CHAPTER X

Visual acuity and its variations

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

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

For the study of visual acuity and its variations, the well-known Snellen test-charts of the type used by oculists are very convenient. Letters of various sizes printed in black on white card and arranged in rows and columns appear in these charts. The letters are of large size and few in number in the top rows and progressively diminish in size and increase in their number in the following rows. The sizes of the letters in the chart are such that when it is placed at a distance of 8 m from an observer with normal vision in a well-lighted room, he can read all the letters without difficulty or hesitation.

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

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

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

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

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

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

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

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

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

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

An impressive demonstration of the statements made above may be given, using appropriate arrangements of the nature already described. A test-chart containing a series of rows of printed letters of progressively diminishing size is held by the observer in his hand and moved away from an area strongly illuminated by monochromatic light to a region in which the chart is much less strongly lit up. Viewing the chart in these circumstances, it is noticed that the successive rows of letters become illegible, commencing from those of smallest size and followed by those of larger size. Simultaneously, the colour of the illuminated chart exhibits a rapid change, beginning from a rich hue resembling that of the light-source as viewed directly and falling off to a much paler hue and progressively approaching an achromatic sensation. The experiment may be made with monochromatic light of various colours, viz., the yellow light of a sodium vapour-lamp, the green and the blue radiations of mercury-vapour isolated by appropriate colour-filters, and also with the light from a tungsten filament lamp covered by a deep red filter. The rapid weakening of the colour sensation which accompanies the rapid diminution of visual acuity is noticeable in all cases. But the effect is particularly striking as exhibited by the blue-violet λ4358 radiations of the mercury vapour-lamp.

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

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

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

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

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

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

CHAPTER XI

Vision in dim light

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

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

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

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

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

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

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

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

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

Observations with colour-filters: The observer takes a seat in a completely darkened room at a distance of about 5 m from a white screen which he faces. The light of the sky enters the room and falls on the screen through an aperture covered by an iris diaphragm the diameter of which can be varied over a great range of values from 20 cm down to a few mm. The screen of which the illumination is thus controlled is viewed by the observer through one or another of a set of suitably chosen colour-filters placed before his eye. The observations are made at a series of levels of brightness commencing from the lowest possible at which the illumination of the screen is so feeble that it remains invisible to the observer until after a prolonged stay by him in complete darkness. The results of the observations are quite different for the different colour-filters and indicate how the luminous efficiency of the spectrum in its various regions alters with the level of the illumination of the screen.

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

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

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

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

A more satisfactory procedure for the study of the spectrum of twilight will now be described. The observer sits in his room 2 m away from a window which faces north or east and is provided with wooden shutters. These shutters when fully open allow a clear view of the sky. But only a vertical slit a few mm wide is allowed to remain open between them, while the shutters of all the other windows are closed, thereby making the room completely dark. The observer views the slit through a replica-grating held before his eye, fixing his attention on its first-order diffraction spectrum. Since the spectrum is an image of the slit formed by diffraction, it has the full length of the slit which may be a metre or more. A spectrum of this length is seen running through the field of view from end to end. It thereby becomes possible to study the spectrum as seen both by foveal vision and by peripheral vision over a wide range of visual angles.

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

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

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

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

The source of light employed is the same as before, viz., a coiled-coiled tungsten-filament-lamp kept cool by a fan blowing air on it and emitting a brilliant white light. This is placed in an annexe separate from the completely darkened room in which the spectrograph and the observer are located, and at a distance of 5 m from the instrument. The collimator is directed towards the source of light and a screen prevents the entry of light into the observing room except through an aperture 5 cm in diameter covered by a ground-glass sheet which diffuses the light forwards. The distance between this sheet and the slit of the spectrograph being 4 m, the diffusion results in the flux of light entering the instrument being greatly diminished. A further diminution is effected by an iris-diaphragm which covers the aperture and enables it to be reduced from a maximum diameter of 5 cm down to 3 cm. The slit-width of the spectrometer can also be varied from 1 mm down to a few hundredths of a mm.

