CHAPTER XVII

The visual synthesis of colour

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

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

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

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

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

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

Cuprammonium: Dissolving copper sulphate in distilled water and adding ammonia in excess, we obtain a solution exhibiting a characteristic blue colour. When the concentration of the solution is high, the transmission by it is confined to the region of the shortest wavelengths and indeed, the cuprammonium filter is usually employed for isolating this part of the spectrum. When, however, the solution contained in a cell 2 cm thick is progressively diluted by addition of distilled water, striking changes may be observed in the spectrum of the light transmitted by it. The transmission, which at first is confined to the violet end of the spectrum, extends towards longer wavelengths. It ceases to be confined to the blue region of the spectrum and the green sector is also transmitted. This progressively gains in strength until as seen through the spectroscope, the green actually appears more luminous than the blue sector. With further dilution, the transmission extends into the orange and the red of the spectrum, but the yellow region remains faint, the orange and the red much exceeding it in brightness. Throughout this series of changes, the colour of the transmitted light is perceived as blue. The observations make it evident that the blue colour of the transmitted light and the extinction of the yellow in its spectrum are connected phenomena.

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

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

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

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

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

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

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

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

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

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

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

CHAPTER XVIII

The superposition of spectral colours

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

The perceptions of light and colour are the result of certain processes in which the retinae of our eyes play the leading role. The picture of these processes which has emerged from the studies described in the preceding chapters of this book is that we are concerned with certain pigmentary substances present in the retina which absorb the energy of the incident light and thereby enable it to be perceived. Four such substances have been recognised. One of them is a carotenoid pigment which functions in the wavelength range extending from the extreme violet end of the spectrum upto the boundary between the blue and the green sectors which may be placed at 5000 Å.The three others are hemeprotein complexes which are of the same chemical nature but are in three different states of oxidation. These enable us to perceive respectively the green, yellow and red sectors of the spectrum. That the absorption spectra of these pigments overlap is evident from the fact that we observe a continuous sequence of colour in which intermediate colours between green and yellow and between yellow and red are readily recognisable. Within the wavelength range between 5000 Å and the extreme red end of the spectrum, monochromatic light is perceived with a colour which varies with its position in the spectrum and is determinable with considerable precision. Such precision is highest in the wavelength range around 5800 Å which is the centre of the yellow region in the spectrum.

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

It is clear that this third case is on a different footing from the other two.

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

If ν_1 and ν_2 be the frequencies of the light incident on the retina, the corpuscular energies are given by $h\nu_1$ and $h\nu_2$ respectively. We shall assume that ν_1 and ν_2 correspond to wavelengths both greater than or both less than 5000 Å. Not all the corpuscles of these energies incident on the retina would be absorbed and contribute to the perception of light. If the numbers which are actually so effective are in the proportion of N_1 to N_2 during any small interval of time, the total energy available in that interval would be $N_1h\nu_1 + N_2h\nu_2$. If N_1 is large compared with N_2, there would clearly arise the possibility that only the more intense component would be perceived and that the weaker component would be masked or suppressed. But if N_1 and N_2 are comparable with each other, the sensory mechanism would find it possible to perceive both the spectral components but not separately. It would perceive the mixture as monochromatic light of frequency equal to

$$(N_1h\nu_1 + N_2h\nu_2)/(N_1 + N_2)h,$$

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

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

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

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

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

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

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

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

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

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

Similar observations can also be made using two mercury lamps as the sources, one to give the λ4358 radiation, and the other with a suitable filter to isolate the green λ5461 rays. It is found that when the relative brightness of the two superposed radiations is correctly adjusted, the result is a perfectly achromatic sensation. If one or the other is in excess, the field of superposition exhibits a bluish or a greenish tinge respectively.

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

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

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

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

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

Observations by this method confirm and usefully supplement the results obtained by the other methods. They establish the conclusions already set forth

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*For plate VI, see p. 592.

