin, should be mentioned the phenomenon known as the air-glow. Much more disturbing is the atmospheric diffusion arising from the illumination of towns and cities at night by electric lights. This is indeed so disturbing that the author found it necessary to move out of Bangalore to various places ten or twenty or thirty miles away to make a critical study of the features of the night-sky.

An observer holding a colour-filter before his eyes can readily note the difference which the filter makes to the appearance or the visibility of particular features in the night-sky. Such observations make it evident that even the brightest stars are very weak in comparison with the artificial light-sources with which we are familiar. Whereas even distant street-lights can be seen through a filter of red glass and exhibit the vivid colour to be expected, the effect of its interposition before the eye is a blackout of the night-sky, a blackout which extends even to the brightest stars, if the filter transmits only the extreme red end of the spectrum. Filters of red glass of which the cut-off is at 600 millimicrons permit some of the brighter stars to be seen through them, but the night-sky is for the most part excluded from vision.

Sheets of blue glass of the kind used as window panes are commercially available. They freely transmit light of wavelengths less than 480 millimicrons and exhibit strong absorption bands in the yellow and red sectors of the spectrum. But the absorption of the green sector by such a plate is far from being complete. But by holding four such plates together, it is possible to extinguish the green completely without greatly weakening the blue part of the spectrum. When held before the eye, the combination of four plates results in a blackout of the night-sky, only a few of the brightest stars remaining visible. Observing the sky successively through one, two, three and four plates, it becomes evident that it is the partial transmission of the green in each case which enables the fainter stars to be seen, the blue of the spectrum contributing but little to their visibility. It may be remarked that a red star, *e.g.*, Betelgeuse goes out of sight earlier in the sequence than other bright stars such as Sirius and Rigel.

A colour-filter which is of a pale yellow hue by transmitted light and completely cuts out all wavelengths less than 480 millimicrons when held before the eye of an observer viewing the night-sky appears both colourless and quite transparent. In other words, the extinction by it of the blue part of the spectrum is without effect on the observed luminosity of the objects seen through it. But a glass filter of a deeper yellow colour which has a cut-off at 510 millimicrons is distinctly inferior to it in respect of transparency. A filter of orange hue which has a cut-off at 540 millimicrons results in a drastic reduction of luminosity when the night-sky is viewed through it. As these two filters absorb appreciable fractions of the green sector of the spectrum, their behaviour is in accord with expectation.

The sheets of green glass which are commercially available are not completely transparent to the green sector of the spectrum and this reveals itself when the night-sky is viewed through a sheet of such glass. Greatly superior to it in this respect are filters of gelatine dyed green by appropriate dye-stuffs. For example, a filter prepared with lissamine green which is completely opaque to the yellow, orange and red sectors of the spectrum nevertheless appears both colourless and transparent when the night-sky is viewed through it. Very similar is the behaviour of gelatine filters which appear of a blue-green colour by transmitted light in daytime and which, while completely excluding the red, orange and yellow sectors of the spectrum, freely transmit the green and blue sectors. Such filters may be readily prepared by staining gelatine films with an appropriate dye-stuff, *e.g.*, cyanin or disulphine blue. Held against the night-sky, these filters appear both colourless and transparent.

The Spectrum of the Night-Sky.—A very convenient arrangement for visual study of the spectrum of skylight is for an observer to take his seat on the floor beneath the dome of an observatory of which the shutters are nearly but not completely closed, leaving a narrow slit a few centimetres in width open between them. The slit extends from the zenith up to the foot of the dome, thus covering a wide range of visual angles. Holding a replica grating before his eye, the observer views the slit, fixing his attention on one of the two first-order diffraction spectra which appear projected on the interior surface of the dome, running parallel to the slit through which the light of sky finds entry, the spectra appearing respectively on the two sides of the slit. The dome can, of course, be turned round to face any desired part of the sky. As the dome and walls of the observatory exclude the admission of light except through the slit, the observer finds himself in practically complete darkness, and this greatly facilitates his study of the spectrum. The arrangement can be used for observations of the spectrum of skylight during the twilight hours or at night after the cessation of twilight. In the latter case, the light finding entry through the slit is very dim provided there is no moon and the sky is clear. But the observer being then in total darkness, his eyes are very sensitive to faint light, and there is no difficulty in viewing the spectrum and taking note of its characteristics. It does not exhibit an observable colour and appears as a strip of light much narrower than the spectrum of skylight as seen before or immediately after sunset. This is to be expected since only the green sector of the spectrum is perceived in these circumstances. The absence of the other parts of the spectrum can be readily checked with the aid of colour-filters which transmit red or blue light. When such a filter is inserted between the diffraction grating and the observer's eye, the diffracted image of the slit in the dome is totally extinguished.

On clear moonless nights, when a particularly bright star can be glimpsed through the slit, its individual spectrum can be seen as a bright streak of colour running across the strip of light which is the diffracted image of the slit as seen by the observer. But the streak does not, as a rule, extend visibly beyond the green of the spectrum. Fainter streaks can occasionally be glimpsed which represent the spectra of individual stars. Indeed, at least in theory, the entire diffracted image of the slit is made up of the spectra of the individual stars of which the light reaches the eye of the observer with his grating. But in practice, these are either too faint to be perceived individually or else are lost in the spectrum of the background illumination.

The effect of the presence of moonlight on the observed spectrum of the night-sky can be readily studied with the same arrangements. The principal effect is an increased brightness, such increase being dependent on the phase of the moon and on the particular part of the sky under observation. When the moon is at least half-full, the added luminosity due to scattered moonlight has a perceptible effect on the character of the spectrum of the night-sky. No colour is observed, but the width of the strip of light seen as the spectrum is noticeably enhanced, and its extinction by the introduction of a red or a blue filter before the diffraction grating ceases to be total, especially in the case of the blue filter.

Visibility of the Stars.—The lucid stars, in other words, those which can be perceived by the unaided vision in the most favourable circumstances are a few thousands in number. The very bright stars are relatively few and those which are less bright become progressively more numerous as they go down in the scale of luminosity. Using a pair of binoculars of which the objectives have an aperture of five centimetres each, the number of stars which are visible shows a great increase. The brilliancy of the stars which can be seen without optical aid is also greatly enhanced. From these facts of observation, we may infer that the factor which limits the visibility of stars to a relatively few is their low luminosity. In other words, the vast majority of the stars are not seen by reason of the fact that the light they emit and which reaches us is far too weak to excite a persistent sensation.

A convincing demonstration of the correctness of the foregoing inference is furnished by observations of the night-sky through a pair of polaroid sheets of adequate size (at least ten centimetres square) mounted in circular frames so that they can be held covering both the eyes of the observer and rotated with respect to each other. A protractor with an index attached to the frames enables the angle of setting of the polaroids with respect to each other to be read off at a glance. When the polaroids are in a parallel setting, the brightness of the transmitted light is the maximum: as the setting is altered, the transmission progressively diminishes and becomes zero when the polaroids are in the crossed position. In the parallel setting, the well-known constellations of bright stars, *e.g.*, Canis Major, Orion and Ursa Major, can be seen and present their usual appearance. But as the setting is altered, the stars pass out of sight in succession, the fainter ones first, followed by the others and finally also by the brightest stars. During this operation, the constellation becomes unrecognisable and finally disappears altogether.

There is a finite range of settings, one on either side of the crossed position, within which each star remains invisible. This range is greatest for the fainter stars, and smallest but nevertheless finite and measurable for the bright stars such as Sirius, Rigel and Betelgeuse. The range of settings within which a star remains out of sight is an inverse measure of its brightness. It is worthy of note that the background illumination of the sky does not stand in the way of making the observations. For, the background is reduced in its brightness in the same ratio as the star under observation when the polaroids are rotated with respect to each other.

Fluctuations of Starlight.—The corpuscular nature of light necessarily plays a highly important role in our visual perception of the stars. It is obvious that it would not be possible to perceive a star steadily as a point-source of light unless the stream of light-corpuscles reaching the particular spot on the retina is continuous and of sufficient strength. Failing this, we can only expect to perceive the star by fits and starts; in other words, it would present a fluctuating luminosity. Such an effect would be exhibited most clearly by the fainter stars and would be less and less evident as the star goes up in the scale of luminosity. It should be remarked that the fluctuations in the luminosity of the stars referred to here are altogether different in their characteristic features from the well-known phenomenon of the scintillation of the stars. The latter phenomenon has its origin in the local variations of the refractivity of the earth's atmosphere. The brighter stars exhibit that effect to the same extent as the feebler ones and it may indeed be more readily noticeable with the brighter stars than with the fainter ones. The scintillations of atmospheric origin would naturally depend greatly in their frequency and magnitude on the condition of the atmosphere, and in particular circumstances they may be extremely rapid. Further, the position of the star, *viz.*, whether it is nearer the horizon or the zenith is found to have a noteworthy influence. In all these respects, the fluctuations of starlight with which we are here concerned differ from the familiar phenomenon of the twinkling of the stars. Hence, the attentive observer can easily distinguish between them and recognise the nature of the effects which are noticed by him.

Actually, there is no difficulty whatever in perceiving and recognising the fluctuations in brightness of the fainter stars which arise by reason of their low luminosity taken in conjunction with the corpuscular nature of light. Observations of it are best made with stars which are high up in the sky and on clear calm nights when the brighter stars in that vicinity do not exhibit the variations in luminosity of atmospheric origin in a conspicuous manner. The fluctuating brightness of the fainter stars is most clearly evident when two or more faint stars which are fairly close together are viewed by the observer and their relative luminosities are kept under constant comparison. It will be found that these are constantly changing. A very convenient set of stars for such observations is the well-known star-group Pleiades. But there are many other star-groups which can serve just as well.

The Milky Way.—The stars perceived by our unaided vision all belong to the Galaxy in which our Sun is but one amongst a vast number of such luminaries. We perceive a star as an individual speck of light in the sky by reason of its luminosity being sufficiently great and its distance from us sufficiently small to ensure that the luminous flux from it entering the pupil of the observer's eye and reaching the retina is sufficient to give rise to a persistent sensation. The stars which satisfy this condition are an exceedingly small fraction of the great number constituting the Galaxy. It might seem at first sight that these circumstances would result in the existence of the Galaxy for ever remaining outside the field of direct visual perception. There are however certain circumstances which lead us to modify this conclusion.

We have, in the first place, to take note of the characteristics of human vision at low levels of illumination. These are very well illustrated by holding a wire-mesh at the distance of distinct vision and viewing it against a bright background of which the illumination can be progressively reduced. When the illumination is adequate, the apertures in the mesh through which light can pass are perceived well-defined and clearly separated from each other. As the illumination is progressively reduced, a stage is reached when the individual apertures cease to be visible and the entire mesh appears as a uniform field of illumination, but exhibiting noticeable fluctuations in brightness over its area. The latter phenomenon becomes more and more conspicuous as the illumination is further lowered.

What has been stated above is entirely relevant to the visual perception of the field of stars appearing in the sky at night. The brighter stars may be perceived as individual points of light. But the great majority are much too feeble to be thus perceived. In these circumstances, the physiological characteristics of vision result in the field under observation appearing as an area of continuous illumination which however exhibits recognisable fluctuations of luminosity. The general illumination of the sky on a clear night, apa from disturbances of terrestrial origin mentioned earlier, evidently arises in this manner. Its brightness would naturally depend on the density of the stars in the part of the field under observation. The vast majority of the stars in the Galaxy are, owing to their great distances from us, of extremely low luminosities. But this is set off by the great numbers present at such distances. Hence, the luminosity of the sky which they produce is sufficient to be readily observable. That this luminosity is particularly conspicuous in certain regions is readily understood from the general form of the Galaxy as a flattened spiral and the position of the Sun at a point considerably removed from its centre.

As is to be expected in view of the extreme feebleness of the light of the Milky way, it is completely blacked out when a filter of red or blue glass is held by the observer before his eyes. *Per contra*, the Milky way is seen with undiminished brightness through any colour-filter which does not sensibly absorb the green sector of the spectrum. The fluctuating character of the light of the Milky way will be evident to an observer who watches it attentively. This results in the shimmering appearance which is its characteristic feature.

CHAPTER XIII

ADAPTATION OF VISION TO DIM LIGHT

In the two preceding chapters, we dealt with the functioning of human vision at low levels of brightness. It emerged that the differences between vision in bright light and in dim light are not of such a nature as to place them in two distinct categories; *per contra*, they have features in common which make it evident that human vision is of one kind only and not of two kinds as has been surmised or believed hitherto. In view, however, of the enormous range of levels of brightness in which our eyes can function, it is not surprising that certain differences in the manner of such functioning are noticeable over this range. These differences have been discussed in considerable detail earlier in the present work.

In the present chapter we shall consider the phenomena which come to notice when there is a sudden transition from bright light to dim light, instead of the slow and progressive change which occurs in the twilight period between day and night. The tasks which the visual mechanism is called upon to perform at high and at low levels of illumination respectively are very different. The stream of radiant energy entering the eye in the latter case is a mere trickle compared with the massive flow in the former. That the physiological mechanism would take time to adjust itself so that it can perform satisfactorily in dim light is only to be expected. This period is usually referred to as that needed for adaptation of vision to the altered level of illumination. The nature of this process clearly needs elucidation.

It is a matter of familiar experience that an observer who has been out-of-doors and enters a dimly-lit room finds at first that he is unable to perceive the objects in the room and has the feeling of being in a dark chamber. Later, his vision improves and there is a progressive increase in the apparent brightness of the walls of the room and of the objects located in it. It is these features which characterise the process of adaptation. A convenient procedure for studying them in detail is to place a screen of white plastic material of suitable size, say a square metre, in a completely darkened room into which, however, skylight enters through an opening of adjustable size and falls upon the screen. The observer takes up a position at a suitable distance from the screen, say five metres, from which he can keep it in view. The opening through which the light finds entry being an iris-diaphragm, the illumination of the screen can be varied at will over a wide range of values.

If the aperture of the iris is set at the minimum and the screen is therefore only feebly illuminated, the observer entering the darkened room from an adjoining room which is brightly lit will at first fail to perceive the screen, and some minutes have to elapse before it becomes visible to him. This period is much prolonged if the observer before entering the darkened room has been out in the open and has exposed his eyes to light of high intensity. *Per contra*, the period is much shortened if the illumination of the screen by the opening in the iris is set at a fairly high level. Indeed, when the iris is fully open and the screen is brightly illuminated, it would become visible to the observer immediately. With the same arrangements, it is possible also for the observer to follow the progressive brightening of the screen during the period of adaptation.

An insight into the nature of the process of adaptation is obtained by placing an ophthalmic test-chart of the usual kind alongside the screen under observation so that they are equally illuminated. This illumination may be such that an observer entering the room from outside can perceive both the screen and the ophthalmic chart at once but at first only feebly. In the course of the next few minutes, both the screen and the chart brighten up. Whereas at the beginning, the letters on the chart are totally indistinguishable, they come into view in a regular sequence, the letters of the larger sizes first and those of smaller sizes later, until when the adaptation is complete, they can all be seen as clearly as could be expected. During the same period, the fluctuations of luminosity noticeable on the screen which at first are highly pronounced later become progressively more subdued. The visual appearance of the screen and of the chart at the various stages of adaptation are thus closely related to each other.

If during the period of adaptation when the screen and the chart have not attained their maximum brightness, the observer who has been viewing them from a distance moves forward and comes quite close to them, a remarkable effect is noticed. The screen suddenly brightens up and the fluctuations of luminosity on it cease to be observable. Simultaneously also, the chart brightens up and all the letters on the chart (including even those of the smallest sizes) become perfectly clear and legible. The increase in visual acuity which occurs when the observer comes close to the chart is extremely rapid and is evidently the effect of the greatly increased brightness of the chart in the same circumstances.

If the illumination of the screen and of the chart are initially at a very low level, they are both invisible to the observer when he first enters the darkened chamber. Several minutes have to elapse before they become visible. The screen when first seen then shows large and very conspicuous fluctuations of luminosity over its area, and the chart also behaves similarly, no trace of the letters printed on it being noticeable. Later, the screen brightens up and the fluctuations of brightness over its area become more subdued. The letters of largest size on the chart also become distinguishable. If the observer comes very close to the screen and the chart, they brighten up and the letters on the chart become suddenly visible in the same manner as previously described.

The foregoing observations make it evident that the two features which are characteristic of the process of visual adaptation, *viz.*, the initial failure to perceive very feeble light and its subsequent perception with a progressively increasing brightness have a common origin and are indeed only different phases of the same phenomenon. The nature of that phenomenon is revealed by the progressive changes in the character of the fluctuations of luminosity visible on the screen and the progressive increase of visual acuity during the period of adaptation. These observations make it evident that the effect of exposure of the eyes to bright light is to diminish the response of the receptors of vision in the retina to an extent determined by the strength of such light and the duration of the exposure. This weakening reduces the ability to perceive light in general and particularly the ability to perceive light of low intensity. In the latter case, the weakening may be such as to make perception of feeble light impossible. Given time, however, the receptors recover from this state which may be described as one of nervous fatigue. They are then ready once again to function.

During the period of adaptation, the usual photometric relationships are departed from. In other words, the apparent luminosity of an object may differ greatly from that to be expected from its actual illumination. A rather surprising example of this arises when two screens of the same material but greatly differing in their sizes are set side by side so that they are equally illuminated. The observer viewing them from some distance will find that the smaller screen appears distinctly less bright than the larger one. Another example of such an anomaly has already been mentioned above; this is the remarkable increase in the apparent brightness of an illuminated screen during the period of adaptation noticed by an observer who comes very close to it. Such an increase is not to be expected and is indeed not observed in ordinary circumstances.

