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# The new physiology of vision—Chapter XXXV. The faintest observable spectrum

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It is a noteworthy characteristic of human vision that it can function usefully and enable us to perceive objects illuminated by light at enormously different levels of brightness. The magnitude of these differences is indicated by a comparison between the illumination provided by the light of the noonday sun and the illumination received from the star-lit sky on a clear moonless night. Somewhere between these extremes is the illumination by the light of the full-moon shining in a clear sky. Astronomers rate the Sun as a star of magnitude—26·8 and the full-moon as a star of magnitude—12·0. These figures indicate that moonlight is about half-a-million times weaker than sunlight. Star-light is, of course, much weaker than the light of the full-moon. It has been estimated that the integrated light from the stars received at ground level is weaker than sunlight by a factor of three hundred million or thereabouts.

The question naturally arises whether the apparatus of human vision is the same and functions in the same manner over the whole of this enormous range of intensity of the light perceived by it. This is an issue of great importance and interest. The term "apparatus of vision" is here intended to refer not to any particular area in the retinae of our eyes, as for example, the foveal region, but to the whole of the retina or at least to the part of it that can be observed to function in wide-angle vision. A method of investigating this problem which suggests itself is to study the spectrum of white light over the whole of this range of brightness making use of a technique which enables us to perceive simultaneously the functioning of the foveal region and of the outlying parts in the retina. The present investigation describes such a technique and sets out the surprising results which have emerged from the studies made with it.

*The technique of study*: An extended linear source of light and a replica diffraction grating together make all the equipment that is needed for the purpose of the present study. The observer holds the diffraction grating close to his eye and views the line-source which may be at any convenient distance, the grating being held with its rulings parallel to the line-source. The observer's field of view will then include the line-source as well as the diffraction spectra of various orders on either side of it. As the two diffraction spectra of the first order are usually much brighter than those of higher orders, the observer can view one or the other of those two spectra. Since the line-source may be of any convenient length, the spectrum under view will cover a great range of visual angles, both above and below the visual axis of the observer.

If the line-source is an elongated slit, it will be fully illuminated only if it is backed by an extended field of light. Hence, for such studies, a source of diffuse illumination covering the entire length of the slit is necessary. Since the aim of the investigation is to carry the study down to the lowest levels of illumination at which the spectrum can be perceived, it is necessary for the observer to be inside a completely darkened room and to remain there long enough to enable him to perceive the feeblest illumination. This may be for an hour or such longer period as may be found to be necessary. The only light which should find entry into the room is that passing through the slit under observation.

Two distinct choices are available for the light-sources to be studied. The first choice is that of the natural sources of diffuse light which are available over a great range of brightness, viz., the sun-lit sky in daytime, the progressively altering illumination of the sky during the twilight period, the sky illuminated by the light of the moon in its various phases, and finally the star-lit sky on a clear moonless night.

The other choice is that of artificial sources of light. As we are concerned with the spectrum of white light, we naturally choose a source emitting light at a high temperature and hence a source which is inherently of high luminosity. The question here arises of a procedure by which the light can be reduced to the lowest levels of luminosity, but without any change in its spectral character. The procedure which has been devised and which enables this aim to be realised is to allow a beam of light from a tungsten-filament lamp run at a high temperature to be diffused by a milk-white plastic screen, three such screens in succession being employed. The screens have polished surfaces which reflect a part of the incident light. But they are so placed with respect to each other that these reflections are not made use of, but only the light that diffused in directions other than that of regular reflection by the surface of the screen. The light is much enfeebled in this manner but without any change in its spectral character. By placing the three screens which operate by such diffusion at suitable distances from each other, the brightness of the light that is received and diffused by the third screen and thereafter passes through the slit under view by the observer is enormously reduced. It should be mentioned here that the luminosity of the spectra as seen by the observer is determined by the width of the slit and its distance from the observer. It can be altered through a great range of values by the observer approaching towards the slit or moving away from it.

*Observations during twilight*: To study the spectrum of skylight during the twilight period, the observer places himself at a distance of about three metres from one of the windows of a room, all of which are covered by wooden shutters, but of which one can be opened a little so as to admit light from the sky through a narrow vertical slit about 150 cm in length. The opening of the slit can be varied, about a centimetre being the most suitable, though narrower slits can also be made use of. The resolution and dispersion provided by the diffraction grating in these circumstances is such that a great many of the Fraunhofer lines in the solar spectrum are clearly seen when the sun-lit sky is viewed through the slit by the observer with the grating held in front of his eye. To serve as a standard of comparison, a white diffusing screen of sufficient size is set up at a suitable distance so that it can be viewed through the slit. If the screen is lit up by direct sunlight, the solar spectrum seen by the observer exhibits the features characteristic of fairly high levels of brightness. The greatest luminosity is then in the yellow sector of the spectrum and the blue sector shows all its three different colours, viz., blue, indigo and violet in the order of diminishing wavelength.