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

CHAPTER XIX

Colours of physical origin

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

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

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

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

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

Interesting effects are observed when the white-light interference patterns are viewed through a plate of glass which has been doped with neodymium oxide.

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

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

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

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

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

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

The colours of rotatory dispersion: The property exhibited by plates of quartz of rotating the plane of polarisation of light traversing the crystal along its optic axis provides a simple and very useful method for the study of the colours of composite light. A plate of quartz 1 mm thick and cut normal to the optic axis rotates the plane of polarisation by 15° of arc at the red end of the spectrum increasing to 50° at the violet end. If an extended source of light is viewed through the plate held between two crossed polaroids, the rotation results in a restoration of the light, but this can be extinguished for any particular region of the spectrum by turning one of the polaroids with respect to the other so as to compensate for such rotation. If the spectrum of the light coming through along the optic axis is examined through a spectroscope, it will be found to exhibit a perfectly dark band crossing it at the wavelength at which the light is extinguished, while on either side, the spectrum remains visible. The position of the band of extinction is observed to shift when one of the polaroids is rotated. It can therefore be set so as to place the extinction in any desired region of the spectrum. The colour of the light emerging through the polaroids and the crystal in the axial direction can then be observed and its relation to the part of the spectrum which is extinguished can be determined.

A plate of quartz 5 mm thick is very convenient for the observations. The difference of the rotations at the two ends of the spectrum does not then exceed 180° of arc, and hence there is only one band of extinction to be seen in the spectrum, and by setting the polaroids suitably, this can be moved from one end of the spectrum to the other. The varying colour of the light emerging in the axial direction can then be followed. Thinner plates of quartz may also be used and the region of extinction in the spectrum may likewise be moved from one end of it to the other. But the effective width of the spectral band of extinction would then be greater. This may be an advantage in certain cases. Such observations enable us firmly to establish various propositions which are fundamental in the theory of colour perception and which we shall now proceed to consider.

A colour which is well-known and easily recognised is that which goes by the name of purple. Already in Chapter XVII it has been shown by observations on the light transmitted by aqueous solutions of certain dye-stuffs that the purple sensation is perceived when the yellow sector of the spectrum has been eliminated by absorption, while the red, green and blue sectors of the spectrum appear with full strength. This result receives an independent confirmation from studies on the colours of rotatory dispersion. Observations with quartz plates of various thicknesses ranging from half a mm to 6 mm show that when the polaroids are so set that the colour of the transmitted light is purple, the spectroscope reveals that a band of extinction covers the yellow sector of the spectrum while the red, green and blue continue to be visible.

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

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

An important question concerns the colour which is complementary to green. In other words, if the green is excluded from the spectrum while the red, yellow and blue sectors are in full strength, what is the colour that is perceived? This question can be readily answered with the aid of a quartz plate which is 5 or 6 mm thick. The polaroids are set so that the colour of the light emerging in the axial direction is purple. Spectroscopic examination shows that the yellow of the spectrum has then been extinguished. One of the polaroids is then turned round so that the band of extinction moves from the yellow well into the green and is at the centre of the green sector. The yellow and red sectors as well as the blue sector are seen quite brilliantly, while the green is almost entirely cut out from the spectrum. The transmitted light appears of a rose-red hue which is thus the complementary colour to green.

A block of colourless quartz 15 mm thick with polished faces normal to the optic axis and held between crossed polaroids exhibits the colours of rotatory dispersion quite conspicuously when viewed against a bright field of illumination. The pattern consists of concentric rings of colour around a coloured centre, the rings being alternately green and rose-red. A noteworthy feature observed in these patterns is that the bands of contrasting colour have sharply defined boundaries separating them from each other. The positions of these boundaries coincide with the lines of zero intensity in the same patterns as seen with the monochromatic light of a sodium lamp. A block of this thickness exhibits three bands of extinction in the spectrum of the light which has traversed the crystal along its optic axis. The change in the colour of the transmitted light occurs when one of the bands of extinction passes over from the red to the green sector in the spectrum.

