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 photo-chemical 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 $\varepsilon = h\nu$. 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 figure 1(A) and (B) in plate I. In figure 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 figure 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

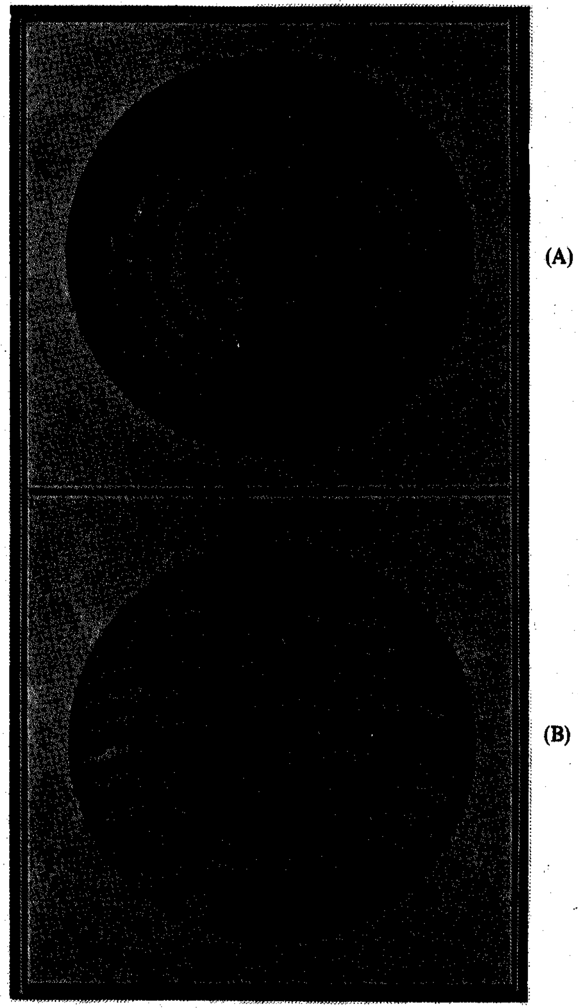

Figure 1. Interference patterns in sodium light.

Plate I

from one end to the other, from say 4000 Å units at the violet end to say 7000 Å 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 mm 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 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 figures 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 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.

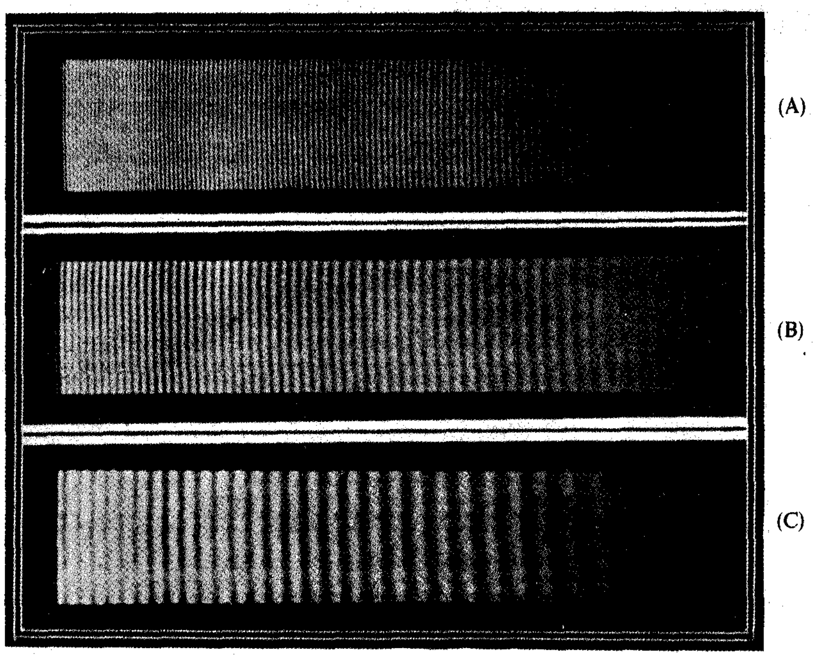

Figure 2. Channelled spectra of white light.

Plate II

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 figure 148 of Polyak's book and even better shown in figure 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 × 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 figure 3, and those observed with lissamine-green in figure 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)*.

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*For plate III, see p. 589.

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 × 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 mm, 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 ultraviolet 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. 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)*.

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*For plate IV, see p. 590.

CHAPTER V

Fluctuations of luminosity in visual fields

The phenomena 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 (*Curr. Sci.*, 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 mm thick and has a polished surface. A screen of this material 150 × 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 cm and a minimum of 2 mm 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 wavelength 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 1 mm 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 mm. 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 cm 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 figure 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 table 1.