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

Observations with mercury lamps: A very instrúctive modification of the arrangements described above is to replace the tungsten-filament lamp by a mercury-vapour lamp enclosed in a bulb of the type which is commercially available. With such a lamp at a distance of 5 m from the slit of the collimator and with the slit-width set at a tenth of a mm, all the strong lines of the mercury arc appear on the ground-glass screen of the spectrograph and can be viewed through a magnifier. It is noteworthy that the two so-called yellow lines λ 5790 and λ 5770 are recognisably different in their colour, the former being distinctly orange-yellow and the latter distinctly greenish-yellow. When a plate of ground-glass is put in and covers the aperture through which the light of the mercury lamp has to pass before it reaches the spectrograph, there is a great diminution in the brightness of the spectrum. The lines λ 4358 and λ 4046, and the faint continuous spectrum disappear, while the yellow lines λ 5790–5770 become much weaker than the green λ 5461. The weak λ 4916 also ceases to be visible. When the iris-diaphragm covering the aperture is progressively closed down, further changes appear in the spectrum. The yellow lines become fainter and fainter and finally disappear. But the green line λ 5461 continues to be visible as the sole surviving feature of the spectrum till the very end.

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

CHAPTER XII

The night-sky

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

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

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

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

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

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

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

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

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

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

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

Visibility of the stars: The lucid stars, in other words, those which can be perceived by the unaided vision in the most favourable circumstances are a few thousands in number. The very bright stars are relatively few and those which are less bright become progressively more numerous as they go down in the scale of luminosity. Using a pair of binoculars of which the objectives have an aperture of 5 cm each, the number of stars which are visible shows a great increase. The brilliancy of the stars which can be seen without optical aid is also greatly enhanced. From these facts of observation, we may infer that the factor which limits the visibility of stars to a relatively few is their low luminosity. In other words, the vast majority of the stars are not seen by reason of the fact that the light they emit and which reaches us is far too weak to excite a persistent sensation.

A convincing demonstration of the correctness of the foregoing inference is furnished by observations of the night-sky through a pair of polaroid sheets of adequate size (at least 10 cm square) mounted in circular frames so that they can be held covering both the eyes of the observer and rotated with respect to each other. A protractor with an index attached to the frames enables the angle of setting of the polaroids with respect to each other to be read off at a glance. When the polaroids are in a parallel setting, the brightness of the transmitted light is the maximum: as the setting is altered, the transmission progressively diminishes and becomes zero when the polaroids are in the crossed position. In the parallel setting, the well-known constellations of bright stars, e.g., Canis Major, Orion and Ursa Major, can be seen and present their usual appearance. But as the setting is altered, the stars pass out of sight in succession, the fainter ones first, followed by the others and finally also by the brightest stars. During this operation, the constellation becomes unrecognisable and finally disappears altogether.

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

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

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

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

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

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

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

CHAPTER XIII

Adaptation of vision to dim light

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

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

It is a matter of familiar experience that an observer who has been out-of-doors and enters a dimly-lit room finds at first that he is unable to perceive the objects in the room and has the feeling of being in a dark chamber. Later, his vision improves and there is a progressive increase in the apparent brightness of the walls of the room and of the objects located in it. It is these features which characterise the process of adaptation. A convenient procedure for studying them in detail is to place a screen of white plastic material of suitable size, say a square metre, in a completely darkened room into which, however, skylight enters through an opening of adjustable size and falls upon the screen. The observer takes up a position at a suitable distance from the screen, say 5 m, from which he can keep it in view. The opening through which the light finds entry being an iris-diaphragm, the illumination of the screen can be varied at will over a wide range of values.