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

The answer to this question, in other words, the real explanation of the blue colour of the sky is that it is a consequence of the masking or suppression of all the other colours in the spectrum by its blue sector. In Chapter XVII, we have already noticed that such masking may be demonstrated with the aid of a dilute solution of cuprammonium. Adding water to this solution contained in a cell which is 2 cm in depth, the spectrum of the light transmitted by the cell may be progressively extended so as to cover, besides the blue sector, also the green, yellow and red sectors, in other words, the whole of the spectrum. In this process, the intensity of the light which passes through the cell increases rapidly. But so long as the yellow and red sectors exhibit an appreciable diminution of their intensity relatively to the blue sector, the colour of the transmitted light remains a clear blue.

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

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

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

CHAPTER XX

The colours of foliage and flowers

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

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

Extensive studies carried out by the author using these techniques have enabled a comprehensive view to be obtained of the nature of floral colours and of their relationship to the absorptive properties of the pigments contained in the material of their petals. Perhaps the most interesting discovery made in the course of these studies is that in many cases, the light emerging from the petals exhibits a series of discrete absorption bands which are usually three in number. These bands appear in the region of wavelengths between 480 and 650 mμ. Their positions and the strength of the absorption in the different bands determine the observed colour of the flowers. There is no difficulty whatever in obtaining

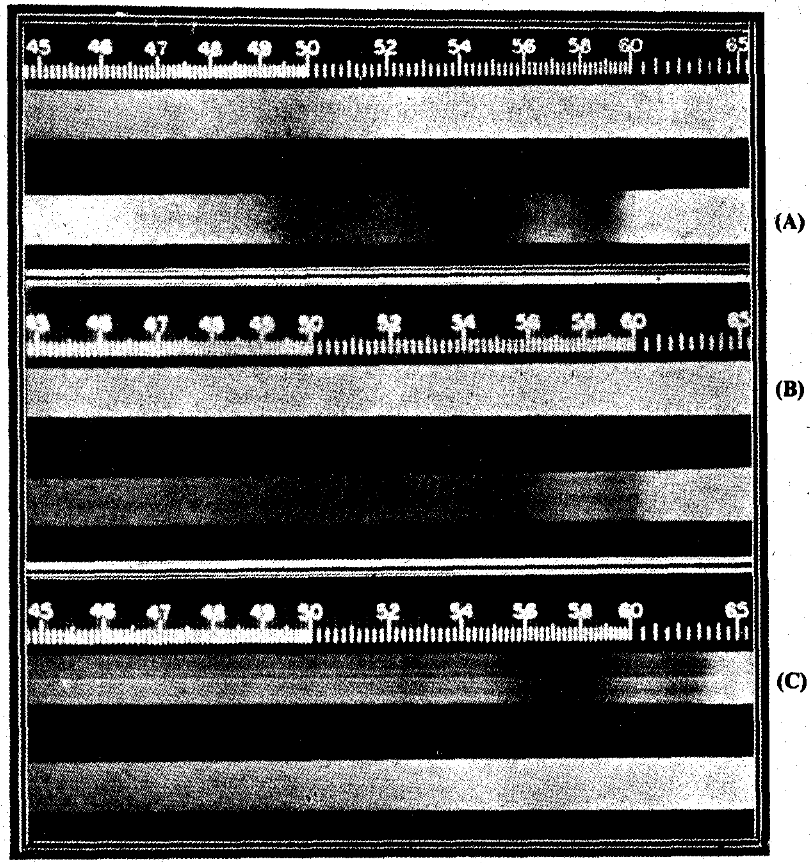


Figure 9. Absorption spectra of flowers. (A) *Spathoglottis plicata* (B) *Purple cineraria* (C) *Clitoria ternata.*

Plate VII

photographic spectra accompanied by wavelength scales which exhibit these bands in a conspicuous fashion. Many such spectrograms have been obtained and a selection from them has been reproduced with this chapter. They help to show clearly how the observed colour of the flowers is related to the spectral character of the light emerging from their petals.