Observations with Monochromatic Light.—In the foregoing paragraphs, we have dealt with observations on the adaptation of vision to dim light, without concerning ourselves with the spectral characters, either of the bright light which determines the nature and duration of the process of adaptation or of the dim light which is sought to be perceived. It is evident, however, that these aspects require consideration, both in view of the theoretical interest of the subject, as also in view of its practical applications. In earlier chapters, studies on the luminous efficiency of the spectrum at different levels of illumination have been set out and it has been noticed that whereas at the highest levels, the yellow sector of the spectrum takes the leading position, this is no longer the case at the medium and lower levels. At these latter levels, the parts of the spectrum appearing both at the long-wave and the short-wave ends progressively diminish in importance. The red, orange and yellow sectors diminish in luminous efficiency and then fall out completely. Likewise, the regions which normally exhibit the colours of violet, indigo and blue lose their luminosity in the order stated and finally go out of the spectrum. At the lowest levels of illumination, therefore, we are only concerned with the green sector. The question then arises whether exposure of the eyes to bright light appearing elsewhere than in the green sector of the spectrum would have any effect on the subsequent visibility of dim light. We have also to consider the relative efficiency of bright light in different parts of the spectrum in delaying the perception of faint light.

We shall first consider the influence of monochromatic light of high intensity on the visibility of dim light. Sources which are particularly suitable for such a study are a sodium-vapour lamp and a mercury-vapour lamp respectively, as they are commercially available with high candle-powers. The yellow light of a sodium-vapour lamp is sufficiently monochromatic and needs no filtration. Four plates of blue window-glass held together suffice to isolate the λ 4358 light of the mercury-vapour lamp from the other radiations accompanying it. A sheet of ground-glass held near the source is helpful as it diffuses the light which is viewed by the observer from a comfortable distance. The observations begin after allowing a sufficient period for complete dark-adaptation before the light of high intensity is switched on.

It is switched off after an interval of say ten minutes. The observer thus turns towards a faintly illuminated screen which was clearly visible to him before the monochromatic light was switched on. The effect of exposure to this bright light on the visibility of the dimly lit screen then becomes apparent.

Observations with monochromatic yellow and blue light made in the manner described establish that these radiations have an effect of the same nature as that of exposure to bright daylight on the ability subsequently to perceive dim light. The process of adaptation to dim light shows the same sequence of phenomena in all these cases. Since the λ 5890 and λ 4358 radiations both lie outside the spectral range accessible to observation at the lowest levels of illumination, their ability to suppress or delay the perception of dim light is significant. It indicates that the effect of exposure to bright light on dim light vision is manifested even if the bright light does not lie within the wavelength range which is effective for perception at the lowest levels of illumination. This strongly supports the suggestion made above that the phenomenon of adaptation is to be interpreted as a recovery from a state of nervous fatigue produced by continued exposure to bright light.

Instead of monochromatic light, we may employ the white light emitted by a tungsten-filament lamp of high candle-power, *viz.*, 1500 watts. A sheet of ground-glass which is one foot square and held at some distance from this source diffuses the light of the luminous filament. The observations are made in a completely darkened room by an observer whose vision has been fully dark-adapted in the first instance. He views the illuminated sheet of ground-glass through a pair of goggles which transmit only limited regions of the spectrum and accordingly exhibit the colours to be expected, *viz.*, red, green or blue. The time of exposure to the bright light is the same in every case, *viz.*, five minutes or ten minutes. Immediately after the light is switched off, the observer removes the goggles and turns his eyes towards a dimly-illuminated white screen which was clearly visible to him in the first instance. It is found in every case that the screen is not visible at first, but later comes into view and progressively brightens up till it reaches its full original brightness. This effect is most conspicuous, in other words, the time taken is longest, in the case of the green goggles. It is observed also with the red and the blue goggles, but is much less striking in their cases.

Localisation in the Retina.—A remarkable effect came under notice in the course of the studies set forth above. The illuminated sheet of ground-glass one foot square made use of in the studies and viewed steadily from a distance of two feet does not, of course, cover the whole field of vision of the eyes of the observer. When the bright light is switched off and the observer turns his eyes directly towards the dimly-lit screen, it falls within the field of view in the retina influenced by such exposure. It is not perceived in the first instance but later during the period of adaptation becomes visible with much reduced brightness. On the other hand, the dimly-illuminated screen as seen by averted vision is imaged on a part of the retina not previously exposed to bright light and it is visible immediately with its normal brightness. This difference in brightness of the screen as seen by averted and by direct vision however progressively diminishes during the period of adaptation and finally disappears. From these observations, it is evident that the effect of the incidence of bright light is limited to the regions of the retina exposed to it and that it does not extend over the rest of the retina. In other words, the effect is localised in the exposed regions.

The ability to perceive and locate the position of faintly luminous objects in a dark background is of great practical importance in certain circumstances, as for example, in the navigation of ships and in the operations of military aircraft. The maximum of sensitivity to dim light is then essential, and to secure this, the observer has to protect his vision from the effects of exposure to bright light. It may be remarked that these effects are particularly strong and of great duration if a source of light of high intrinsic intensity and of small angular extension is directly viewed for any appreciable interval of time. On the other hand, even brightly illuminated objects which are seen by the light which they diffuse and which cover extended areas in the field of vision produce effects which are, in comparison, negligible even after prolonged exposures. This is readily established by observational studies. The protection of the eyes from the effects of bright light by wearing coloured spectacles is a measure often adopted in practice. Since green light is found to produce the largest effects, filters which exclude this region of the spectrum but transmit the rest freely should be the most useful.

CHAPTER XIV

THE CHROMATIC RESPONSES OF THE RETINA

THE technique for the observation of the living retina described in Chapter III yields highly interesting and significant results, despite its extreme simplicity. As already set out in detail in that chapter, the observer seated at some little distance from a brilliantly lit white screen views it steadily for a few minutes through a selected colour-filter and then suddenly withdraws the filter, while continuing to view the screen with his attention fixed at some particular point on it. He then sees on the screen a picture which is a highly enlarged projection of his own retina, exhibiting colours dependent on the particular colour-filter which was employed. The picture is fugitive but can be restored and kept under view by the observer, merely by putting back the colour-filter before his eye and then suddenly removing it, again and again as often as desired.

Though colour-filters of gelatine on glass prepared with selected dye-stuffs are particularly well-suited for these studies, useful observations can also be made using such filters as are commonly available, *e.g.*, plates or disks of coloured glass. We shall now briefly describe the effects observed in these cases. With a disk of yellow glass which cuts off the whole of the blue sector of the spectrum while freely transmitting all greater wavelengths, one finds on withdrawing the filter that the whole of the screen appears covered by a blue glow. The centre of the screen at which the observer has fixed his vision and where the projection of the fovea of his retina is located does not however exhibit this glow. It appears as a round disk with a sharply-defined edge and of a pale yellowish colour with a dark spot at the centre. The blue glow appears to be of uniform brightness over the whole of the screen under observation. When the observations are made with a filter of orange hue which cuts out wavelengths less than 540 mμ while all greater wavelengths are transmitted, the effects observed are very similar to those noticed with the yellow filter, except that the glow of the screen is more brilliant and is bluish-white in colour and not blue. With a filter of red glass which transmits only wavelengths greater than 600 mμ the observer notices on removing the filter that a round yellow spot appears on the screen where his vision had been directed. Elsewhere on the screen, a brilliant but short-lived glow is noticeable exhibiting a slightly bluish tint.

A beautiful effect is noticed when the observations are made with a plate of green glass which transmits light freely in the wavelength range between 500 mμ and 570 mμ, but cuts out both longer and shorter wavelengths. When such a plate is held before the eye for a minute or so and then removed, the region of the fovea appears on the screen as a disk of orange-yellow colour, while the rest of the screen exhibits a brilliant rose-red hue. The colour and the intensity of this hue as seen in the marginal parts of the screen and as seen in the area immediately surrounding the foveal spot differ very noticeably. The margins are of a deeper hue but less luminous than the regions near the centre. When the observations are made with a plate of blue glass as the colour-filter, the foveal region appears as a disk of indefinite hue surrounded by a brighter field of a pale yellow colour. A bright spot can be seen at the centre of the fovea. Surrounding it a radial fibrous structure is visible bounded by a well-defined outer margin.

Filters of Crystal Violet.—Quite spectacular effects are observed when gelatine films on glass dyed with *crystal violet* are employed for these studies. It is worthwhile making a set of five such filters dyed to various depths of colour, the lightest being a pale blue and the deepest a dark purplish-blue. Spectroscopic examination shows that the absorption by the dye exhibits two distinct bands, one which is fainter appearing in the green from 540 mμ to 570 mμ and the other which is deeper in the orange-yellow from 590 mμ to 620 mμ. In the most heavily dyed filter, these bands spread out, their overlap resulting in a cut-off extending from 530 mμ to 640 mμ, while the rest of the spectrum is freely transmitted. With the most heavily dyed filter, the observer notices on its removal, a brilliant disk of green colour at the centre of the field with a bright spot at its centre and a radial structure surrounding the bright spot. Outside it, the observer also notices an extended area of circular shape of which the diameter is some five times greater than that of the foveal disk. The colour of this area is a greenish-yellow and its luminosity is much less than that of the central disk. Beyond this circular area and surrounding it is a region exhibiting an orange-yellow hue. With the less-heavily dyed filters, these effects become progressively less spectacular. In particular, the luminosity of the central bright disk falls off rapidly, practically ceasing to be observable with the palest blue filter.

Cyanin Filters.—A set of six filters were prepared with this well-known dye-stuff, their colours by transmitted light ranging from a deep blue to a light blue. The absorption spectra of the filters showed a regular progression, the deepest filter exhibiting a practically complete extinction of the yellow, orange and red regions in the spectrum, while the lightest filter showed a well-defined absorption band in the wavelength range from 630 mμ to 670 mμ. The visual effects produced and observed with these filters also alter in a progressive fashion. With the filter which exhibits a cut-off extending from the yellow towards greater wavelengths, the observer notices a disk of yellow light with a bright spot at the centre and a bright rim around its margin appearing in the foveal region. Surrounding this and exhibiting a yellow colour, a circular area also manifests itself which has a diameter some three times greater than that of the foveal disk. Outside this again, there is a field of light extending to the outer limits of the screen and exhibiting an orange hue.

Observations with the other five filters show that the yellow foveal disk and the surrounding yellow region become less and less prominent in the series relatively to the outer parts of the field. With the two lightest filters, they can be observed only with some difficulty. On the other hand, the outermost areas continue to be visible and to exhibit colour. This colour shows a perceptible change from an orange to a reddish hue in the sequence.

Filters of Cotton Blue.—This dye-stuff incorporates itself smoothly into gelatine films, making admirably clear filters exhibiting a blue colour of which the depth is determined by the quantity of the dye taken up. Spectroscopic examination shows that the absorption by the dye is strongest in the yellow region of the spectrum, *viz.*, at 580 mμ. The filters are completely transparent to the shorter wavelengths in the spectrum upto about 550 mμ. Beyond the yellow again, there is a sensible absorption which results in the orange and red of the spectrum being much weakened.

When such a filter is held before the eye of the observer who views a brightly-illuminated white screen for a little while and the filter is then removed with the vision fixed at a particular point on the screen, a picture of the observer's retina flashes into view. The most conspicuous feature in the picture is a bright yellow disk which is an enlarged image of the fovea with a bright yellow spot at its centre and a distinctly brighter rim around its margin. Encircling the foveal disk appears an area of circular shape with a fairly well-defined outer margin. This has a diameter some four times greater than that of the foveal disk. The colour of this region is yellow with a slight greenish tinge. The rest of the screen displays a glow of which the yellow hue is readily distinguishable from the colours noticed in the region which it surrounds.

Colour-Filters of Magenta.—A set of three filters were prepared with this well-known dye-stuff. All three showed a strong absorption in the wavelength range from 550 mμ to 580 mμ, accompanied by a weaker and more diffuse absorption in the wavelength range between 500 mμ and 550 mμ, while the rest of the spectrum showed no observable diminution of intensity in its passage through the filter. In effect, the most heavily-dyed filter cuts off the whole of the greeen in the spectrum, while the other two filters were less effective in this respect.

All the three filters behaved similarly when held by the observer before his eye and then quickly removed while he continues to view the illuminated screen with his attention fixed at a particular point in it. The only difference noticeable as between them is that the less strongly-dyed filters have to be held before the eye for a longer interval of time before being removed. Following the removal of the filter, the entire area of the screen exhibits a greenish-yellow glow which vanishes after a few seconds. But it may be instantly restored by putting back the filter and then removing it again. In effect, the observer sees on the screen a projection of his own retina as illuminated by light in the wavelength range between 500 mμ and 580 mμ. This is made evident by the appearance at the centre of the field of a disk which does not exhibit the greenish-yellow glow seen over the rest of the screen and which is differentiated from the surrounding area by its relative feebleness and its pale blue colour.

From the foregoing, it emerges that the effects observed with the magenta filters are strikingly different from those exhibited by the other filters and described in the preceding paragraphs. These differences are clearly attributable to the regions of the spectrum exciting the response of the retina being different. It may be remarked that in the present case, we are concerned exclusively with the response of the retina to light appearing in the green sector of the spectrum.

The Significance of the Results.—Numerous filters prepared with other dye-stuffs and exhibiting different depths of colour have been utilized for these studies. But it is unnecessary to describe the results obtained with them, since the examples dealt with in the foregoing paragraphs are sufficiently representative. The fact which impresses itself on the observer is that in nearly all cases, the picture of the fovea as seen on the screen differs notably both in its intensity and in its colour from the field which surrounds it. In some cases, as for example with the crystal violet filters, the fovea stands out brilliantly against a field of much lower intensity. In other cases, as for example, with the magenta filters, it is so feeble as to be discernible only with difficulty. These facts of observation may be summed up by the statement that the response of the foveal region to light appearing in the wavelength range from 560 mμ to 600 mμ is far greater than its response to other parts of the spectrum and that it also differs notably from that of the retina elsewhere. It is worthy of note that the regions in the retina immediately surrounding the fovea also exhibit a behaviour which differs noticeably from that of the regions further away from it.

CHAPTER XV

THE VISUAL PIGMENTS

THE results of the investigations described in the preceding chapters provide a firm basis for some inferences regarding the nature of the materials which enable the retina to function as a receptor of vision. It may be remarked that the spectrum of white light divides itself naturally into four sectors which may be referred to respectively as the blue sector, the green sector, the yellow sector and the red sector. The wave-length limits of the four sectors may be put respectively as from 400 mμ to 500 mμ, from 500 mμ to 560 mμ, from 560 mμ to 600 mμ and from 600 mμ to 700 mμ. The subdivision of the spectrum into four parts with the wavelength limits assigned to them is based on the observed behaviour of the spectrum in the respective ranges. The red sector of the spectrum is the first to disappear from sight when the level of illumination is lowered sufficiently. Likewise, the blue sector is that which goes out of sight last, leaving the green sector as the one which continues to be visible at very low levels of illumination. The yellow sector is the most luminous of all the sectors at high levels of brightness, but it progressively becomes weaker at lower levels and when the red sector has gone out of sight, it also follows suit.

The Blue Sector.—Evidence from diverse sources enables us definitely to identify the visual pigment which functions in the blue sector of the spectrum as a carotenoid. The carotenoids are pigments of vegetable origin which find their way into human blood through the food products which are consumed. The two pigments of this nature with which we are here concerned are β-carotene of which the chemical formula is $C_{40}H_{56}$ and xanthophyll of which the composition is indicated by the formula $C_{40}H_{56}O_2$. Both of these pigments have elongated molecules terminating in end-groups, each of which contains a closed ring. The chemical relationship between the two compounds is indicated by the fact that xanthophyll is also known as a dihydroxy-α-carotene, the two hydroxyl groups occupying positions in the end-rings which terminate the molecule. The light absorption curves of the two compounds are not quite the same. The curve for a solution of xanthophyll in hexane is reproduced below. It will be seen that the strength of the absorption drops steeply down from a maximum at 475 mμ to a low value at 500 mμ and becomes quite small at still greater wavelengths. At 445 mμ, there is another peak of strong absorption, and still another peak at 420 mμ, while intermediately, there are dips in absorption located at 460 mμ and 430 mμ respectively. The absorption strength falls off rapidly as we proceed from the peak at 420 mμ further towards the ultra-violet.

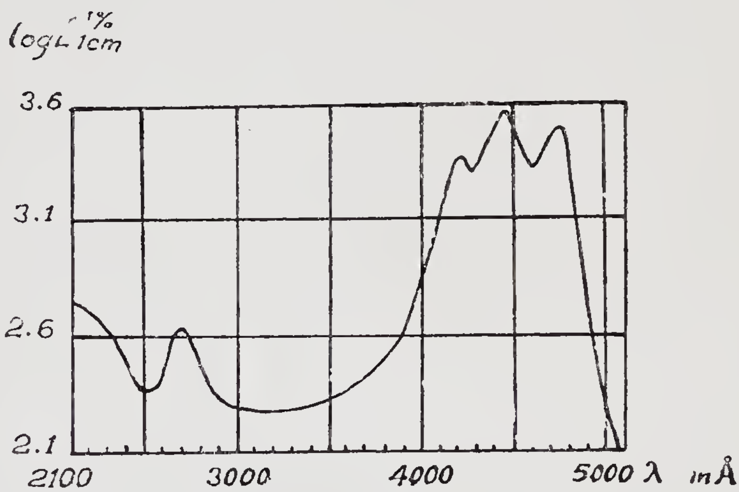


Fig. 7. Light Absorption Curve of Xanthophyll in hexane solution (After Karrer & Jucker)

There is a close correspondence between the features exhibited by the light-absorption curve of xanthophyll and the observed characters of the blue sector in the spectrum of white light. The limits of the blue sector have been indicated as the wavelengths between 400 mμ and 500 mμ. It will be seen from Fig. 7 that this is also the range in which the absorption of xanthophyll is most marked. A noteworthy feature in the spectrum of white light is the very rapid change in colour from blue to green manifesting itself at 490 mμ, a traverse of ten angstroms in wavelength along the spectrum being sufficient for a readily observable difference in colour. This is precisely the location in the spectrum where the curve of light-absorption for xanthophyll drops steeply from a high to a low value. We are therefore justified in regarding the rapid colour change as a consequence of the pigment functioning in the blue becoming less effective and giving place to another pigment functioning in the green.