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

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

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

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

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

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

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

We shall first consider the influence of monochromatic light of high intensity on the visibility of dim light. Sources which are particularly suitable for such a study are a sodium-vapour lamp and a mercury-vapour lamp respectively, as they are commercially available with high candle-powers. The yellow light of a sodium-vapour lamp is sufficiently monochromatic and needs no filtration. Four plates of blue window-glass held together suffice to isolate the λ 4358 light of the mercury-vapour lamp from the other radiations accompanying it. A sheet of ground-glass held near the source is helpful as it diffuses the light which is viewed by the observer from a comfortable distance. The observations begin after allowing a sufficient period for complete dark-adaptation before the light of high intensity is switched on. It is switched off after an interval of say ten minutes. The observer thus turns towards a faintly illuminated screen which was clearly visible to him before the monochromatic light was switched on. The effect of exposure to this bright light on the visibility of the dimly lit screen then becomes apparent.

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

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

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

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

CHAPTER XIV

The chromatic responses of the retina

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

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

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

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

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

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

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

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

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

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

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

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

CHAPTER XV

The visual pigments

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

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

430 mμ respectively. The absorption strength falls off rapidly as we proceed from the peak at 420 mμ further towards the ultra-violet.

There is a close correspondence between the features exhibited by the light-absorption curve of xanthophyll and the observed characters of the blue sector in the spectrum of white light. The limits of the blue sector have been indicated as the wavelengths between 400 and 500 mμ. It will be seen from figure 7 that this is also

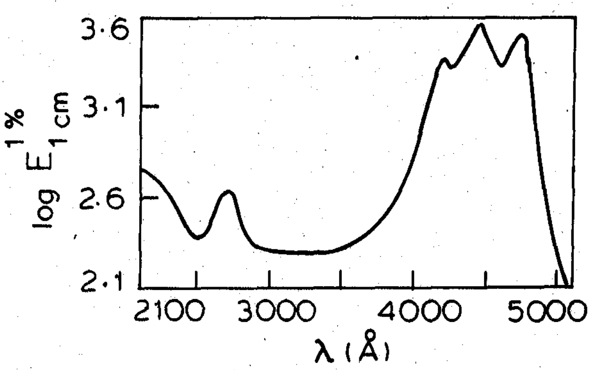

Figure 7. Light absorption curve of xanthophyll in hexane solution (after Karrer and Jucker).

the range in which the absorption of xanthophyll is most marked. A noteworthy feature in the spectrum of white light is the very rapid change in colour from blue to green manifesting itself at 490 mμ, a traverse of 10 Å in wavelength along the spectrum being sufficient for a readily observable difference in colour. This is precisely the location in the spectrum where the curve of light-absorption for xanthophyll drops steeply from a high to a low value. We are therefore justified in regarding the rapid colour change as a consequence of the pigment functioning in the blue becoming less effective and giving place to another pigment functioning in the green.

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

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

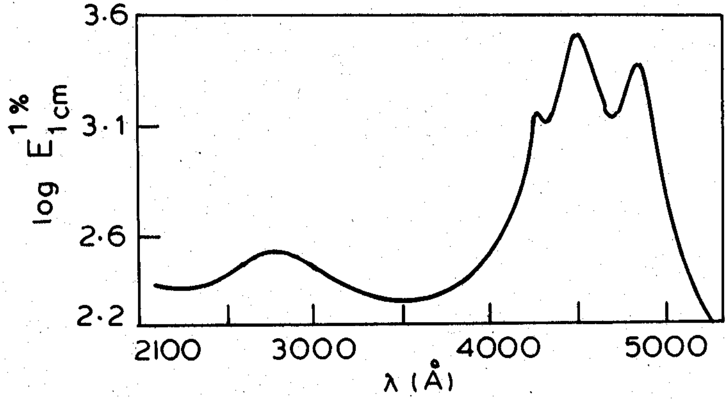

Figure 8. Light absorption curve of β-carotene in hexane solution (after Karrer and Jucker).

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

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

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

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

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

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

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

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

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

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

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

CHAPTER XVI

Defective colour vision

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

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

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

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

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

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

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

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

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

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

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

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