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

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

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

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

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

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

The aster and its varied colours: Asters are very attractive flowers by reason of the rich and varied colours which they exhibit. The flowers appear in bunches at the end of long leafy stalks, each flower consisting of a great many petals grouped around a common centre. The material commercially available at Bangalore

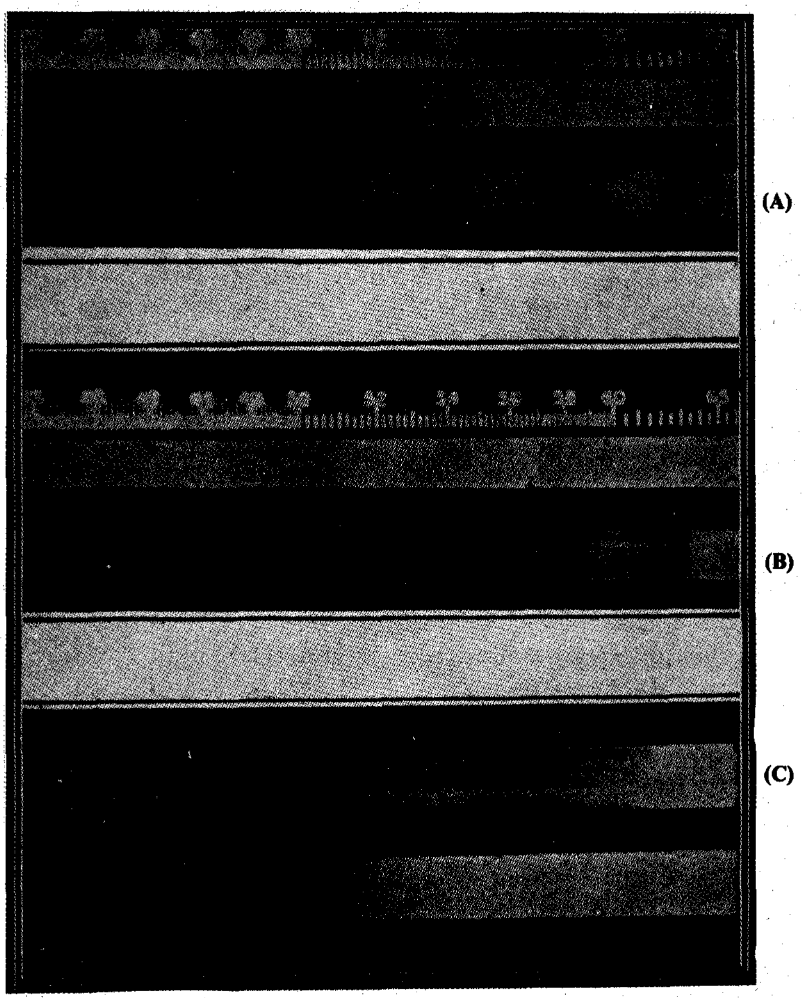


Figure 10. Absorption spectra of flowers. (A) Delphinium. (B) Lobelia. (C) Blue cornflower.