A further remarkable parallelism is the appearance of bands of higher luminosity in the spectrum which coincide in their respective positions with the absorption maxima of xanthophyll. The observer views the first-order diffraction spectrum of a luminous tungsten filament produced by a grating held before his eye. The bands commence with a noticeable fall in luminosity in the spectrum where the green ends and the blue begins. Following this, a bright band with a maximum of intensity at 470 mμ is readily recognisable. A further drop in luminosity is followed by a recovery and a second maximum of brightness at 435 mμ is noticed. Beyond this again, there is a further drop in intensity followed by a recovery in which the third and last maximum at 410 mμ is discernible. The first maximum at 470 mμ falls in the blue region, the second maximum at 435 mμ in the indigo and the third maximum at 410 mμ appears in the violet.

It may be remarked that these features observed in the spectrum of white light lead us to identify the visual pigment functioning in the blue sector as xanthophyll and not as β-carotene. The reason for this will be evident when we compare Fig. 7 which is the light-absorption curve of xanthophyll with Fig. 8 which is the curve for β-carotene dissolved in hexane. There are some noteworthy differences between the two absorption curves. The absorption by β-carotene extends well beyond 5000 Å into the green and its steepest fall appears at 5000 Å, instead of 4900 Å as in the case of xanthophyll. The third maximum in the case of β-carotene is a relatively inconspicuous dip in a steeply falling part of the curve unlike the well-marked feature noticed with xanthophyll. These features disqualify β-carotene for recognition as the visual pigment functioning in the blue sector of the spectrum.

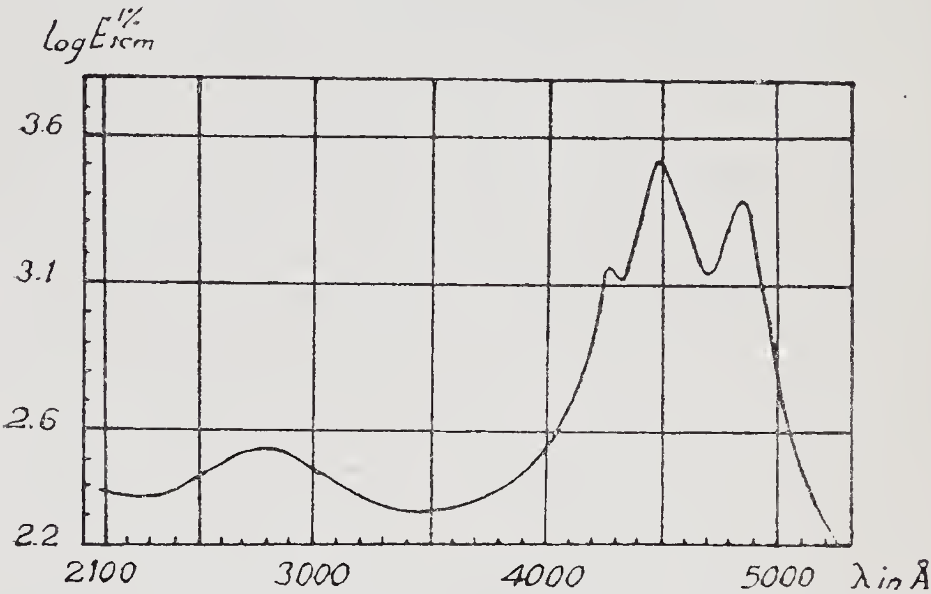


FIG. 8. Light Absorption Curve of β-Carotene in hexane solution (After Karrer & Jucker)

It is scarcely surprising that it is xanthophyll and not β-carotene that plays the role of visual pigment. For, as is well known, xanthophyll is not a precursor of vitamin-A, whereas β-carotene possesses high vitamin-A potency and is known to break up into two equal fragments to form vitamin-A and that this again is a constituent part, along with proteins, of the substance long-known and recognised as the "visual purple" present in the retina. This visual purple is a photo-labile substance, evidently intended as a protective material to prevent damage by light to the delicate tissues in the retina and to maintain them in a healthy state. But the same photo-labile nature disqualifies it from functioning as a visual pigment properly so-called, for which we need a material that is chemically stable and which can pass on the light-energy which it absorbs without itself suffering destruction.

The conclusions arrived at in Chapter IX regarding the perception of polarised light by our eyes may here be briefly recalled. Viewing a brilliantly illuminated surface through a polaroid sheet and a colour-filter which transmits only the blue light of the spectrum, we observe two brushes of light in the field crossing each other, one which is perfectly dark and the other is a bright blue and these brushes rotate in the field when the polaroid is rotated. From the detailed study of this phenomenon, it emerged that it owes its origin to the radial structure of the foveal region in the retina and to the material which enables us to perceive blue light having elongated molecules which orientate themselves along the radii of this structure. This finding is in agreement with the identification of the visual pigment for the blue sector of the spectrum as xanthophyll.

Some General Remarks.—The carotenoid pigments owe their power to absorb light in the visible region of the spectrum to the presence in their molecular structure of a succession of conjugated ethylenic bonds, *e.g.*, eleven such bonds in β-carotene and ten such in xanthophyll. That a yellow pigment is present in the retina is indicated by ophthalmoscopic observations through colour-filters. That this pigment is xanthophyll and that it is the vector of vision in the blue part of the spectrum is established by the facts set forth in the preceding paragraphs. The blue of the spectrum, though colourful, is of low intensity, the visual luminosity at 450 mμ being less than a twentieth part of that observed in the yellow at 580 mμ at the ordinary or daylight level of illumination. This indicates that the carotenoids are of low efficiency as visual pigments and suggests that the visual pigments which function in the more luminous parts of the spectrum are of a different nature. That they are products of human metabolism may be taken for granted. For, it can scarcely be supposed that the functioning of the visual organs which is so fundamental to life would be left solely to depend on materials which adventitiously find their way into the blood stream.

A group of organic compounds exhibiting colour and playing highly important biological roles are known as the pyrrole pigments. Amongst them may be mentioned particularly the chlorophyll present in the green leaves of plants and the colouring matter of red blood. Most pyrrole pigments contain four pyrrole rings linked by four carbon atoms which hold them together in the form of a closed planar ring containing a large number of conjugated double bonds. The porphyrins are compounds of this nature and when dissolved in organic solvents exhibit a typical four-banded absorption spectrum in the visible region. An atom of the metallic element iron can replace the two atoms of hydrogen within the tetrapyrrolic ring, the iron atom being then equally bound to the four nitrogen atoms. Compounds of this nature are known as hematins. These are found widely distributed in the cells of plants, animals and micro-organisms. As examples, may be mentioned the cytochromes which exhibit characteristic absorption spectra in the visible region.

Various considerations suggest that the visual pigments which function in the red, yellow and green sectors of the spectrum and enable us to perceive light in these parts of the spectrum are *heme* pigments, in other words, iron-porphyrin complexes linked to protein. They are compounds of which the absorptive power for light is great and there is good reason to believe that they can function efficiently as visual pigments. No special assumptions are necessary to account for their presence in the retina. For, the bacillary layer which contains the retinal structures functioning as visual receptors is directly in contact with the choreocapillary layer and the choroidal membrane which are highly vascular and are in position to supply these materials. A further important remark is that a *heme*-protein complex can appear in three different forms or states, *viz.*, the ferrous, the oxygenated ferrous and the ferric states, the absorptions by which lie in different parts of the spectrum. The entire visible spectrum other than the blue can thus be covered by these pigments.

The Yellow Sector of the Spectrum.—The absorption of light by the *heme* pigments *in vivo* is readily demonstrated with the aid of a pocket spectroscope. If, through the instrument one views the everted eye-lids or the lips of any person, it will be noticed that an intense dark band obscures the yellow sector in the spectrum and covers the spectral range between 570 mμ and 590 mμ. A fainter band can also be seen in the green region of the spectrum in the vicinity of 540 mμ. The intense absorption in the yellow sector which thus comes into evidence is a characteristic property of the oxygenated form of the *heme* pigments. The presence of material of this nature in the retina would explain not only our ability to perceive yellow light but also various characteristic features of the yellow sector of the spectrum studied and described in earlier chapters. The intensity of the absorption centred at 580 mμ would result in the yellow of the spectrum, in appropriate circumstances exhibiting a high degree of luminosity, indeed higher than any other part of the spectrum. The spectral sharpness of the absorption would also result in a highly developed power of colour discrimination in that part of the spectrum. This has already been demonstrated by the measurements made by two different methods and fully set out in Chapter VIII. At the wavelength of 5800 angstroms, a traverse of 15 angstroms along the spectrum in either direction is sufficient to give rise to an observable change of colour. Thus, the identification of the visual pigment for the yellow sector finds itself confirmed in three different ways: *Firstly*, the precise agreement in the position of its spectral absorption with the location of the yellow sector; *Secondly*, the strength of the absorption which is capable of explaining the observed great luminosity of the yellow sector and *thirdly*, the high power of colour discrimination in this region which is to be expected by reason of the sharpness of the absorption band.

The Red and the Green Sectors.—The recognition that the *heme* pigment in the oxygenated ferrous state enables us to perceive the yellow in the spectrum leads us to assume that the same pigment in the reduced ferrous state and in the ferric state can similarly function respectively in the green and the red sectors of the spectrum. Definite evidence that this is actually the case is forthcoming when we set the spectroscopic behaviour of the pigments of this nature as determined by laboratory studies alongside of the observed features of human vision.

One of the most striking characteristics of human vision is that the extension of the red end of the spectrum depends greatly on the strength of the illumination. At fairly high levels of illumination, the spectrum may extend upto 700 mμ or even beyond. But as the level of brightness is lowered, the spectrum contracts in a readily observable fashion, the limit of visibility falling to 650 mμ very quickly, and then more slowly to 630 mμ. It remains at 630 mμ until a further large drop of luminosity leads to the complete disappearance of the red from the spectrum. From these facts of observation, it may be inferred that the visual pigment functioning in the red sector presents a definite maximum of absorption at the wavelength of 630 mμ and that at greater wavelengths, the absorption drops down steeply to very low values. This is the actually observed spectroscopic behaviour of the *heme* pigment in the ferric state.

A further striking confirmation of this identification is forthcoming from the studies of the power of colour discrimination in the spectrum described in Chapter VIII. It was there shown that results of the measurements indicate a feature analogous to that observed at 580 mμ in the yellow but of a less striking nature in the red at 630 mμ. From the shape of the graph at this wavelength, it may be inferred that a maximum of the absorbing power of the visual pigment is there located.

Laboratory studies of the spectroscopic behaviour of the *heme* pigment in the fully reduced ferrous condition show that it exhibits a powerful absorption in the spectral range between 580 mμ and 520 mμ with a maximum at 555 mμ. The molecular coefficient of extinction of the ferrous form of the pigment at 555 mμ is about four times greater than for the absorption at 630 mμ of the ferric form of the pigment. This great difference helps us to understand why the green sector of the spectrum is much more luminous than the red sector and survives at the low levels of illumination at which the red sector has completely disappeared.

A further remark may be made, *viz.*, that in the wavelength range between 500 mμ and 600 mμ, the effects of all the three forms of the *heme* pigments would be superposed. The observed results would be determined by their relative proportions as well as by their effectiveness at each wavelength in the range under consideration. Why we observe a continuous sequence of colour in the spectrum and not just three sharply divided colour sectors is thereby made intelligible.

CHAPTER XVI

DEFECTIVE COLOUR VISION

It is appropriate that normal and abnormal colour vision are dealt with in chapters which follow one after the other. Being related subjects, the methods adopted for their study are necessarily the same or similar, and the findings have to be considered together in any final assessment.

Earlier in this work, we had to discard the idea that the perception of the colour of yellow light in the spectrum is a secondary or derivative sensation resulting from the superposition of the red and green sensations as primaries. The recognition of spectral yellow as an independent sensation is indeed necessary in any rational approach to the subject of colour. In the preceding chapter, we have seen that the visual pigment which functions in the yellow is different from those functioning in the red and green sectors of the spectrum, though standing in a close chemical relationship to them. Likewise, it is not possible to arrive at any understanding of the nature or origin of defective colour vision unless it is recognised at the outset that the sensation of yellow stands in a category by itself independent of either red or green. Indeed, this becomes clear when Dalton's own statement regarding his personal colour perceptions is recalled. He is quoted as having said that he could only distinguish in the spectrum two hues, *viz.*, yellow and blue, the former being perceived over the entire range of the spectrum in which normal observers perceived the usual succession of red, orange, yellow and green, while he perceived as blue the region which others perceived as blue and violet, though he also recognised the violet appearing as a more saturated blue.

Dalton's description of the spectrum of white light is closely matched by that given by an observer who will be referred to here by the pseudonym of Asoka and who being a qualified man of science could be trusted to describe accurately what he himself saw. Asoka was presented with the spectrum of a very brilliant source of white light appearing on the ground glass screen of a constant-deviation spectrograph, arrangements being made to vary the brightness of the spectrum over a wide range of values. He placed the commencement of a spectrum of moderate or high luminosity at the long-wave end precisely where it is placed by a normal observer. But he described the parts of the spectrum where a normal observer sees red, orange, yellow and green as being yellow in colour. He also placed the point of maximum luminosity in the spectrum at the same position as an observer with normal vision, *viz.*, at 580 $m\mu$. Asoka observed the luminosity to fall off in the region of transition where the colour changes to blue, as is also noticed by a normal observer. The blue of the spectrum was named by him as blue and its termination as placed by him agreed with that noticed by normal observers. The spectrum at a low level of luminosity did not appear to Asoka to exhibit colour, though to a normal observer, the green was clear enough. The long-wave end of the spectrum had shifted to shorter wavelengths, alike to Asoka and to an observer with normal vision. The point of maximum luminosity in the spectrum had also shifted towards shorter wavelengths and to the same extent for Asoka as to a normal observer.

More detailed studies were made by other observers who were also qualified scientific men. We shall here reproduce *verbatim*, what a physicist who will be referred to here as Krishna wrote when he was asked to view the bright sky through a Zeiss pocket spectroscope provided with a wavelength scale in the eye-piece and to record what he saw. "The spectrum appears visible at about 4100 Å where it is violet, and the blue is distinct at 4300 Å and extends to 4750 Å where the transition to green begins. The green is visible from 4750 Å to 5000 Å. The region 5000 Å to 5200 Å is greenish-yellow. The yellow which is what appears as the brightest part of the spectrum extends from 5200 Å to 6000 Å. This is followed by the orange from 6000 Å to 6200 Å, while the red region is covered by 6200 Å to 6750 Å. My estimate of the region of maximum luminosity would be at 5700 Å to 5800 Å."

It will be seen that while Krishna puts the orange and the red where a normal observer would perceive those colours, his yellow extends towards shorter wavelengths and covers the region described by a normal observer as green. It is therefore not surprising that the green and the yellow lines of a mercury-lamp as seen through the spectroscope did not appear to Krishna to be of different colours.

Of particular interest are the observations recorded by a young science student who will be here referred to as Dhruva who was asked to record the colour of the spectrum of a brilliant source of white light, emerging through a slit placed within the eye-piece of a wavelength spectrometer.

Dhruva recorded the colour seen by him from 720 $m\mu$ to 680 $m\mu$ as red, from 680 $m\mu$ to 670 $m\mu$ as orange, from 660 $m\mu$ to 530 $m\mu$ as yellow, from 520 $m\mu$ to 510 $m\mu$ as green, from 500 $m\mu$ to 470 $m\mu$ as blue and from 460 $m\mu$ to 440 $m\mu$ as violet. The enormous range of the spectrum perceived by Dhruva as yellow in colour is noteworthy. A large part of the region described by a normal observer as red was perceived by Dhruva either as orange or as yellow. A large part of the spectrum perceived by a normal observer as green was also perceived by Dhruva as yellow. It is evident that his vision is a closer approximation to the Daltonian type than that of Krishna.

Mention may also be made of the reports made by three other observers. The physicist whom we shall refer to here as Arjuna was aware of the deficiency in his own colour perception, having noticed that the green and the yellow lines of a mercury-lamp as seen through a spectroscope did not appear to him to differ in colour. He described the spectrum of white light as consisting of red and orange regions followed by a bright yellow, light blue, dark blue and violet. At very low levels of illumination, only the region that had appeared yellow continued to be seen, but it then exhibited no colour except at the long-wave end where it appeared as slightly orange.

Another physicist who will be referred to here as Ganesh was asked to map the colours of the spectrum with the aid of a wavelength spectrometer. Commencing at the violet end, he listed the wavelengths at which the colours mentioned made an appearance as follows: violet, 415 mμ; indigo, 421 mμ; blue, 440 mμ; blue-green, 470 mμ; green, 495 mμ; yellow 523 mμ; orange, 620 mμ; red, from 680 mμ upto the limit 750 mμ. It will be noticed that in the colour perceptions of Ganesh, the sensation of yellow appears over the part of the spectrum seen by normal observers as green, yellow and orange, while a large part of the spectrum which appears red to normal observers is perceived by Ganesh as orange in hue.

A science student whom we shall name here as Drona was aware of his defective colour vision since he could not perceive the difference between the green and the yellow lines in the spectrum of the mercury vapour lamp. Viewing the spectrum of a tungsten-filament lamp through a wavelength spectrometer, he reported the following sequence of colours and their respective wavelength ranges, Red from 710 mμ to 630 mμ; Orange from 620 mμ to 610 mμ; Yellow from 600 mμ to 540 mμ; Light Green from 530 mμ to 510 mμ; Green 500 mμ; Bluish-green 495 mμ; Blue 490 mμ to 475 mμ; Intense Blue from 470 mμ to 450 mμ. It is clear from these figures that Drona's colour sensations differ considerably from those recorded by Dhruva and by Ganesh.

