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