Plate VIII

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

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

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

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

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

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

The spectra of red flowers: One of the best known of garden flowers is the China

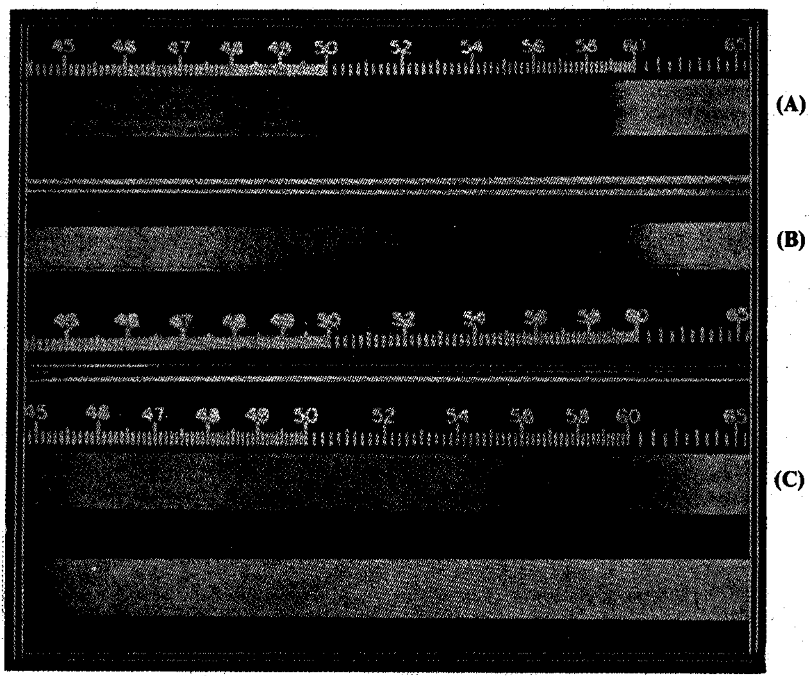


Figure 11. Absorption spectra of flowers. (A) Purple balsam. (B) African violet. (C) Morning glory.

Plate IX

Rose (*Hibiscus rosa sinensis*) which has large single blooms from which long bunches of stamens hang out. The petals exhibit a rich red hue. Spectroscopic examination shows a complete extinction of the blue, green and yellow sectors in the light which comes through them, the red sector commencing from 600 mμ being in full strength in the transmitted light. The spectral characters of the floral pigment responsible for this spectral behaviour is better understood when it is extracted by the aid of acetone, leaving the petals colourless. The extract exhibits a deep red colour and an intense absorption covering all wavelengths less than 600 mμ. Using short absorption paths or else by diluting the extract with acetone, thereby allowing light of smaller wavelengths to come through, a strong absorption band between 580 and 590 mμ, reveals itself, as also another strong band between 530 and 550 mμ. There is also a weak absorption band at about 500 mμ. The blue sector of the spectrum can be seen coming through, though only weakly. If, instead of the Chinese Hibiscus, we use red or crimson roses, precisely similar phenomena are observed.

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

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

The tree known as *Solanum grandiflorum* of which the popular name is the nightshade or potato tree, flowers profusely. The petals have a violet colour which in the course of a few days fades away and becomes nearly white. In the wavelength range between 570 and 595 mμ, there is nearly complete extinction and there is a noticeable diminution of the intensity of the green of the spectrum. There are also detectable absorption bands at 545 and at 635 mμ. The red and the green are alike suppressed from perception by the violet of the spectrum.

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

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

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

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

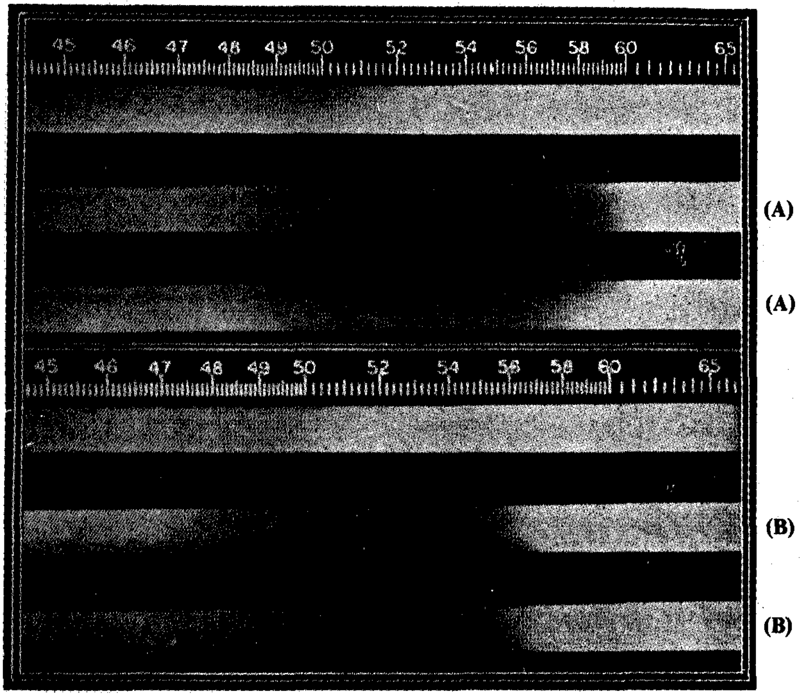


Figure 12. Absorption spectra of flowers. **(A)** *Lagerstroemia flos reginae* (purple). **(B)** *Lagerstroemia flos reginae* (rose-red).