The Nature of Defective Colour Vision.—To an observer with normal vision, the spectrum of white light exhibits two regions in which the progression of colour is exceptionally rapid. One of them is at 490 mμ where the perceived colour changes from blue to green. The other is at 580 mμ which is the centre of the yellow sector. Here the alteration of colour with wavelength is so rapid that the two lines of the yellow doublet 5770–5790 angstroms in the mercury spectrum are observably different in hue. In the wavelength range from 580 mμ to 630 mμ, the colour to a normal observer alters rapidly from yellow through orange to red. Beyond 630 mμ, the luminosity falls off and the colour-progression s'ows down.

From the reports of the observers named above, it is clear that the colour-change in the vicinity of 490 mμ is perceived by all of them. But the progression of colour at 580 mμ has disappeared. To all of them, the yellow doublet and the green line of the mercury spectrum appear indistinguishable in colour and the part of the spectrum seen as yellow has extended itself so as to cover the whole or nearly the whole of the range of wavelengths perceived by a normal observer as green in colour. An extension of the yellow region towards greater wavelengths is also evident from the reports of three of the observers, *viz.*, Asoka, Dhruva and Ganesh, what is normally perceived as orange or red being perceived by them as yellow or as orange. But the reports of the other three observers, Krishna, Arjuna and Drona do not indicate such an extension.

The recognition that the yellow of the spectrum is an independent sensation which is distinct in its origins from either the red or the green leads us to a simple and quite natural explanation of the differences between normal and defective colour vision. In the spectrum of white light as seen by an observer with normal vision, there is a considerable overlap of the regions in which green, yellow and red are respectively perceived. That indeed is the reason why the green of the spectrum passes over to the yellow in a continuous fashion, a greenish-yellow being a recognisable stage. Likewise, the progressive change from yellow to red is evident in our perception of orange as a colour different from either. Defective colour vision is then readily explicable as the result of a large increase in the strength of the yellow sensation relatively to the green and the red sensations. The regions of the spectrum in which there is an overlap between yellow and green or between yellow and red would then exhibit altered colours different from those seen by a normal observer.

The green and the yellow of the spectrum of white light appear in closely adjacent regions. The maximum of the green sensation is at about 555 mμ and the maximum of the yellow is at 580 mμ. That there is a large overlap of the green and yellow sensations is clear from the fact that a progressive change of colour between 520 mμ and 560 mμ is noticeable to an observer with normal vision. It is therefore to be expected that a large increase in the strength of the yellow sensation relatively to the green sensation would, in the region of overlap, make it impossible to distinguish colours which to a normal observer appear as green and yellow respectively.

The position is not quite the same with regard to the perception of colours in the red region of the spectrum. The maximum of the yellow at 580 mμ and the maximum of the red at 630 mμ are well separated from each other. The red of the spectrum also extends, though with reduced intensity upto 700 mμ and even beyond. The region of overlap between the yellow and the red which appears orange to a normal observer is in the wavelength range from 600 mμ to 620 mμ. Any large increase in the strength of the yellow sensation would result in the orange being perceived as yellow, and it might also result in the sensation of orange extending further into the red. But the replacement of the red sensation by the perception of yellow over the entire spectrum must be regarded as rather an exceptional case.

It is worthy of remark that there is a fairly close resemblance between the appearance of the spectrum of white light to an observer with defective colour vision and its appearance to an observer with normal vision at very high intensities of illumination. For this purpose, an extremely brilliant source of white light, *e.g.*, a tungsten-filament of the kind used in projection lanterns, may be viewed through a replica grating held in front of the eye. In the first-order spectrum of this source as seen from a great distance, it is possible to distinguish the separate regions in which the blue, green, yellow, orange and red appear. But when the observer moves closer to the source and the spectrum then shortens and becomes much more brilliant, the green, yellow and orange merge into a single band of colour in which the differences between them are barely recognisable.

Likewise, one may expect that the appearance of the spectrum of white light to an observer with defective colour vision would alter at low levels of illumination in such manner as to approach more closely to what is seen by a normal observer. This is found to be actually the case and the explanation given above of the origin of defective colour vision thereby finds impressive support. For this purpose, the spectrum of the light emitted by a long luminous tungsten-filament at various temperatures is viewed through a replica diffraction grating. Two of the observers, *viz.*, Krishna and Arjuna named earlier, were asked independently to make such observations and record by sketches what they saw. Their observations as subsequently compared were substantially in agreement. At low levels of brightness, *viz.*, when the filament emitted a dim red glow, its spectrum presented much the same appearance to them as to an observer with normal colour vision. But as the spectrum brightened up, the yellow sector made an appearance and then spread out, progressively replacing the green sector and to some extent also the red sector, till at high levels of brightness the extent of its spread far exceeded the width of the regions exhibiting other colours on either side of it.

Colours of Interference Patterns.—The colour vision of the observers named above was also examined by other methods besides those set forth in the preceding paragraphs. A particularly interesting and significant technique of ascertaining their perceptions of light and colour was to present interference patterns on a large scale as seen by white light and ask them to record a detailed description of what they saw in the patterns. Not having been subjected to such a test earlier, the observer's statement would be entirely unprejudiced and hence would be of special value. Further, the comparison of their descriptions with the results of the studies of these same patterns made by an observer with normal vision and set forth in Chapter VII above could be expected to be particularly illuminating.

The first of such tests was made with the observer named above as Asoka. He was shown the coloured rings of an interference pattern formed on a large scale and had no difficulty in counting the number of rings visible in it, which he gave as seven. But the rings appeared to him to be yellow in colour and to be separated from each other by darker circles. In the first two or three of these rings he noticed that indications of blue were visible.

Both the circular ring pattern and the straight fringes due to a wedge-shaped air film were studied by the other observers and the features noticed by them were recorded in detail. An intercomparison of the descriptions given by them and of the features in such patterns as seen by a normal observer discloses both the points of agreement and the points of difference to be expected. It will suffice here to mention the descriptions given by Dhruva of the Newtonian ring pattern, as it is typical of the manner in which such a pattern presents itself to an observer whose colour vision approximates to the Daltonian type. Around the central dark spot, there is a broad region exhibiting a light blue colour with an outer yellow fringe. These are surrounded by a dark blue circle which is the most prominent feature in the entire pattern. This is followed by a wide ring of yellow colour which is very prominent by reason of its luminosity. Following this again is a circle with a very distinct blue colour of which the width is slightly less than that of the one previously mentioned. The next ring again is a yellow circle not so distinct as that mentioned earlier. The next ring again is a blue circle of very light colour. Further out, there are other rings in which alternations of colour may be perceived, but they are not distinct and cannot be accurately described.

CHAPTER XVII

THE VISUAL SYNTHESIS OF COLOUR

Colours of varied nature present themselves to us in diverse circumstances. Of particular interest are those cases in which the colour has a physical origin and manifests itself as natural phenomena on a large scale, *viz.*, the blue of the sky, the colours of sunrise and sunset, and the dark blue of oceanic waters. In the biological field, familiar examples are the colours of birds and butterflies and of the foliage and flowers of trees and plants. Man-made products such as textiles and ceramics utilize colour to enhance their attractiveness. The list of artificial products displaying colour includes a variety of dyes, pigments and paints. All such cases have, as a common feature, the fact that the observed colour arises from a superposition of light from different parts of the spectrum reaching the eyes of the observer simultaneously. The observed colour is accordingly in the nature of a composite sensation, as distinguished from the pure colours of the spectrum.

The problem thus presents itself of determining the nature of the relationship between the perceived colour and the spectral characteristics of the light that produces the sensation. The obvious procedures for dealing with this problem are empirical methods which may be divided into two groups, *viz.*, the analytical and the synthetic. The analytical procedure employs the spectroscope to determine the characteristics of the light perceived by the observer and by noting their relationship to the colour in numerous cases seeks to arrive at certain general conclusions. The synthetic procedure makes use of various devices by which selected colours are superposed on each other, and the results of such superposition are observed. The defects of this latter method are obvious. For, thc selection of the colours chosen for the superposition is necessarily arbitrary and the conclusions drawn from such observations are therefore of questionable validity.

Already in an earlier chapter which dealt with the colours exhibited by interference patterns, it has been shown that the study of such patterns yields results which are highly significant for our knowledge of the characteristics of human vision. In a later chapter, it will be shown that the study of the colours of rotatory dispersion likewise yields further results of importance. The special advantage of using such physical methods is that they enable us to study the colours of light of which the spectral composition is precisely known and can be varied at will to cover a diversity of cases. The validity of the conclusions thus arrived at is thereby ensured.

But empirical methods, however useful they might be, cannot enable us to reach a complete understanding of the subject. For that purpose, it is necessary to proceed from first principles and endeavour to ascertain how the visual perceptions of composite light are determined by the physical nature of light and the processes by which the sensations of light from different parts of the spectrum are summed up by the visual mechanism. In following this road to knowledge, we have of necessity to make use of the results obtained and set forth in our earlier chapters regarding the perception of the colours of monochromatic light.

Various considerations indicate that the two parts of the spectrum of which the wavelengths are respectively smaller and greater than 5000 angstroms should be regarded as distinct units in relation to the present subject. The junction between the two parts is a region in the spectrum at which a rapid change of hue is a noteworthy feature. Colour-filters are available which freely transmit one part of the spectrum as thus divided up and cut off the other, or *vice versa*. The colour of the filters having this property as seen by transmitted light is a bright yellow in one case, and a bright blue in the other. The filters are complementary, so that if they are held together, no light passes through the combination. If a white card illuminated by direct sunlight is viewed through the yellow filter, it appears dazzlingly brilliant. But as seen through the blue filter, the card appears bright but by no means exceptionally bright. It thus becomes obvious that there is an enormous difference in the integrated luminosities of the two parts of the spectrum. Nevertheless when they are superposed, the colours are suppressed and we perceive only white light. This, indeed, is one of the most remarkable features of human vision.

In numerous cases, colour results from the selective absorption of particular regions in the spectrum, while the other regions are freely transmitted and appear in the light transmitted through the material. Using substances with these properties which are freely soluble in water and by varying the concentration of a solution of the substance contained in a cell of moderate thickness, an observer can follow the changes in the colour and intensity of the transmitted light and determine how these changes are related to the characters of the spectrum of the transmitted light which is also kept under view. By this simple technique, it is possible to study numerous examples and arrive at some useful results. We shall here refer to some particular cases from which significant conclusions emerge.

Cuprammonium.—Dissolving copper sulphate in distilled water and adding ammonia in excess, we obtain a solution exhibiting a characteristic blue colour. When the concentration of the solution is high, the transmission by it is confined to the region of the shortest wavelengths and indeed, the cuprammonium filter is usually employed for isolating this part of the spectrum. When, however, the solution contained in a cell two centimetres thick is progressively diluted by addition of distilled water, striking changes may be observed in the spectrum of the light transmitted by it. The transmission, which at first is confined to the violet end of the spectrum, extends towards longer wavelengths. It ceases to be confined to the blue region of the spectrum and the green sector is also transmitted. This progressively gains in strength until as seen through the spectroscope, the green actually appears more luminous than the blue sector. With further dilution, the transmission extends into the orange and the red of the spectrum, but the yellow region remains faint, the orange and the red much exceeding it in brightness. Throughout this series of changes, the colour of the transmitted light is perceived as blue. The observations make it evident that the blue colour of the transmitted light and the extinction of the yellow in its spectrum are connected phenomena.

Even when the cuprammonium solution is extremely dilute, the colour of the transmitted light remains blue. The blue sector of the spectrum is present in full strength, while the green sector shows no appreciable weakening. But the strength of the yellow sector is much weakened. The red sector is still quite strong, but the reduction of its intensity is noticeable and a slight contraction is also remarked at the red end of the spectrum. The situation may be summed up by the statement that as the result of the changes noted above, all other colours in the spectrum are suppressed or masked from observation by the blue which alone is the perceived colour.

Chromium Chloride.—Strong solutions of the chloride of chromium exhibit a deep green colour which owes its origin to a transmission band in the 500 mμ–550 mμ region of the spectrum. Holding up a cell containing such a solution against a strong light and examining the light coming through it with a pocket spectroscope, the transmission band in the green is found to be accompanied by another located near the red end of the spectrum. It is the intermediate region containing the yellow of the spectrum which is most strongly absorbed. Dilution by successive additions of distilled water results in a large increase in the brightness of light transmitted by the cell, but the colour remains green. Spectroscopic examination in these circumstances reveals that the band of transmission in the green has broadened in either direction and that the red sector has also made its appearance in the transmitted light. When the dilution has been carried far enough, the red region of the spectrum is quite conspicuous and it is only a little less bright than it is normally. But the yellow sector is much weakened.

It is noteworthy that the colour of dilute solutions of chromium chloride remains green, despite the presence of the red sector with considerable strength and the feeble extension into the blue that is also noticeable. It is to be inferred that as a result of the weakening or extinction of the yellow in the spectrum, the green which is present in full strength succeeds in suppressing or masking from observation all the other colours.

The Purple Sensation.—The dye-stuff bromcresol purple when dissolved in water and highly diluted exhibits a dark band of absorption covering the wavelength range from 570 mμ to 610 mμ, there being no noticeable absorption of either shorter or longer wavelengths. In other words, the red, green and blue sectors of the spectrum are freely transmitted and only the yellow sector of the spectrum is extinguished. The colour of the transmitted light is purple and this is evident even with extremely dilute solutions.

Very dilute solutions of the dye-stuff bromphenol blue exhibit a powerful absorption in the wavelength range from 575 mμ to 610 mμ, while freely transmitting the rest of the spectrum. A cell containing the solution exhibits a purple colour. Stronger solutions exhibit an absorption covering the spectral range from 540 mμ to 620 mμ, and transmit light of a deeper purple colour.

Crystal violet and methyl violet are two other well-known dye-stuffs which exhibit a powerful absorption of the yellow sector of the spectrum besides a relatively weak absorption appearing in the green sector. Very dilute solutions of both of these dyes exhibit a purple colour by transmitted light.

Solutions of Rhodamine.—Spectroscopic examination of the light transmitted through a cell containing this dye-stuff at various stages of dilution and observations of the corresponding changes in the colour of the light which comes through are highly instructive. Weak solutions show an intense absorption covering the wavelength range from 530 mμ to 570 mμ. Increasing the concentration step by step, a stage is reached at which the green sector of the spectrum from 500 mμ to 570 mμ is totally extinguished without any noticeable reduction in brightness of the rest of the spectrum. At this stage, the colour of the transmitted light is a rich rose-red, which we therefore recognise as the true complementary colour to the green. Weaker solutions give a similar colour but of less saturated hue.

When the strength of the solution is further increased, the absorption band extends towards smaller wavelengths, and by successive stages reduces the extension of the blue sector. The colour of the transmitted light then changes progressively from rose-red to a fuller red. The blue of the spectrum, though visible in the spectroscope, is masked or suppressed from observation by the red sector which is present in full strength.

We may sum up the results which emerge from the foregoing studies. As will be seen in later chapters of the book, they are in full agreement with what is observed in numerous other cases. The highly important role in vision played by the yellow sector of the spectrum has already been remarked upon in earlier chapters. It now emerges that this region of the spectrum practically controls our perceptions of the colours of composite light, its presence or absence making all the difference to the sensory impression which is produced. A particularly interesting case is that in which the yellow sector is absent, while the red, green and blue sectors are present in their normal strength. The composite sensation is then the well-known and easily recognised purple colour.

Another important finding is the colour which is complementary to the green of the spectrum, in other words, the composite sensation which results from a superposition of the red, yellow and blue sectors in the spectrum of white light. This is both accurately and suitably described as rose-red, for the reason that the petals of many varieties of roses exhibit the colour, the origin of which is an absorption of the green sector of the spectrum by their petals; the more complete is such absorption, the deeper is the colour observed.

The masking of colours from perception by other colours which are present in strength is another phenomenon of great interest which comes into evidence in the cases dealt with in the foregoing paragraphs. We shall meet with numerous other cases of the kind in later chapters. The visual processes which result in such masking will also be considered in due course.

CHAPTER XVIII

THE SUPERPOSITION OF SPECTRAL COLOURS

LIGHT which is not monochromatic but appears simultaneously in different parts of the spectrum is perceived by our eyes. What is the nature of the visual process which sums up the effects of the different spectral components and what is the final result? These issues are obviously of a fundamental nature and they will be dealt with in the present chapter. We shall in the first place indicate the theoretical approach made to the subject and deduce certain observable consequences. We shall then proceed to describe the techniques of study which enable these consequences to be tested experimentally. The results are found completely to confirm the theoretical expectations.

The perceptions of light and colour are the result of certain processes in which the retinae of our eyes play the leading role. The picture of these processes which has emerged from the studies described in the preceding chapters of this book is that we are concerned with certain pigmentary substances present in the retina which absorb the energy of the incident light and thereby enable it to be perceived. Four such substances have been recognised. One of them is a carotenoid pigment which functions in the wavelength range extending from the extreme violet end of the spectrum upto the boundary between the blue and the green sectors which may be placed at 5000 angstroms. The three others are hemeprotein complexes which are of the same chemical nature but are in three different states of oxidation. These enable us to perceive respectively the green, yellow and red sectors of the spectrum. That the absorption spectra of these pigments overlap is evident from the fact that we observe a continuous sequence of colour in which intermediate colours between green and yellow and between yellow and red are readily recognisable. Within the wavelength range between

5000 angstroms and the extreme red end of the spectrum, monochromatic light is perceived with a colour which varies with its position in the spectrum and is determinable with considerable precision. Such precision is highest in the wavelength range around 5800 angstroms which is the centre of the yellow region in the spectrum.

We shall first consider the simple cases in which the incident light contains only two monochromatic components. Here again, we have to distinguish between different possibilities. Both spectral components may fall within the spectral range in which *only* the carotenoid pigment functions or *only* the *heme* pigments. The third case is that in which one spectral component is perceived with the aid of the carotenoid pigment and the other through the agency of the *heme* pigments. It is clear that this third case is on a different footing from the other two.