Table 1. Diameter in mm

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 1 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:

$$h\nu^* = h\nu \pm kT.$$

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 ±215 wave-numbers. If expressed in wavelengths, 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 and 6500 Å respectively as the limits within which a critical study of colour discrimination is possible, the uncertainty of ±215 wave-numbers would be equivalent to ±38 Å at the violet end of this region and of ±89 Å 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 ±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 ±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 figure 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 Å. The noteworthy features in the graph are the very conspicuous dips in the wavelength region between 4900 and 5000 Å and in the yellow of the spectrum around 5800 Å. Higher elevations appear elsewhere and especially in the parts of

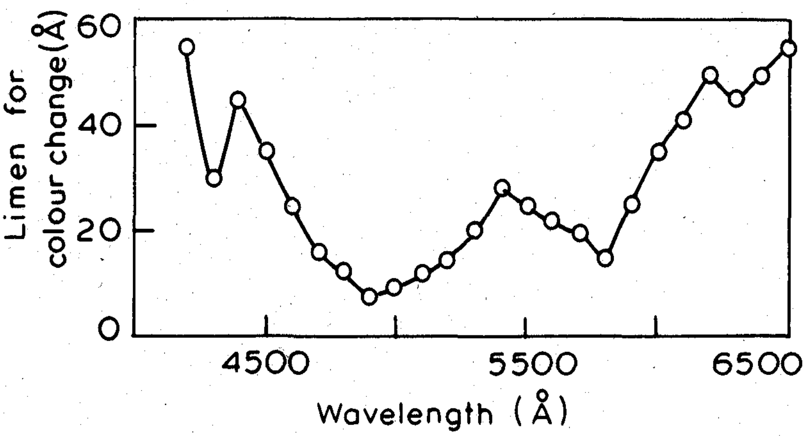

Figure 5. Discrimination of colour in the spectrum.

the spectrum near its two terminations. The lesser dips in the curve at 4300 Å in the short-wave region and at 6300 Å in the long-wave region correspond to points in the spectrum at which fairly rapid changes in colour are visually noticeable.

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 was effected by varying the widths of the entrance-slits of the two 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 entrances-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 Å 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.

The results obtained in the manner set forth above are shown as a graph in figure 6. A comparison with those shown earlier in figure 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 Å and 5800 Å. At 5400 Å, both curves exhibit a turning point where the colour changes but slowly. Dips of a minor character appear at 4300 Å and 6300 Å in both figures. In both figures also, the curve rises steeply on the two sides of the dip at 5800 Å and somewhat less steeply on the two sides of the dip at 4900 Å. The asymmetrical shape of the graph on either side of the wavelength of 4900 Å 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

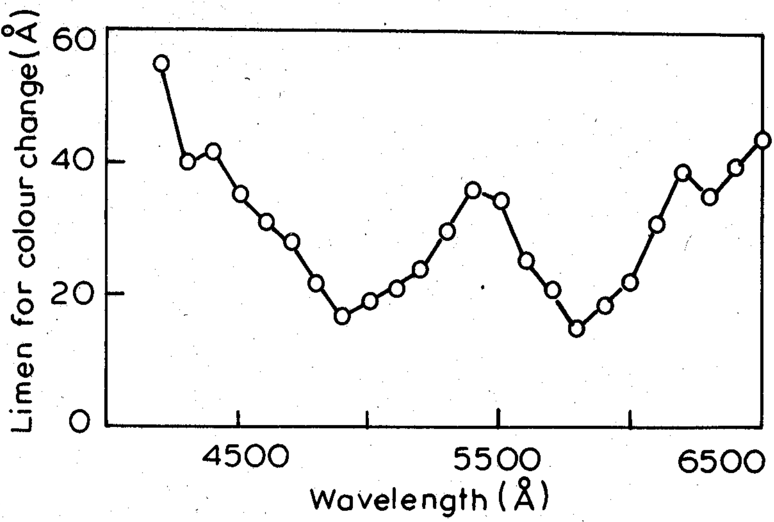

Figure 6. Discrimination of colour in the spectrum.

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 figure 6, table 2 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 2, 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

Table 2. Colour sensitivity of the eye.

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

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 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 90° 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 polarisation 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 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 90° 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 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 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 $\lambda 4358$ 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 $\mathrm{m}\mu$ 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 and 500 $\mathrm{m}\mu$. 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 and 500 $\mathrm{m}\mu$ 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 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.

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*For plate V, see p. 591.