Plate X

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

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

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

CHAPTER XXI

The colours of gemstones

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

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

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

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

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

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

CHAPTER XXII

Dyes and textiles

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

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

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

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

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

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

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

CHAPTER XXIII

The reproduction of colour

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

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

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

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

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

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

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

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

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

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

CHAPTER XXIV

Night-blindness

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

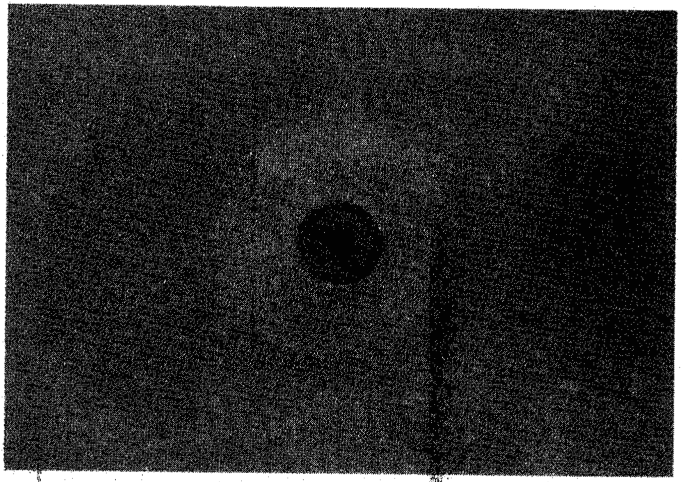
Murthy (age 26 years) is a young man in excellent health and apart from night-blindness is endowed with perfect vision, not needing any glasses either for near or for distant vision. He was examined by various tests for colour perception and for colour discrimination, and here again he was found to be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

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

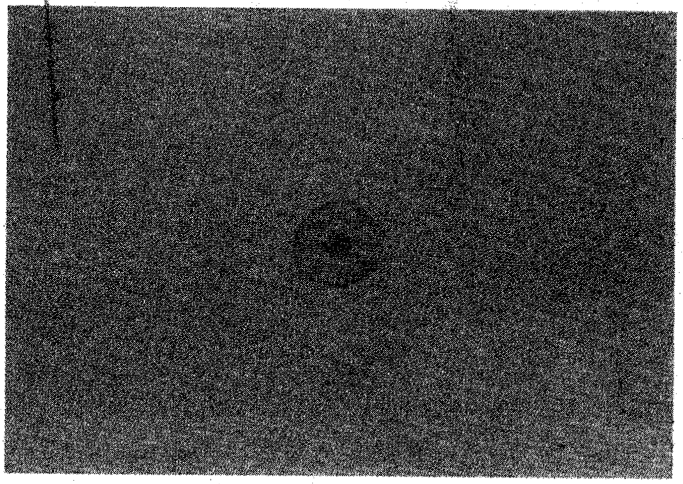
It appeared of interest to investigate whether Murthy differed from normal individuals in respect of his sensitivity to dim light in the central and peripheral regions of the retinae of his eyes. To test this, a uniformly illuminated screen which diffuses the light over a wide range of angles is employed.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

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

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



(3)



(4)

Figures 3 and 4. Views of the retina.