The carotenoid pigment consists of long-chain molecules the absorption spectrum of which exhibits three well-defined maxima of which the position varies a little with the solvent employed. For the particular case in which the solvent is ethanol, they have been located at 476 mμ, 446·5 mμ and 420 mμ respectively, the three peaks together covering the wavelength range between 500 mμ and 400 mμ in which the absorption is most conspicuous. The wave-number differences between the absorption peaks are of the same order of magnitude as the vibrational frequencies associated with the ethylenic bonds present in the molecule. We are therefore justified in assuming that the absorption spectrum represents the result of a combination of an electronic transition with vibrational transitions. Whether this be the case or not, it is clear from the form of the absorption curve that the molecule can exist in different energy states between which transitions can occur. It accordingly becomes necessary to consider such transitions as a possible part of the process occurring in the retina.

If ν_1 and ν_2 be the frequencies of the light incident on the retina, the corpuscular energies are given by $h\nu_1$ and

$h\nu_2$ respectively. We shall assume that ν_1 and ν_2 correspond to wavelengths both greater than or both less than 5000 angstroms. Not all the corpuscles of these energies incident on the retina would be absorbed and contribute to the perception of light. If the numbers which are actually so effective are in the proportion of N_1 to N_2 during any small interval of time, the total energy available in that interval would be $N_1 h\nu_1 + N_2 h\nu_2$. If N_1 is large compared with N_2, there would clearly arise the possibility that only the more intense component would be perceived and that the weaker component would be masked or suppressed. But if N_1 and N_2 are comparable with each other, the sensory mechanism would find it possible to perceive both the spectral components but not separately. It would perceive the mixture as monochromatic light of frequency equal to

$$(N_1 h\nu_1 + N_2 h\nu_2)/(N_1 + N_2)\, h$$

in other words, as light having a frequency which is the weighted average of the frequencies of the individual components.

We shall next consider the cases in which one of two spectral components has a wavelength less and the other a wavelength greater than 5000 angstroms. As a consequence, both kinds of visual pigment function. Here, again, there is the possibility that one of the two spectral components in the light may mask the other and prevent its being perceived. But in the present case, the two components can influence each other in such manner as to modify the nature of the resulting sensation and make it quite different from what either of them by itself would produce. Such modification would arise by reason of a transfer of part of the corpuscular energy from one of the spectral components to the other, the transfer being made possible by the two pigments being in actual physical contact with each other. The carotenoid pigment can exist in various energy-states represented by light of wavelengths over the range from 4000 to 5000 angstroms. It can therefore either take up or give up energy so as to pass from one state to another during the process which results in the perception of light and colour. The energy thus taken up or given up would pass from one spectral component to the other. We may represent this process as below:

$$h\nu_1 + h\nu_2 \rightarrow h\nu_1^* + h\nu_2^*$$

Here ν_1 and ν_2 are the frequencies of light in the incident radiation having shorter and longer wavelengths respectively, while ν_1^* and ν_2^* are the frequencies of the light as actually perceived. Since we are concerned with a transfer of energy, the two sides of the equation are equal, and hence

$$\nu_1 - \nu_1^* = \nu_2^* - \nu_2$$

In other words, when ν_1 diminishes, ν_2 increases by an equal amount of *vice versa*. The magnitude of the energy transferred may vary within the limits set by the absorption spectrum of the carotenoid pigment. Hence the radiations actually perceived would not be the incident monochromatic components, but would each consist of wide spectral bands of frequency. Indeed, in particular cases, the spectral bands covered by ν_1^* and ν_2^* may together make up the entire visible spectrum.

The sensation resulting from the superposition of the two monochromatic radiations would thus depend greatly on their positions in the spectrum and especially on their intensities. Either of them may mask the other and prevent its being perceived, if it be of sufficient intensity. But if they are of comparable strength, the perceived colour would depend on the relative strength of the spectral bands of frequency into which the two components are perceived as spread out. In particular cases, the resulting sensation may even be perfectly achromatic.

Observational Proof.—The remarkable result indicated by the foregoing theory that changes in the frequency of the incident radiations occur in the retina and determine the perceived colours readily admits of demonstration by quite simple methods. The most convenient light-sources to use for such observations are respectively a sodium vapour lamp and a mercury arc. The former gives yellow light of wavelength λ 5893 without any need for filtration. Two sheets of blue glass held together can isolate the λ 4358 radiation of mercury, completely excluding the green and yellow rays which are its accompaniments. Diffusing screens of ground-glass placed before the sources enable us to view them without discomfort as extended areas of illumination exhibiting their respective colours. Merely by moving the sheets of ground-glass nearer to or further away from the light-sources, large variations in brightness of these areas can be obtained. The visual superposition of the colours may be effected by the simple device of a plate of glass held at an angle by the observer who then views the reflected image of one source against the background of illumination provided by the other source.

When the superposed fields of illumination are of comparable brightness, one of them being of orange-yellow colour and the other a deep blue, the field of superposition appears of a beautiful rose-red colour, thereby clearly showing that the frequency of the yellow light has been shifted down, transforming it into red light. The shift in the opposite direction needed to transform the yellow light into green light has to be larger than the shift downwards needed for its transformation to red light. It is therefore not surprising that in the resulting sensation the red predominates and that together with the blue of the mercury source, gives a rose-red sensation.

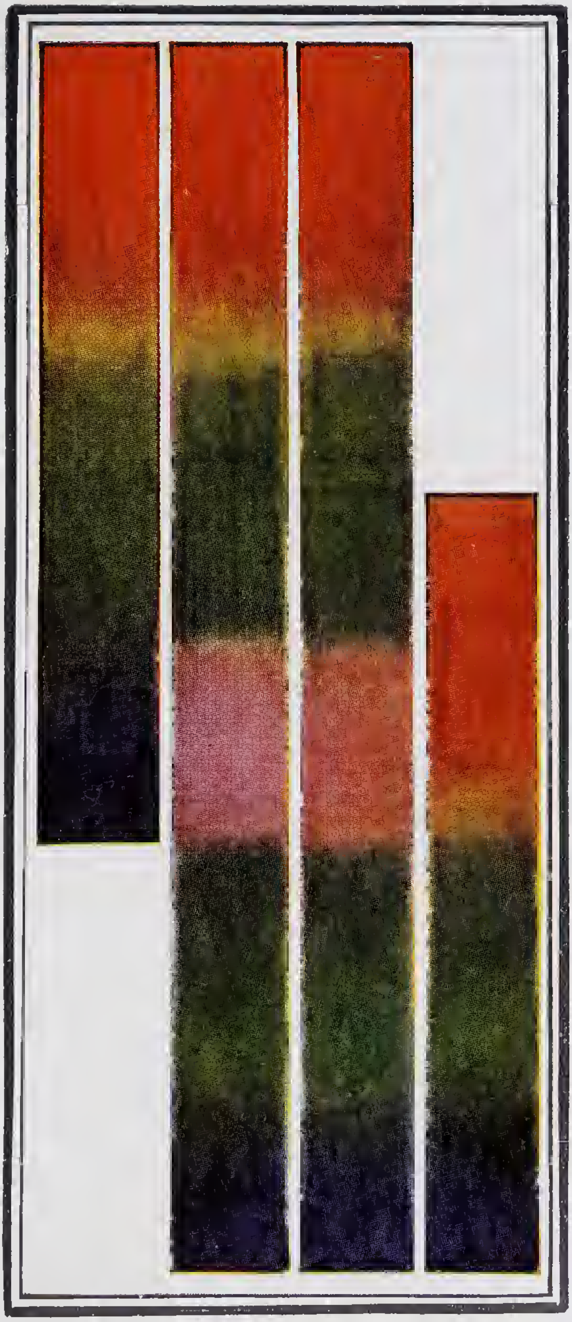
It should be mentioned that if in the observations, the blue is set at a sufficiently high intensity, it completely masks the yellow which is then not perceived. Likewise, if the yellow is set at a sufficiently high level of brightness, it completely masks the blue which is then not perceived. There is also an intermediate stage where the rose-red appears of a paler hue approaching an achromatic sensation.

Similar observations can also be made using two mercury lamps as the sources, one to give the λ 4358 radiation, and the other with a suitable filter to isolate the green λ 5461 rays. It is found that when the relative brightness of the two superposed radiations is correctly adjusted, the result is a perfectly achromatic sensation. If one or the other is in excess, the field of superposition exhibits a bluish or a greenish tinge respectively.

The Colours of Superposed Spectra.—A very simple technique has been devised and used by the author which yields results of great interest. The principle of the method is that the observer sees simultaneously two spectra of white light dispersed to the same extent, but superposed in positions which are displaced with respect to each other, so that the regions which overlap can be varied at will. It is desirable that the brightness of the spectra can be varied so that they can be of equal intensities, or one of them can be brighter and the other feebler as desired. With these arrangements, the observer sees the effect of superposing monochromatic light of two different wavelengths in various regions of the spectrum simultaneously. The wavelength differences and the regions of the spectra in which the superposed radiations are located are adjustable as desired. It is very useful so to arrange matters that strips of the two superposed spectra remain visible above and below the region of overlap, so that the observer can see at a glance what the colours superposed actually are in the region under view.

The author has found it convenient in practice to use two independent sources of white light, as for example, two luminous tungsten-filaments held parallel to each other and at a suitable distance apart, and to view the diffraction spectra of the first order of these sources through a replica grating held before the observer's eye. By varying the distance apart of the two sources or by the observer moving towards or away from them, the spectra can be seen superposed in various positions relative to each other. By adjusting the heating current passing through one of the filaments, the relative brightness of the superposed spectra can be altered as desired. It is easily arranged that the two

Plate VI



The colours of superposed spectra

spectra which overlap along their length in the middle of the field can be seen separately above and below it.

The boundary between the blue and green sectors of the spectrum which overlaps the other appears as a sharply defined line of separation between regions exhibiting totally different colours. Particularly striking effects are noticed when the blue sector of one spectrum overlaps the regions in the other which exhibit colours ranging from yellow to orange. The region of overlap then exhibits a brilliant rose-red colour wholly unlike the other colours of the spectrum. An effort has been made to reproduce this effect in the colour-sketch appearing in Plate VI.

It is possible also to study the results of superposing the blue sector of one spectrum on various other regions in the second spectrum, as for example, on its green sector, though the effects are, in these cases, of a less striking character. It is likewise possible to observe the effects of superposing the red, yellow and green of one spectrum on these colours in the other spectrum. Such effects are noticeable if the superposed colours are of comparable intensities. But if they are of different orders of brightness, the more luminous sector suppresses the weaker one, its own colour remaining apparently unaffected.

Studies with Two Monochromators.—Another technique for the study of the superposition of spectral colours employs two spectrographs of the well-known type in which the spectra can be displaced by a rotation of the dispersing prisms. The eye-pieces of the observing telescopes are removed and adjustable slits are placed in the focal planes through which limited regions of the spectra can emerge. Enlarged images of these slits are projected on a sheet of ground-glass so as to coincide for the most part, leaving areas on either side of the region of overlap so that the colours which are superposed can also be individually perceived. Tungsten-filament lamps of high wattage of the kind used in projection lamps are placed close to the slits of the spectrographs, thereby ensuring the formation of spectra of adequate brilliance in the respective focal planes. The ground-glass sheet on which the patches of colour appear is viewed by the observer from a comfortable distance. By rotating the drums, any two desired locations in the spectra can be seen superposed on each other. By opening or narrowing the collimator slits, their relative brightness can also be varied.

Observations by this method confirm and usefully supplement the results obtained by the other methods. They establish the conclusions already set forth and make it evident that the synthesis of colour is effected by the processes which have been discussed in detail in this chapter. It may be remarked that the superposition of light from the two extreme ends of the spectrum or near thereto results in the perception of a rose-red colour over a wide range of the relative intensities of the red and the violet which are thus superposed. Outside this range, only one or the other of the two colours is perceived, the brighter colour masking the feebler.

CHAPTER XIX

COLOURS OF PHYSICAL ORIGIN

THE basic facts and principles relating to the perception of the colours of composite light have been set forth and established in the preceding two chapters. It is however not without interest to consider various actual cases of importance and to show how they illustrate the ideas regarding the composition of spectral colours expounded in this book. There are, of course, a great variety of such cases which could be discussed and dealt with. Colour plays an enormously important role in human life and activity, and the production of materials exhibiting colour is a substantial part of human industry and of scientific technology. The dyeing of textiles may be mentioned as an outstanding example of the kind. Such activities create a demand for the precise specification of colour and for methods by which colour exhibited by various materials can be subjected to precise comparison and measurement. A further consequence of the interest in colour is the demand for the reproductions of colour by special techniques and especially by photography and the wide dissemination of such reproductions by the art of colour printing. To deal with the fields indicated above in their entirety from the standpoints adopted in the present work would need more than one treatise. We shall, therefore, restrict ourselves to the consideration of some leading cases and to some topics of special importance.

The Colours of Interference.—The general nature of interference patterns and their appearance as seen by monochromatic light were described in Chapter II. They were discussed in greater detail in Chapter VII. Methods for producing them on a large scale so that they could be conveniently observed and studied without optical aid were also indicated in that chapter. We shall here consider rather more fully the explanation of the chromatic features of such patterns when observed in white light, since they are an excellent illustration of the production of colour by purely physical methods. The colours of interference arise by reason of the intensity of the light reflected by the thin films which exhibit such colours being dependent on the wavelength, and hence different for the different parts of the spectrum. It is obvious that the relative luminosity of the different colour regions in the spectrum would play a highly important role in determining the visible result of superposing the interference patterns due to light of different wavelengths. Since the interferences for any particular wavelength consist of areas on the film which are alternately dark and bright, it is to be expected that the pattern as observed with white light would exhibit a series of maxima and minima of illumination, the positions of which would be determined by the wavelength of the most luminous part of the spectrum. This is actually the case and the measurements of these positions set out in Chapter VII showed that the effective wavelength is close to the wavelength of the yellow light of the sodium vapour lamp, and quite outside either the green or the greenish-yellow part of the spectrum.

A very convenient procedure for exhibiting the role played by different colour sectors of the spectrum in interference patterns is to view them through colour-filters of different sorts. We may begin by considering the blue sector of the spectrum which lies in the wavelength range between 400 mμ and 500 mμ. Since it is the least luminous part of the spectrum, it is not to be expected that it would make any sensible contribution to the observed colour-sequence except in those regions where the rest of the spectrum is present with low intensities. This is actually the case. On viewing the pattern through a yellow plate of glass which cuts out the blue completely and leaves the rest of the spectrum unaffected, it is found that no change is detectable anywhere, except in two narrow strips contiguous to the two most conspicuous minima of intensity in the white light patterns.

Here, the observed colour changes on the introduction of the filter from a blue or a bluish-green to a clear green.

A plate of red glass which cuts out all wavelengths less than 600 mμ is effectively a monochromatic light filter. The interference pattern as seen through it exhibits a large number of dark bands alternating with bright bands. Two sheets of green glass put together which transmit only the region between 500 mμ and 560 mμ behave likewise. The difference between the effective wavelengths in the two cases results in a contraction of the pattern when we change from the red filter to the green filter, all the bands moving in the same direction to their new positions. It is easy to compare the positions of the colour bands in the white light pattern with the positions of the dark and bright bands as seen respectively with the red and the green colour-filters. It is then found that the red bands as seen with white light coincide in position with the dark bands as seen with the green filter. *Vice versa*, the green bands in the white light pattern coincide with the dark bands as seen with the red filters. Their positions in both cases are adjacent to the positions of minimum illumination in the white light pattern, but in the two cases appear on opposite sides of those positions.

These observations make it evident that the manifestation of colour in the white light patterns results from the red or the green sector of the spectrum (as the case may be) masking or suppressing the perception of all the other colours of the spectrum which appear with low intensities. Such masking becomes incomplete as we proceed to the higher orders of interference and the minima of illumination in the pattern fade away as a consequence.

Interesting effects are observed when the white-light interference patterns are viewed through a plate of glass which has been doped with neodymium oxide. This filter totally absorbs the wavelength range between 570 mμ and 600 mμ, in other words excludes the yellow sector, while the green and the red sectors come through freely. The introduction of this filter before the eye results in a large increase in the number of interferences visible and the pattern then covers the whole field. But the different areas show quite different features. The exclusion of the yellow results in the first few bands exhibiting highly saturated reds and greens with sharply defined boundaries between the contrasted colours. We have next a succession of five alternately dark and bright bands which are practically achromatic. Beyond this again, we have a succession of bands exhibiting colours but in the reverse order and much less saturated.

These effects arise by reason of the suppression of the yellow sector. The result is that the pattern then represents a superposition of two sets of interferences due to the red and green sectors of the spectrum, the bands of which are spaced differently. That the colour bands show sharply defined boundaries is a demonstration that the observed effects arise from a masking of the weaker by the stronger colours and not from an additive composition of colours.

Some interesting features are also observed when the interference patterns are viewed through an orange-coloured plate of glass which cuts out all wavelengths less than 540 mμ. Many more bands can be seen than are visible with white light, and the minima of illumination in the pattern are also more conspicuous, at least six of them being clearly seen. The first few rings show the yellow colour at the maxima of illumination. All the other bands in the pattern appear alternately green and red, these areas of colour being sharply defined and of equal width.

Fraunhofer Diffraction Patterns.—Colours having a purely physical origin are also observed when a brilliant source of white light of small extension is viewed by an observer holding before his eye an opaque screen pierced by tiny apertures through which light can find entry. Particularly striking effects are produced if these apertures are numerous and are arranged in a regular two-dimensional array and thus form what is usually referred to as a diffraction grating. Such a grating disperses light of different wavelengths in different directions, thereby resulting in the formation of what are known as diffraction spectra. We are however not concerned here with such spectra, but with the diffraction patterns of individual apertures in which the effects produced by the various wavelengths in the continuous spectrum of white light overlap and thereby give the colours of composite radiation. For our present purpose, it will suffice to consider the best known and indeed the simplest of all such patterns, *viz.*, the case of a linear source of white light viewed through a narrow slit bounded by sharp parallel edges.

The nature of the diffraction pattern resulting from the passage of light through a long slit with parallel edges is well-known. It consists of a series of parallel bands, the central band being twice as wide as those on either side of it. If the observations are made with monochromatic light, the bright bands are separated from each other by a series of equally-spaced dark lines appearing on each side of the pattern. The central band is the brightest of all, while the successive bands on either side of it fall off progressively in brightness. The angular spread of the pattern is proportional to the wavelength of the light, the nature of the pattern however remaining the same.

It is worthy of remark that the minima of illumination in the white light patterns are conspicuous, the first two on each side being almost perfectly dark. The disposition of the colours seen in the white light patterns is very clearly related to the positions of these minima of illumination, four of which are clearly seen. Measurements of the positions of these minima with a source of white light and also with sodium light show a close agreement. The situation is thus analogous to what has been observed in the patterns of interference and set out fully in Chapter VII. The sequence of colour seen in the diffraction pattern resembles that noticed in the interference pattern of a wedge-shaped film of air. We need not therefore discuss it here further.

The Colours of Rotatory Dispersion.—The property exhibited by plates of quartz of rotating the plane of polarisation of light traversing the crystal along its optic axis provides a simple and very useful method for the study of the colours of composite light. A plate of quartz one millimetre thick and cut normal to the optic axis rotates the plane of polarisation by 15 degrees of arc at the red end of the spectrum increasing to 50 degrees at the violet end. If an extended source of light is viewed through the plate held between two crossed polaroids, the rotation results in a restoration of the light, but this can be extinguished for any particular region of the spectrum by turning one of the polaroids with respect to the other so as to compensate for such rotation. If the spectrum of the light coming through along the optic axis is examined through a spectroscope, it will be found to exhibit a perfectly dark band crossing it at the wavelength at which the light is extinguished, while on either side, the spectrum remains visible. The position of the band of extinction is observed to shift when one of the polaroids is rotated. It can therefore be set so as to place the extinction in any desired region of the spectrum. The colour of the light emerging through the polaroids and the crystal in the axial direction can then be observed and its relation to the part of the spectrum which is extinguished can be determined.

A plate of quartz five millimetres thick is very convenient for the observations. The difference of the rotations at the two ends of the spectrum does not then exceed 180 degrees of arc, and hence there is only one band of extinction to be seen in the spectrum, and by setting the polaroids suitably, this can be moved from one end of the spectrum to the other. The varying colour of the light emerging in the axial direction can then be followed. Thinner plates of quartz may also be used and the region of extinction in the spectrum may likewise be moved from one end of it to the other. But the effective width of the spectral band of extinction would then be greater. This may be an advantage in certain cases. Such observations enable us firmly to establish various propositions which are fundamental in the theory of colour perception and which we shall now proceed to consider.

A colour which is well-known and easily recognised is that which goes by the name of purple. Already in Chapter XVII it has been shown by observations on the light transmitted by aqueous solutions of certain dye-stuffs that the purple sensation is perceived when the yellow sector of the spectrum has been eliminated by absorption, while the red, green and blue sectors of the spectrum appear with full strength. This result receives an independent confirmation from studies on the colours of rotatory dispersion. Observations with quartz plates of various thicknesses ranging from half a millimetre to six millimetres show that when the polaroids are so set that the colour of the transmitted light is purple, the spectroscope reveals that a band of extinction covers the yellow sector of the spectrum while the red, green and blue continue to be visible.

That the yellow sector is the most luminous part of the spectrum at ordinary or daylight levels of illumination is made evident by the same observations which show that its extinction results in the rest of the spectrum being perceived as purple. The setting of the polaroids which results in the axially transmitted light being perceived to be of purple hue is also the setting at which the transmitted light has the minimum visual brightness. Rotating one of the polaroids away from the correct setting in either direction results in a rapid change of the colour of the transmitted light and it also results in a large increase in its luminosity.

The foregoing remarks may be very prettily illustrated by using plates of quartz which are less than a millimetre thick. Held between the two polaroids and viewed against an extended source of illumination, a dark cross is observed in the field when the light which comes through is nearly at its minimum of intensity. This cross at one setting of the polaroids appears blue in colour and at a slightly different setting of a reddish hue. There is an intermediate setting at which the transmitted light is extremely feeble. The dark cross then exhibits a purple colour. But it requires a very bright field of illumination for this colour to be seen and recognised. It may be remarked that at this stage, the light of a sodium vapour lamp is extinguished when viewed in the axial direction through the crystal and the polaroids.

An important question concerns the colour which is complementary to green. In other words, if the green is excluded from the spectrum while the red, yellow and blue sectors are in full strength, what is the colour that is perceived ? This question can be readily answered with the aid of a quartz plate which is five or six millimetres thick. The polaroids are set so that the colour of the light emerging in the axial direction is purple. Spectroscopic examination shows that the yellow of the spectrum has then been extinguished. One of the polaroids is then turned round so that the band of extinction moves from the yellow well into the green and is at the centre of the green sector. The yellow and red sectors as well as the blue sector are seen quite brilliantly, while the green is almost entirely cut out from the spectrum. The transmitted light appears of a rose-red hue which is thus the complementary colour to green.

A block of colourless quartz fifteen millimetres thick with polished faces normal to the optic axis and held between crossed polaroids exhibits the colours of rotatory dispersion quite conspicuously when viewed against a bright field of illumination. The pattern consists of concentric rings of colour around a coloured centre, the rings being alternately green and rose-red. A noteworthy feature observed in these patterns is that the bands of contrasting colour have sharply defined boundaries separating them from each other. The positions of these boundaries coincide with the lines of zero intensity in the same patterns as seen with the monochromatic light of a sodium lamp. A block of this thickness exhibits three bands of extinction in the spectrum of the light which has traversed the crystal along its optic axis. The change in the colour of the transmitted light occurs when one of the bands of extinction passes over from the red to the green sector in the spectrum.

The Blue Sky.—On a clear sunny day and especially after a shower of rain has washed out all dust and haze from the atmosphere, the sky exhibits a blue colour of remarkable depth and purity. In these circumstances, the origin of the light which reaches us and exhibits this colour is evidently sunlight which has been scattered by the gaseous molecules of the atmosphere, the shorter wavelengths having gained in intensity relatively to the longer wavelengths in the spectrum in the process of such scattering. But it is not to be supposed that in the spectrum of skylight, the blue sector is the most luminous part. This is very far indeed from being the case, as becomes evident when the blue sky is viewed through a filter of yellow glass which cuts out the blue but has no influence on the rest of the spectrum. It is found that the filter has little or no observable effect on the brightness of skylight, though its colour is altered to a greenish-yellow. In other words, the blue contributes very little to the luminosity of the sky. When then, it may be asked, does it determine its observed colour?

The answer to this question, in other words, the real explanation of the blue colour of the sky is that it is a consequence of the masking or suppression of all the other colours in the spectrum by its blue sector. In Chapter XVII, we have already noticed that such masking may be demonstrated with the aid of a dilute solution of cuprammonium. Adding water to this solution contained in a cell which is two centimetres in depth, the spectrum of the light transmitted by the cell may be progressively extended so as to cover, besides the blue sector, also the green, yellow and red sectors, in other words, the whole of the spectrum. In this process, the intensity of the light which passes through the cell increases rapidly. But so long as the yellow and red sectors exhibit an appreciable diminution of their intensity relatively to the blue sector, the colour of the transmitted light remains a clear blue.

This remarkable power of the blue sector to suppress the perception of the other colours in the spectrum finds its explanation in the visual processes described and discussed in Chapter XVIII. The superposition of blue light on monochromatic light appearing in any other part of the spectrum results in spreading it out over a wide spectral range of frequencies and thus destroying the specificity needed for the perception of colour. Not much of blue light is needed to carry this process to completion. The surplus of blue light left over is perceived and determines the observed colour.

The Colour of Oceanic Waters.—Great bodies of clear water illuminated by sunlight which penetrates into their depths exhibit a colour resembling the blue of the sky but much superior to it in respect of its saturation. The origin of this phenomenon was investigated by the author and his conclusions were set out in a memoir published in the *Proceedings of the Royal Society of London* for April 1922 under the title of "The Molecular Scattering of Light in Water and the Colour of the Sea". The subject was there discussed in great detail and with a certain measure of completeness. For our present purpose, it is sufficient here to mention only the essential points in the explanation of the phenomenon and the differences between it and the case of the blue of the sky considered in the foregoing paragraphs.

The molecules of water scatter sunlight traversing the liquid to a readily observable extent. Indeed, such scattering is much more powerful than the scattering of sunlight by an equal volume of the gases of the atmosphere, though not as powerful as could be expected in view of the greater density of the material. The restriction of freedom of movement of the molecules in a liquid accounts for this fact. But there is another important difference between the two cases. The atmosphere of the earth may be regarded as transparent to light within the range of the visible spectrum. Water, on the other hand, has a weak absorption arising from the overtones of the characteristic infra-red frequencies of molecular vibration. Such absorption, though weak, is sufficient to reduce very considerably the intensity of the red and yellow in the light emerging after internal scattering from inside a great depth of clear water. Hence, the red and yellow sectors are much weaker relatively to the blue than in the case of the scattering of sunlight by the gases of the atmosphere. The masking by the blue of all the other colours of the spectrum is therefore quite complete. What is accordingly perceived is only the blue end of the spectrum.

CHAPTER XX

THE COLOURS OF FOLIAGE AND FLOWERS

We are concerned in the present chapter with the colours exhibited by foliage and by flowers *in vivo*. These are the colours which we actually perceive and it is their relationship to the spectral character of the light reaching our eyes which is the subject of study. Sunlight is incident on the leaves of growing vegetation or on the petals of the flowers. It enters the material and re-emerges after internal diffusion or scattering. It may also be accompanied by light which is reflected or diffused at the surfaces of the leaves or petals. Such reflections disturb the observed colour. But they are usually not important and their effect can be minimised by an appropriate choice of the direction of observation. They may be completely avoided if the light which emerges after passing through the leaf or flower is examined. Most leaves and flower petals are thin enough to allow sufficient light to emerge in this manner which could be observed visually through a pocket spectroscope containing a wavelength scale. The regions of the spectrum in which there is strong absorption can be recognised, and this may be supplemented by visual comparison of the spectrum with the spectrum of daylight diffused by a matt white surface.

In many cases, immersion of the leaves or petals in a glass vessel containing a suitable organic solvent, as for example, acetone, enables the pigments responsible for their colour to be quickly extracted. The extract may then be transferred to an observation tube of suitable length which is held against a brilliant source of white light. The spectrum of the light coming through the tube can be examined visually. Spectroscopic examination of such extracts is useful in some cases, as for example, when the colour of the flower is so deep as to obscure the nature of the absorption spectrum. Diluting

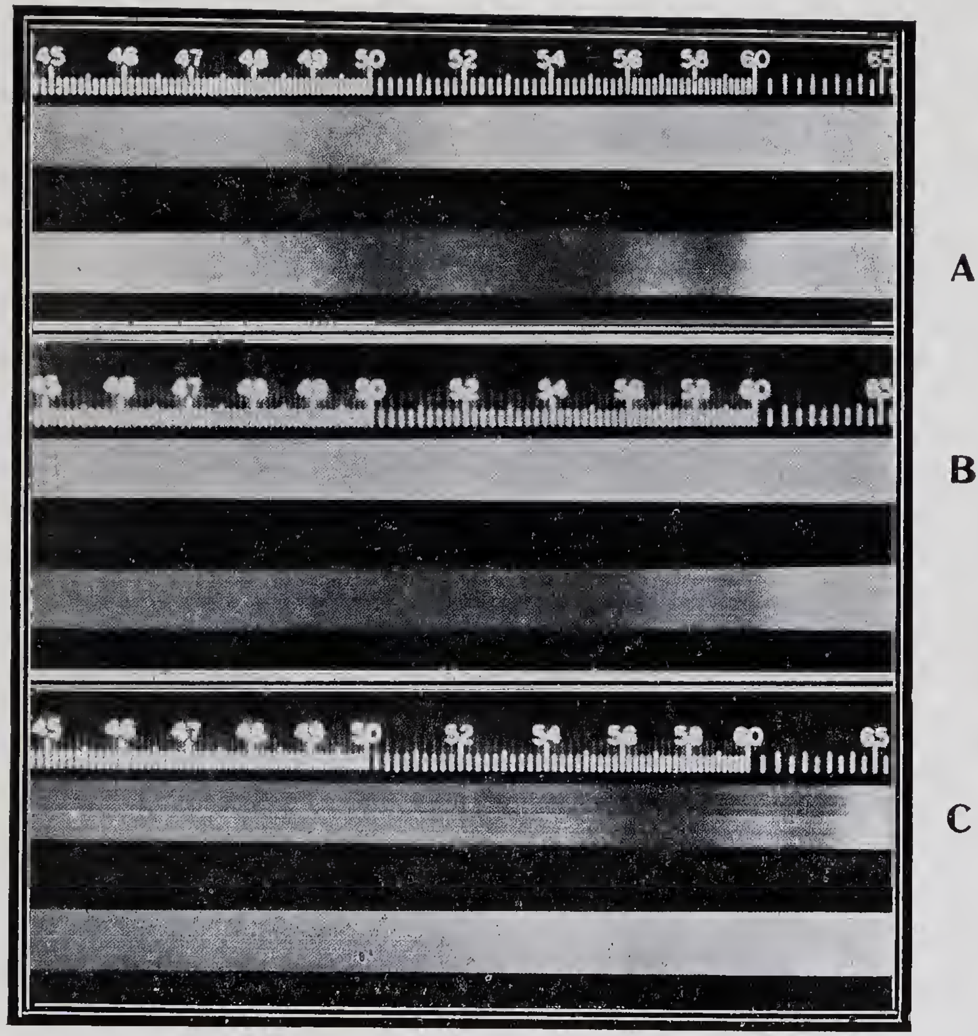


FIG. 9. Absorption spectra of flowers.
A. Spathoglottis plicta.
B. Purple Cineraria.
C. Clitoria ternata.

the extract or using a smaller depth of the absorbing column is then helpful.

Extensive studies carried out by the author using these techniques have enabled a comprehensive view to be obtained of the nature of floral colours and of their relationship to the absorptive properties of the pigments contained in the material of their petals. Perhaps the most interesting discovery made in the course of these studies is that in many cases, the light emerging from the petals exhibits a series of discrete absorption bands which are usually three in number. These bands appear in the region of wavelengths between 480 mμ and 650 mμ. Their positions and the strength of the absorption in the different bands determine the observed colour of the flowers. There is no difficulty whatever in obtaining photographic spectra accompanied by wavelength scales which exhibit these bands in a conspicuous fashion. Many such spectrograms have been obtained and a selection from them has been reproduced with this chapter. They help to show clearly how the observed colour of the flowers is related to the spectral character of the light emerging from their petals.

The Colour of Green Leaves.—The most familiar amongst all colours of biological origin and therefore the first to claim our attention is that exhibited by the foliage of living and growing vegetation. Its spectral nature can be studied in the open air on a large scale. An impressive demonstration of that colour is furnished by the fields in which rice-plants are grown under irrigation. Directing a pocket spectroscope obliquely downwards in the direction at which the colour is seen at its best, the spectral nature of the light exhibiting the colour becomes evident, and this can be compared with the spectral nature of the light of the sky. The spectrum of skylight extends over the entire range from 400 millimicrons to 700 millimicrons. The luminosity of the sky is naturally much higher than that of the green carpet of the rice-fields. But this does not stand in the way of the essential differences in the character of their spectra being recognised. The first and most obvious difference is the complete extinction of the blue-violet sector between 400 millimicrons and 500 millimicrons in the green colour of the vegetation. Another noticeable difference is the contraction of the red sector, which instead of extending to about 700 millimicrons is unobservable beyond about 640 millimicrons. But the part of the spectrum between 590 millimicrons and 640 millimicrons where the orange and the red appear continues to be visible and is not noticeably weakened in relation to the rest of the spectrum. The most significant difference between the two spectra is, however, the nearly complete extinction of the yellow sector in the spectrum of the green light. The spectral range between 560 millimicrons and 590 millimicrons appears indeed much dimmer than the green and red sectors on either side of it, instead of being, as it normally is, the brightest part of the solar spectrum. By reason of the drop in brightness on either side of it, the green sector stands out conspicuously.

It is very instructive to examine the leaves of a plant which are in the successive stages of development, commencing from the tender leaf which has a pale greenish-yellow hue and proceeding by steps to the mature leaf exhibiting a full green colour. It then becomes evident that the progressive change of colour is the result of a more complete elimination of the yellow sector of the spectrum between 560 millimicrons and 590 millimicrons. In other words, for the green of the leaf to be manifested in its full strength, the extinction of the yellow region is essential. With the mature leaves, the fraction of the light which comes through is considerably smaller. This reduction shows itself in a diminished brightness of every part of the spectrum. But much of the weakening is due to the more complete extinction of the yellow region which in the case of the immature leaves is quite luminous and in the mature leaves is not at all discernible.

Even the fully developed leaves of different plants and trees exhibit a wide range of variation in the colour and luminosity which they exhibit. The leaves of some trees, as for example, the well-known fruit-bearing *Artocarpus integrifolius* are of a very dark green colour when mature, though in the earlier stages of their development, they exhibit brighter colours. Spectroscopic examination reveals that the range of wavelengths of the light which filters through the leaf remains much the same, *viz.*, from 520 millimicrons to 640 millimicrons, though the intensity of the light is very much reduced in the case of the mature leaves. What is particularly interesting is that the part of this spectral range in which the orange and the red appear is visible with the leaves in all stages of development. We are obliged to conclude from this that the green of the spectrum has the effect of masking the red and orange, in other words, prevents them from being perceived.

The colour of growing vegetation owes its origin to the pigments which partake in the photosynthetic activity. These materials can be extracted from the leaves by immersion in organic solvents, the most suitable and effective of them being acetone. Placing the acetone extract in a flat glass cell, the colour as seen by transmitted light and its relation to its absorption spectrum can be readily ascertained. A striking demonstration of colour changes entirely analogous to those exhibited by the leaves of plants in the course of their development can be given with the aid of the extracts. For this purpose, a glass cell is filled to about a third of its depth with pure acetone, and the acetone extract which is itself of a dark green colour is then added a little at a time. The acetone in the cell first turns yellow, then to a greenish-yellow and then progressively to a clear green. These changes correspond to the alterations in the character of the absorption spectrum of the liquid contained in the cell. A cut-off of the red beyond 640 millimicrons appears at the very outset, and this is soon followed by the extinction of the blue upto 500 millimicrons. But not until a band of absorption in the yellow between 570 millimicrons and 586 millimicrons manifests itself in the spectrum and is fully developed does the solution exhibit a full green colour.