Plate III

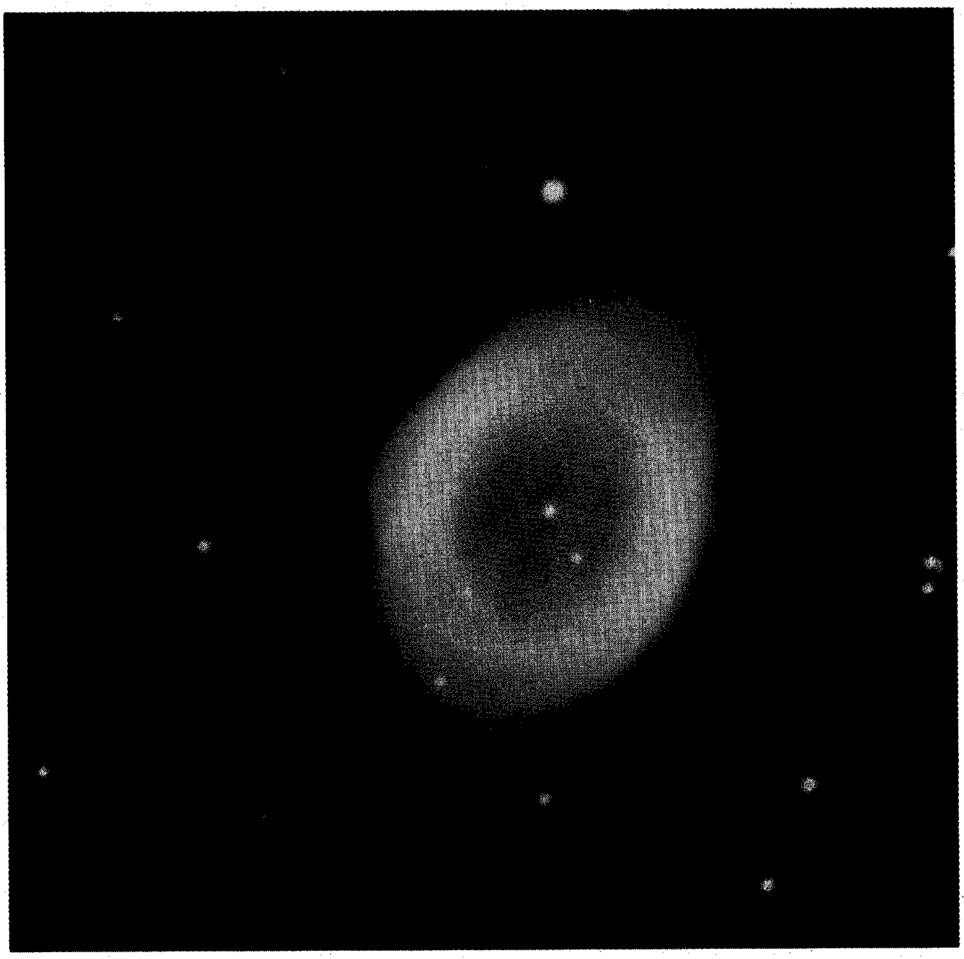
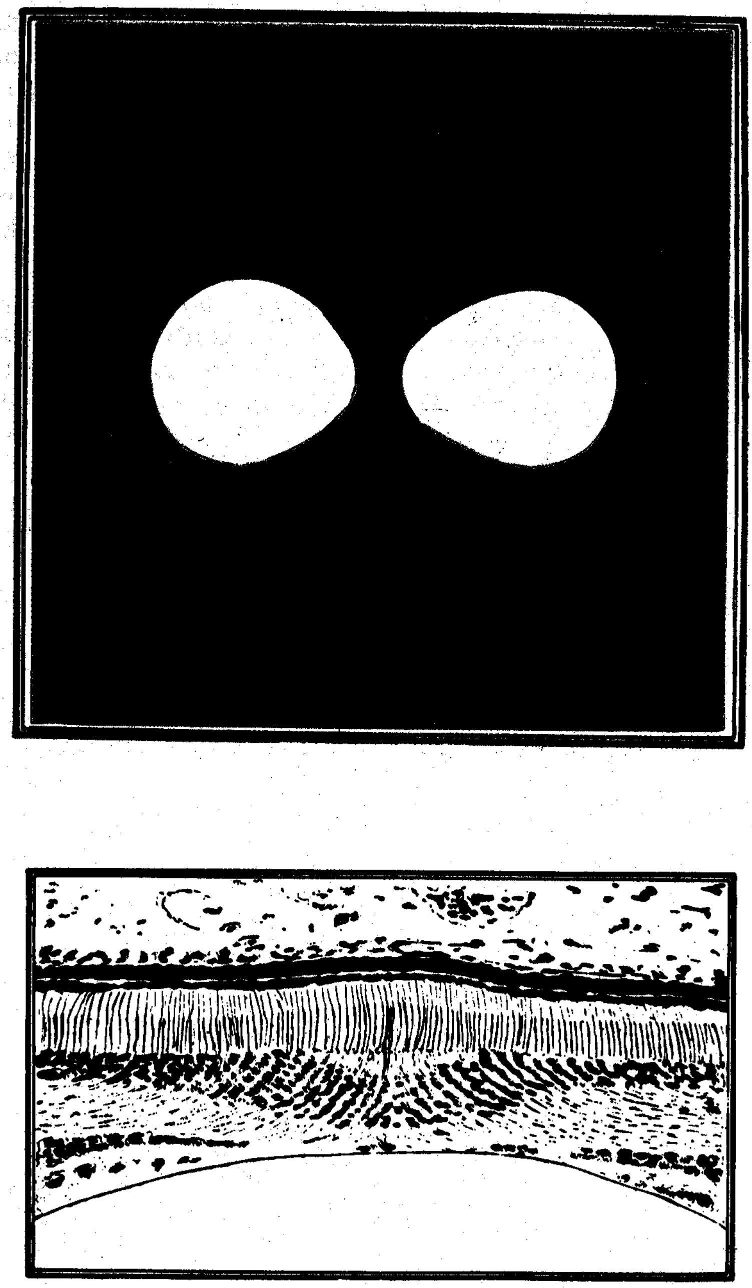
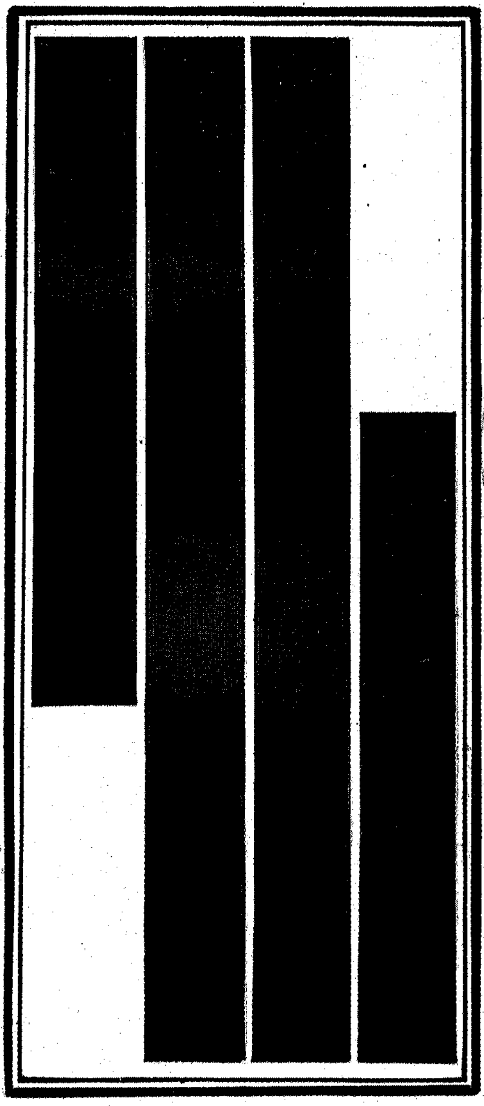


Plate IV. The ring nebula in lyra as seen in large telescopes.



Perception of polarised light and the structure of the fovea.

Plate V



The colours of superposed spectra.

Plate VI