The absorption spectrum of the pigments present in the green leaves can be observed with the leaves themselves. For this purpose, it is best to use a leaf of dark-green colour as for example, the mature leaf of *Artocarpus integrifolius* through which very little light can normally filter through. It should be held close to the very brilliant source of white light provided by a tungsten-filament lamp of high wattage. The light which then emerges through the leaf may be viewed through a pocket spectroscope. The well-known absorption bands due to chlorophyll *a* and chlorophyll *b* appearing near the red end of the spectrum can then be seen and recognised. An absorption band in the yellow region between 570 millimicrons and 586 millimicrons is also very clearly seen. Further, two *bright* bands located, one in the green between 550 millimicrons and 570 millimicrons, and the other in the orange between 586 millimicrons and 613 millimicrons are also noticeable. These two bright bands are also seen in the absorption spectra of the acetone extracts of the leaf pigments.

The explanation usually given of the green colour of leaves is that it is due to the presence of chlorophyll in the leaves. This explanation needs to be qualified and supplemented by the remark that the colour is not ascribable to the characteristic and intense absorption by chlorophyll manifested near the red end of the spectrum. For, the luminous efficiency of this region is very low and the presence or absence of absorption in it can make little difference to the observed colour of the leaves. Actually, as we have seen, the colour is ascribable to the absorption of the yellow sector of the spectrum which is necessary to allow the green sector in the transmitted light to manifest itself to perception. The total extinction of the blue sector in the spectrum also plays an essential role. In this absorption the carotenoid pigments also participate.

The Aster and Its Varied Colours.—Asters are very attractive flowers by reason of the rich and varied colours which they exhibit. The flowers appear in bunches at the end of long leafy stalks, each flower consisting of a great

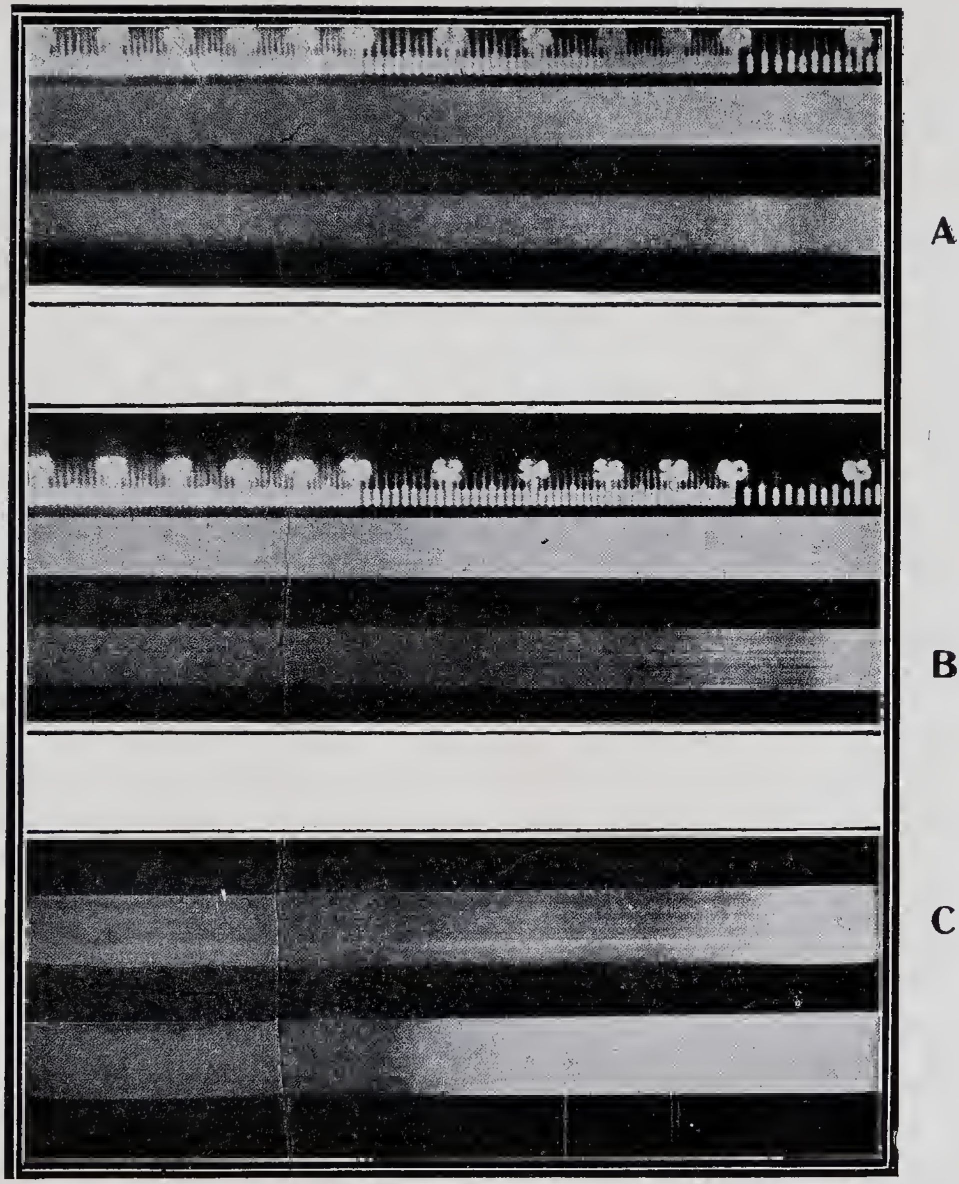


FIG. 10. Absorption spectra of flowers.

A. Delphinium.

B. Lobelia

C. Blue Cornflower.

many petals grouped around a common centre. The material commercially available at Bangalore includes a range of colours which fall into two groups. One group ranges in its hues from different shades of purple to a deep violet. Another group ranges in colour from a pale pink to a full red. To study these colours, all that is necessary is to hold the flower in sunlight and view it through a pocket spectroscope. The relation between the colour and the observed spectrum then becomes apparent.

The purple asters exhibit the entire spectrum of colours except the yellow which is markedly weakened. The extinction of the yellow is nearly complete with the flowers which exhibit deeper purple shades. The violet-coloured flowers show, besides the extinction of the yellow, a considerable weakening of the green sector and also a distinct weakening of the red sector which shows a visible bifurcation by reason of an absorption band which it exhibits. The green and red sectors, despite such weakening, continue to be visible in the spectrum, but are evidently masked from perception by the presence of the blue sector.

The pink asters exhibit all the colours of the spectrum except the green sector which shows a markedly diminished intensity. The flowers in this group which exhibit deeper shades of colour show a nearly complete extinction of the green sector. Though the blue is present in the spectrum with apparently undiminished strength, it is not perceived in the observed colour which the red dominates.

The Purple Orchids.—An absorption spectrum of a very striking nature is exhibited by the petals of the terrestrial orchid known as *Spathoglottis plicta.* This is a hardy plant which grows readily and bears clusters of flowers at the end of long leafless stalks. Viewed either by reflected or by transmitted light, the petals which are of a purplish-red colour exhibit three well-marked absorption bands widely separated from each other. One of them extinguishes the yellow sector of the spectrum. Another appears in the green sector. The third band appears in the blue-green region of the spectrum. The rest of the spectrum does not exhibit any absorption. A reproduction of the spectrum appears as Fig. 9 A in Plate VII. By immersing the petals in acetone, the pigment is readily extracted and the solution exhibits the absorption bands in the same position as the petals themselves but with an observable change in their relative intensities. The author has observed precisely similar spectra with other orchids exhibiting a purple colour.

The Spectra of Blue Flowers.—Discrete absorption bands well separated from each other also appear in the spectra of many other flowers. One of the most striking examples is furnished by the climbing plant *Clitoria ternata*, commonly known as the Butterfly-Pea. The blue flowers of this plant exhibit three such bands. One of them appears in the red region, the second in the yellow sector, and the third in the green sector. The most intense of the three absorption bands is that which appears in the yellow. This spectrum is reproduced as Fig. 9 C in Plate VII. Immersion of the petals in acetone results in a rapid extraction of the colouring matter. The solution exhibits an absorption spectrum of the same nature as the flowers. Since it is possible to make a strong solution using several petals, the absorption observed in this manner is even more striking than that of the flowers observed direct. One can see four bright bands in the spectrum separated by three very dark bands in the positions already stated and some indication of a fourth dark band in the blue-green region of the spectrum.

Other examples of blue flowers exhibiting bands of absorption in the red and yellow sectors of the spectrum are *Delphinium* and *Lobelia* illustrated in Fig. 10 A and Fig. 10 B respectively in Plate VIII.

The Spectra of Red Flowers.—One of the best known of garden flowers is the China Rose (*Hibiscus rosa sinensis*) which has large single blooms from which long bunches of stamens hang out. The petals exhibit a rich red hue. Spectroscopic examination shows a complete extinction of the blue, green and yellow sectors in the light which comes

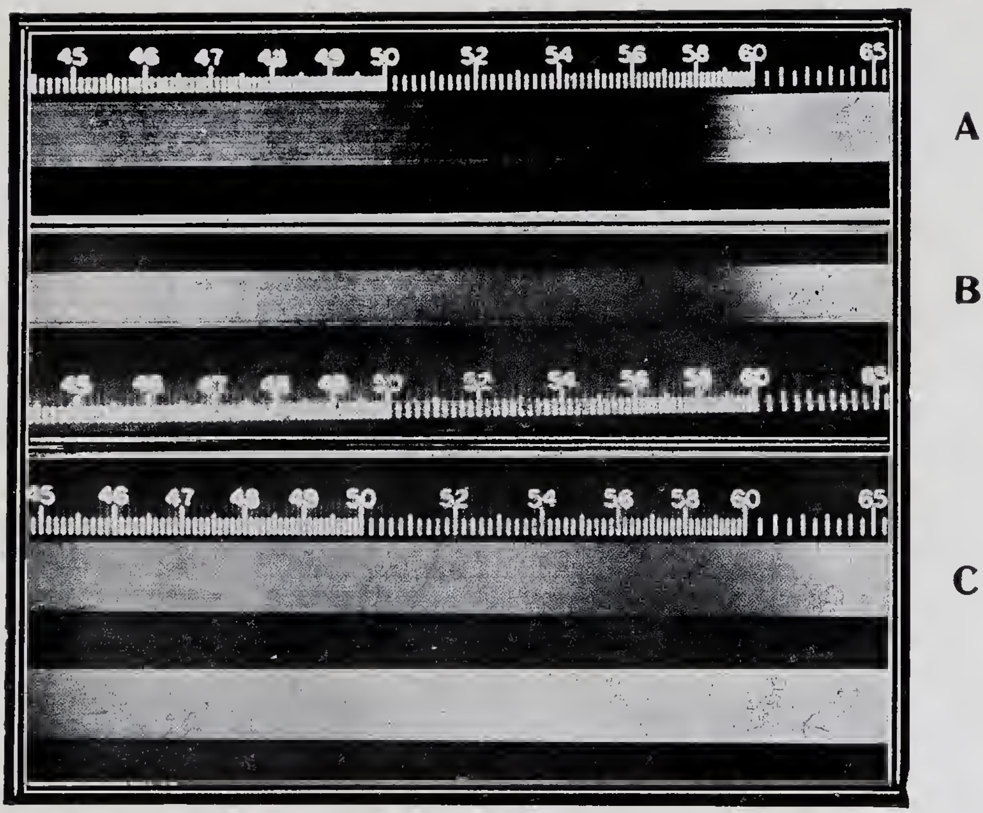


FIG. 11. Absorption spectra of flowers.

A. Purple Balsam.
B. African Violet.
C. Morning Glory.

through them, the red sector commencing from 600 mμ being in full strength in the transmitted light. The spectral characters of the floral pigment responsible for this spectral behaviour is better understood when it is extracted by the aid of acetone, leaving the petals colourless. The extract exhibits a deep red colour and an intense absorption covering all wavelengths less than 600 mμ. Using short absorption paths or else by diluting the extract with acetone, thereby allowing light of smaller wavelengths to come through, a strong absorption band between 580 mμ and 590 mμ, reveals itself, as also another strong band between 530 mμ and 550 mμ. There is also a weak absorption band at about 500 mμ. The blue sector of the spectrum can be seen coming through, though only weakly. If, instead of the Chinese Hibiscus, we use red or crimson roses, precisely similar phenomena are observed.

The Masking of Colour Sensations.—The examination of floral colours *in vivo* with the aid of the spectroscope makes it evident that in the visual perception of colour it is masking and not additive superposition that plays the leading role. This is particularly obvious when we study flowers of which the perceived colour ranges from violet and dark blue to comparatively lighter shades of blue. The following may be mentioned as illustrative examples:

The *Morning Glory* is a climbing shrub of the Convolvulus family (known botanically as *Ipomea learii*) which bears large bell-shaped flowers of which the petals display a dark blue colour. The spectroscope reveals that this colour results from the absorption of light in the spectral region between 560 mμ and 620 mμ, in other words, of the yellow and orange in the spectrum. But there is no noticeable weakening of any other part of the spectrum. These features are evident in the spectrogram reproduced as Fig. 11 C in Plate IX.

The tree known as *Solanum grandiflorum* of which the popular name is the nightshade or potato tree, flowers profusely. The petals have a violet colour which in the course of a few days fades away and becomes nearly white.

In the wavelength range between 570 mμ and 595 mμ, there is nearly complete extinction and there is a noticeable diminution of the intensity of the green of the spectrum. There are also detectable absorption bands at 545 mμ and at 635 mμ. The red and the green are alike suppressed from perception by the violet of the spectrum.

Another flower showing a deep violet colour is that of the shrub *Meyenia erecta.* Seen either by reflected or by transmitted light, the flowers exhibit three absorption bands, one at about 540 millimicrons, a second at about 580 millimicrons and a third at about 630 millimicrons, these being respectively in the green, yellow and red regions. A bright band in the orange centred at 610 millimicrons is a conspicuous feature in the spectrum, while the unabsorbed regions in the green and the red also remain visible.

The plant of which the botanical name is *Saintpaulia ionantha* (known popularly as the African violet) is a small herbaceous perennial which bears flowers which are violet in colour. The spectrum of the light either reflected or transmitted by the flower exhibits the entire range of wavelengths from the red to the violet except the wavelength range from 520 mμ to 600 mμ which is much weakened by absorption. The spectrum of this is reproduced in Fig. 11 B in Plate IX.

The shrub *Centaurea cyanus,* commonly known as the corn-flower, exhibits flowers of a blue colour. The spectroscope reveals that this colour is ascribable to an absorption in the yellow and orange-yellow regions in the spectrum. These features can be recognised in the spectrogram reproduced as Fig. 10 C in Plate VIII.

Plumbago capensis is a shrub which bears clusters of flowers of a pale blue colour. The absorption of light by these flowers is weak and is barely noticeable in the spectrum of the light transmitted by a single petal. But if we hold a few flowers together, the blue colour of the light which penetrates through the mass is conspicuous. Examining this light through a pocket spectroscope, an absorption band is visible in the yellow and fainter bands in the red and the green.

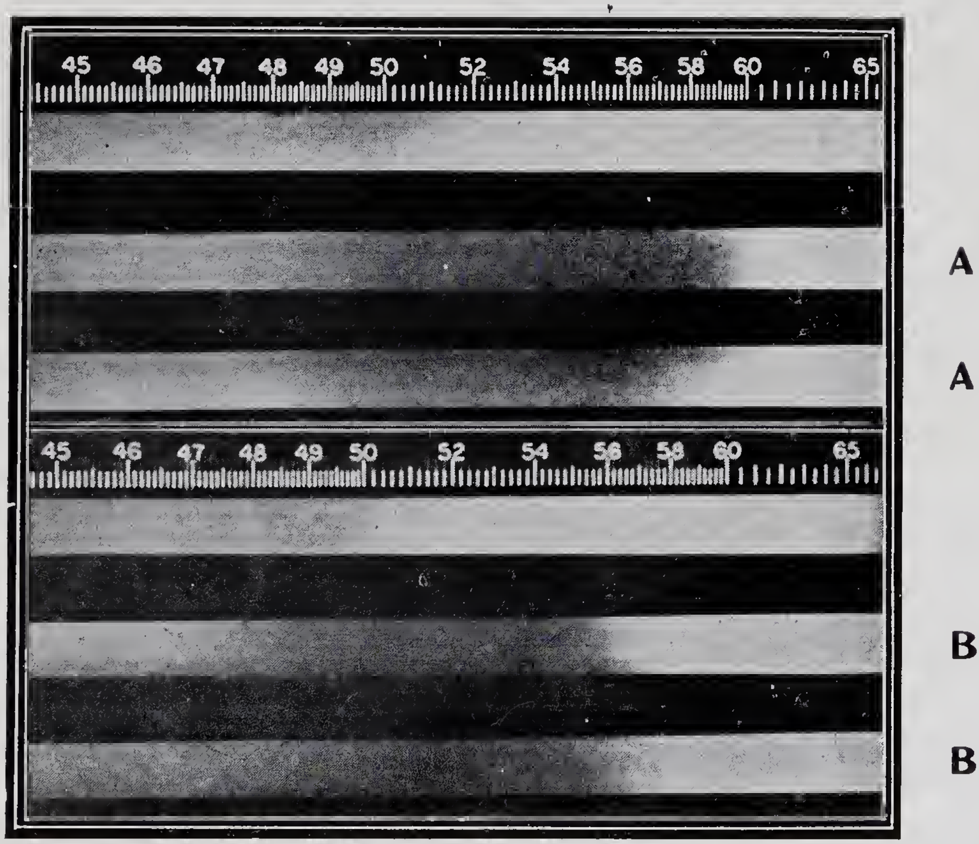


FIG. 12. Absorption spectra of flowers.
A. Lagerstroemia flos reginae (Purple)
B. Lagerstroemia flos reginae (Rose-Red)

Some Flowering Trees.—There are many trees which provide impressive displays of colour in the appropriate seasons when they are covered by a mantle of flowers which can be seen from afar. Special mention may be made here of a few of them by reason of the exceptional nature of such floral display. *Lagerstroemia flos reginae* bears great masses of magnificently coloured flowers. It appears in two varieties, in one of which the flowers have a rose-red colour, and in the other display a delicate purple hue. The spectra of the flowers exhibit the difference very conspicuously. The absorption in one case extinguishes the green sector of the spectrum, while in the other, the yellow sector is quenched. The spectra are reproduced in Plate X.

Another magnificent flowering tree is *Jacaranda mimosifolia*, the beauty of the foliage of which is far excelled by the splendour of the flowers which the tree bears in profusion and which make it appear from a distance as if it were enveloped in a blue mist. Spectroscopic examination shows the origin of the colour of the flowers to be a weak absorption of the yellow sector in the wavelength range from 570 mμ to 590 mμ and another weak absorption in the red sector from 630 mμ to 640 mμ.

Amongst the numerous trees which display yellow flowers, special mention may be made of *Peltaphorum ferrugineum* by reason of the very striking nature of its display. As in the case of all yellow flowers, the colour has its origin in the extinction of the blue sector of the spectrum. The petals of the flowers of *Peltophorum ferrugineum* are however very thin. As the result, the photographed spectra of the transmitted light exhibit the banded structure of the absorption spectrum of the pigments responsible for the colour.

CHAPTER XXI

THE COLOURS OF GEMSTONES

Colour plays a role of the highest importance in gemmology. Many gemstones display beautiful and characteristic hues and it is the precise shade and depth of that hue which determine the esteem with which a gem is regarded by its possessor. Since colour is what we perceive, it is evident that the characteristics of human vision would play a part in such perception which is no less important than the optical properties of the gemstone. It follows that the findings set forth in our earlier chapters are highly relevant in relation to the subject of gemmology. This will now be illustrated by reference to the behaviour of some gemstones studied by the author.

The Green Colour of Emerald.—The emerald has been held in high esteem in India since ancient times and great quantities of this gemstone were used in jewellery over many centuries. Quite recently, emeralds have been mined at various places in Rajaputana. A visit to Jaipur where the emeralds thus found are marketed enabled the author to obtain the material necessary for a study of the colour of this gemstone. The characteristic vivid green colour is exhibited by the hexagonal crystals of beryl of which emerald consists. Some of the material examined by the author consists of section-plates several millimetres thick cut normal to the optical axis and polished so that the spectrum of the transmitted light can be viewed directly. It is also possible to examine the spectrum of the light which passed through the specimen transversely to the optic axis. The depth of the colour varies considerably. Individual crystals may nearly be colourless and transparent. Deeply coloured specimens are also forthcoming.

It emerged from the studies that the perceived colour of emerald stands in the closest relationship to the extinction of the yellow sector of the spectrum in the wavelength range between 560 mμ and 600 mμ. Such extinction is necessary for the green colour to manifest itself with that degree of saturation which is characteristic of the finest emeralds. The blue sector of the spectrum is also weakened, but it can still be perceived in the wavelength range between 450 mμ and 500 mμ. The red sector in the wavelength range greater than 600 mμ is also much weakened but not totally extinguished. The residues left over of the red and blue sectors are masked from perception by the highly luminous green part of the spectrum.

The Red Rubies of Burma.—The mines in the Mogok District of Upper Burma have been for many centuries the source of fine rubies which found their way to other countries. The author is in possession of an ornament of sufficient age to be considered as an "antique" in which a group of these Burmese rubies have been inset with a gold plate at the back to reflect the light forwards and thus exhibit the colour of the stones to the best advantage. The spectral character of the red light thus shown up can be determined by simple inspection through a pocket spectroscope with a wavelength scale. It is found that there is a complete extinction of both the green and the yellow sectors of the spectrum, in other words, of the entire wavelength range from 500 mμ to 600 mμ. The red sector is present in full strength, and the part of the blue sector from 450 mμ to 500 mμ also shows up quite clearly. It is evident that only the red of the spectrum is perceived and that the blue part which is actually present in the reflected light is completely masked from observation.

The Blue Sapphires of Ceylon.—While on a short visit to Ceylon many years ago, the author was the recipient of a gift of material taken out during the working season from the gravel pits near Ratnapura which are the source of the far-famed gemstones of Ceylon. The material when sorted out and examined was found to include numerous pieces of corundum of varied colours. These were then separated from each other and kept apart for detailed study. Of particular interest were the specimens which showed a blue colour and could therefore be used to determine the spectral character of the light from blue sapphires. It emerged from the observations that the transmission through the material results in much reducing the brightness of the red, yellow and green sectors and particularly of the yellow, while on the other hand, the blue sector of the spectrum comes through without noticeable reduction of intensity. Thus, the explanation of the blue colour of the sapphires is that the light in the wavelength range from 500 mμ to 700 mμ which is of diminished brightness is masked from perception by the light of shorter wavelengths.

A special mention may also be made of the corundum specimens exhibiting a purple hue which were found in the collection. This colour was much more evident when the light traversed the material in some directions than in others. The spectroscope revealed that the purple hue had its origin in a practically complete extinction of the yellow sector in the spectrum for the particular direction of transmission of light through the material. It may be remarked that these specimens when placed under an ultra-violet lamp exhibited luminescence of a red colour, whereas the blue sapphires were non-luminescent.

CHAPTER XXII

DYES AND TEXTILES

THE colouring of textile materials by the use of dye-stuffs is an art which dates back to the remotest antiquity. The development of synthetic dyes in great variety on the one hand and of new textile materials by chemical processes on the other hand has much enlarged the range of such activities. As a consequence, textiles form a group of man-made products exhibiting a great range of colours with which it is readily possible to obtain a deep insight into the relationship between the perceived colour and the spectral characteristics of the light reflected or diffused by the material.

Bangalore is well-known as a producer of dyed silk in a variety of colours to suit all tastes. A collection of thirty specimens covering a whole range of hues was procured for the study. A survey of this material furnishes useful illustrations of the basic principles of colour perception set forth in the preceding chapters. The observer has only to view through a pocket spectroscope, one after another, the whole series of samples after arranging them in some suitable order. The specimens should, of course, be examined in a good light. Indeed, the observations are best made with the specimens held in sunlight.

A purple-coloured silk included in the collection exhibited the dark band of extinction of the yellow sector in the spectrum which is characteristic of that hue. Another piece of silk which had a brilliant rose-red colour exhibited a practically complete extinction of the green sector, while the red and the blue sectors were in full strength and nearly the whole of the yellow sector was also present. Scarlet silk exhibited a nearly complete extinction of the yellow sector, while the green and blue sectors were barely visible in its spectrum. Silk which was of a full red colour showed a complete extinction of the yellow sector, while the green sector was barely visible and the blue sector was extinguished. Silk which was of a rich green colour showed the green sector of the spectrum brilliantly, while the yellow was scarcely visible and the blue and red sectors though very weak were clearly seen in the spectrum and were evidently masked from perception by the brilliant green sector.

Five of the silk pieces in the collection showed a sequence of colours ranging from a bright blue to a deep violet and a comparative study of their spectra was therefore of particular interest. A common feature of all the cases is that the entire spectrum is visible from end to end but with the red and yellow sectors much weakened. The great differences in the colour perceived in the sequence are not consequential on any changes in the blue sector of the spectrum but arise from an alteration of the intensities in the green, yellow and red sectors. The progression of colour from bright blue to a darker blue and then to a very dark blue in three silks is the consequence of a progressive falling off in the luminosity of the green sector. The violet colour of the remaining two specimens results from the appearance of very conspicuous absorption bands in the orange-yellow region of the spectrum.

Four pieces of silk exhibited a regular colour sequence ranging from a pale yellow to a deep orange. The spectroscope showed a visible weakening of the blue sector to be the origin of the colour of the pale yellow silk. An extinction of the blue sector, an advance of the absorption further into the green sector and then the nearly complete absorption of the green sector represent the successive stages leading up to a deep orange as the colour of the silk.

Besides the specimen of a rich green colour mentioned above, there were several others which could also be listed as green but differed from it in respect of either colour or brightness or both. One of these specimens calling for special mention was quite brilliant but its colour could be more accurately described as a greenish-yellow. Its spectrum closely resembled that of the other green silks except that the presence of the yellow sector was readily recognisable. The specimen thus illustrates the very great influence which the yellow of the spectrum has on the colour and luminosity of composite light.

Several silks in the collection exhibited colours in which the presence of blue in association with the green could be recognised. Indeed, some could be listed as blue rather than as green. It is a noteworthy fact that in all such cases, the green sector of the spectrum appears far more luminous than the blue sector. It was possible, however, to recognise the progressive increase in the brightness of the blue sector with the change in the observed colour from a green to a greenish-blue.

CHAPTER XXIII

THE REPRODUCTION OF COLOUR

As is well-known, the materials, processes and techniques which are made use of in colour photography are based on the three-colour principle. They assume that our visual perception of colour is a result of a superposition of the visual perceptions of the same field as seen through filters which transmit the parts of the spectrum appearing in the red, green and blue sectors respectively. The existence of the yellow sector of the spectrum as an independent origin for the sensations of light and colour is totally ignored. That this has not resulted in a complete failure of the processes which have been developed for the reproduction of colour obviously calls for explanation or elucidation. It is also evident that in certain circumstances, the techniques adopted would fail to reproduce the visually perceived effects. It is proposed in this chapter to consider both the successes and failures of colour photography based on the three-colour principle.

In an earlier chapter, reference has been made to the use of a filter of glass doped with neodymium oxide for the study of the interference colours of thin films. A small piece of such glass, 5 cm. $\times$ 4 cm. in area and 3 millimetres thick, is quite adequate for such observations. Held against a white background, it is observed to reduce its brightness very considerably and to exhibit a purplish hue in the transmitted light. These effects are due to the complete extinction of the part of the spectrum in the wavelength range from 570 mμ to 600 mμ. There is no visible weakening of the red, green, and blue sectors of the spectrum, though a few faint bands of absorption can be seen in the green. The effect of the practically complete removal of the yellow from the spectrum by the filter is very strikingly exhibited when a highly luminous field, *e.g.*, a sunlit white cloud or a part of the sky in the vicinity of the sun is viewed through the filter held in front of the eye. A surprisingly large reduction in the brightness of the area under view is noticeable. This is incidentally also an illustration of the increasingly important role played by the yellow sector of the spectrum at high levels of illumination.

The effects on the perceived colours produced by observation through the neodymium filter are very curious and interesting. The blue sky, for example, appears bluer, though a little less bright. The green grass on a lawn appears of a deeper green colour, and a similar effect is observed with the leaves of plants or trees which are of a light green hue. But there is no observable effect on the colour of leaves which are themselves dark green. The scarlet flowers of a geranium appear red as seen through the filter, and pale red or pink flowers appear of a deeper red. The face of a fair-complexioned person appears suffused with blood when viewed through the filter. On the other hand, no change is perceivable with flowers or leaves of a bright yellow colour or in the cases of flowers or other objects which are themselves of a bright red or blue colour.

None of the foregoing statements would appear surprising in view of the findings recorded in the earlier chapters regarding colour in various cases. Generally speaking, it may be said that it is the absence of the yellow sector in the spectrum of composite light and not its presence which is significant and results in the perception of vivid colours such as purple, blue, green or red. Hence, processes for the reproduction of colour which take no account of the yellow sector do not suffer thereby and may actually gain in some cases. Some remark is necessary here regarding objects that exhibit a yellow colour in ordinary daylight. Such yellow is, in practically all cases, the result of an absorption of the blue sector of the spectrum, in other words, represents the integrated perception of all the other three sectors taken together, and not of the yellow sector alone. Hence, the exclusion of the yellow sector would result in a substantial reduction of intensity but not in any alteration of colour.

Colour photography based on the three-colour principle however fails to record what the eye perceives in the interference patterns such as those described and discussed in Chapters VII and XIX above when viewed by white light. The reason for this failure is that the variations in the brightness of the yellow sector of the spectrum due to interference determine the characters of the pattern both in respect of intensity and the distribution of colour. It is significant that the pictures in colour obtained of such patterns closely resemble what is seen of them when viewed by an observer through a filter of neodymium glass.

Colour Reproduction by Half-Tone Process.—Some remarks may be usefully made here regarding the processes used for printing pictures in colour on paper with the aid of blocks in half-tone. It is customary to use four colours, *viz.*, yellow, magenta, cyan and black. Usually, the first printing is with the yellow ink, the second printing is with the magenta ink, while the third printing is with the cyan ink. The fourth printing with black ink completes the picture which would otherwise fail to exhibit the local contrasts in respect of brightness exhibited by the object itself.

It should also be mentioned that the printing blocks are prepared by the half-tone process. The cross-line screen used in the process results in the breaking up of the picture into thousands of dots of light of varying size. These dots would appear in the impressions recorded on the paper by each of the four printing blocks. It should be emphasised that it is not the intention that the sets of dots in the impressions left by the four blocks should be coincident. On the other hand, to avoid such coincidence as far as possible, the half-tone screens are set at different angles to each other, these being so chosen as to avoid the appearance of moire patterns or other objectionable features in the reproductions. To secure these results, it is sometimes found desirable to use a different screen-ruling for the yellow plate than for the plates of other colours.

If, in the picture as finally printed, the dots of different colours do not actually overlap, the eye is presented with a mosaic in which areas of white, black, yellow, magenta and cyan of varying sizes are interspersed. It would evidently be not possible for the eye to take note of their individual presence and the visual impression would therefore be a synthesis in which the effects of the individual areas are integrated into a single sensation. This sensation would depend on the relative proportions of the five areas exhibiting different colours. As the absorption spectra of the three coloured inks are very different, we may expect that a wide range of colours would be exhibited in various cases.

When photographic reproductions in colour are viewed through a magnifier, the structures which appear in them as areas of colour are immediately recognisable. In some cases, they exhibit hexagonal outlines, in others they appear as squares. The sizes of the individual dots and the colours which they show can readily be related to the colour exhibited to the eye by the entire group. Where the colour is yellow or blue-green or magenta, the dots of those colours are naturally predominant. In areas exhibiting other colours, the presence of dots of two or three different colours is evident and their influence on the perceived colour is readily traceable.

Summing up, we may say that when we view a photographic reproduction in colour, in general we perceive hues which are not really there, but represent a synthesis effected within the eye of the observer.

CHAPTER XXIV

NIGHT-BLINDNESS

It has long been known that night-blindness or the inability to see properly at night is an affliction caused in some way by poor diet and that it may be cured by the consumption of certain food materials which were found by experience to be capable of remedying the deficiency. But night-blindness unconnected with malnutrition or disease is also known. The author became aware of a case of this kind, and the present chapter commences with a detailed study of the vision and visual characteristics of the person concerned who will be referred to here as Murthy, which is not his real name.

Murthy (age 26 years) is a young man in excellent health and apart from night-blindness is endowed with perfect vision, not needing any glasses either for near or for distant vision. He was examined by various tests for colour perception and for colour discrimination, and here again he was found to be perfectly normal. He was aware of his own disability since his earliest years and described it in some detail. Apart from its being congenital, the disability was also inherited, since his father had it during his lifetime, and one of his sisters at present experiences a similar disability.

Murthy was tested for acuity of vision with the aid of an ophthalmic chart in a darkened room lighted by a window covered by an iris-diaphragm in the manner explained in earlier chapters. Seated at an appropriate distance from the chart, Murthy read off the successive rows of letters correctly and without hesitation in the same manner as a normal observer. This continued to be the case even at low levels of illumination so long as the letters could be read by a normal observer. The existence of a difference between Murthy and a normal observer became evident only at such low levels that a normal observer seated at the usual distance from the chart is unable to read the letters on it. At such levels, the chart continued to be visible to the normal observer but not to Murthy. A noteworthy effect is observed in these circumstances, *viz.*, that when Murthy moved towards the chart and came close to it, the chart could be seen by him and appeared bright enough to permit of his reading the letters on it.

It appeared of interest to investigate whether Murthy differed from normal individuals in respect of his sensitivity to dim light in the central and peripheral regions of the retinae of his eyes. To test this, a uniformly illuminated screen which diffuses the light over a wide range of angles is employed. Such a screen appears brighter over its marginal regions than in the central areas, when the illumination is at low levels and the screen is viewed by an observer close to the screen. The phenomenon is noticeable when white light is employed, as also with monochromatic illumination. Its origin is evidently the greater sensitivity of the retina to dim light in its peripheral regions. Murthy's reports of what he saw of the phenomenon did not seem to indicate any differences between him and a normal observer.

Since Murthy's perception of colour is normal at ordinary or daylight levels of illumination, there was no reason to expect that it would exhibit any abnormalities at lower levels of brightness. The question was however carefully examined using the methods described in the earlier chapters of this book. No abnormality was disclosed by the investigation, and Murthy's sensory reactions to light in the different parts of the spectrum could be described as being identical with those of a normal observer, even in the dimmest light which he could perceive.

Since the inability of Murthy to perceive very dimly illuminated objects from a distance arises both in respect of foveal and of peripheral vision, it is clearly not possible to attribute it to any special features in the structure of his retinae, as for example, a deficiency in the proportion of rods to cones. It is also clearly not possible to attribute it to functional disorders of the kind arising from malnutrition. All the indications are that Murthy's defects of vision are a consequence of the inability of his eyes to transmit stimuli below a certain minimal strength to the centres of perception. Such inability arises also in the case of normal individuals whose eyes have been exposed to bright light, but only as a temporary phase. There seems to be a close similarity between the effects observed in the case of Murthy and those described in an earlier chapter on the adaptation of vision to dim light by normal individuals.

ANALYTIC SUBJECT INDEX

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