In the latitude of Bangalore, the duration of twilight, in other words, the interval between the setting of the sun and the emergence of the fainter stars from the luminous background due to scattered sunlight is about an hour. During this period, great changes manifest themselves in the brightness of the part of the sky under observation. At the same time, however, the eyes of the observer seated in the dark room become enormously more sensitive to faint light. As a result, the slit continues to appear to be nearly as bright as before. But the spectrum of the light emerging through the slit is observed to alter in a remarkable fashion.

Four noteworthy changes may be noted in the appearance of the spectrum in the first half-hour of twilight during which the sky and the landscape illuminated by it both remain fairly bright. One of these changes is in the appearance of the blue sector of the spectrum. The bright blue which precedes the indigo and the violet in the spectrum disappears and is replaced by the darker indigo colour and this in its turn disappears, the "blue sector" then appearing of a violet colour throughout. A little later, the violet colour also fades away, but the "blue sector" continues to be distinguishable from the adjoining green sector by reason of its lack of colour and its much smaller luminosity.

A second noticeable change is in the location of the most luminous part of the spectrum. This exhibits a very definite shift, moving from the yellow sector into the green sector, in other words, from about 580 to about 550 m$\mu$. But the green colour of the spectrum is the wavelength range between 500 and 560 m$\mu$ remains conspicuous. Indeed it appears distinctly more saturated than when the spectrum as a whole is highly luminous.

The third and indeed most striking change in the character of the spectrum is the progressive contraction and final disappearance of the red sector of the spectrum, in other words, of the part of the spectrum included in the wavelength range between 700 and 600 m$\mu$. The longer wavelengths in this region are the first to become too feeble to be observed, despite the greatly increased sensitivity of the eye to dim light. When the visible end of the spectrum is at about 650 m$\mu$, a distinct change is noticeable in the colour of the region between 650 and 600 m$\mu$. It then assumes a deeper red hue. Finally, the spectrum in this region becomes too weak to be observed and disappears from sight. This disappearance occurs long before the twilight illumination of the sky itself becomes unobservable, and while the landscape outside is still clearly visible in all its details.

The fourth and last change in the character of the spectrum is the weakening and disappearance of the yellow sector of the spectrum, in other words of the wavelength range between 560 and 600 m$\mu$. The disappearance of the yellow closely follows that of the red sector. But when the red and yellow sectors are no longer observable, the green sector remains conspicuous. Thus, the spectrum of skylight in the latter part of the twilight period consists principally of the green sector in the wavelength range between 560 and 500 m$\mu$, the maximum of luminosity being at about 540 m$\mu$. This is accompanied by a weak extension towards shorter wavelengths representing the residue of the blue sector which remains visible at this stage.

It should be emphasised that the foregoing features are not in any way different in the different areas of the retina in which the spectrum is visibly manifested.

*The spectrum of the star-lit sky*: The disappearance of twilight from the sky is followed by a further fall in the intensity of the spectrum which nevertheless continues to be visible. All trace of colour having vanished, a method had to be devised to make it possible to ascertain the region of wavelengths in which the spectrum continues to be visible. This is accomplished by the use of a comparison spectrum of which the brightness is not so great as to disturb the sensitivity of the observer's vision but nevertheless allows spectral lines of known wavelength to be discernible. A white diffusing screen is placed below the level of the part of the sky under observation so that it can be seen through the same slit. This screen is illuminated by a beam of light from a distant mercury lamp or sodium lamp reflected by a system of mirrors. The characteristic lines of the spectrum of mercury or of sodium are then seen below and in a line with the continuous spectrum of the sky. The comparison spectrum could be switched off except when it is actually needed for locating the position and extension of the continuous spectrum which it adjoins.

From such observations, it becomes evident that the blue sector of the spectrum is not present in the spectrum of the star-lit sky. The limits of the part of the spectrum which continues to be visible can be determined by reference to the positions of the discrete lines of mercury and of sodium appearing below it. The yellow sodium doublet $\lambda$ 5890–5896 is found to lie well outside the limits of the observable spectrum. Likewise, the violet line $\lambda$ 4358 of the mercury arc lies outside of those limits. On the other hand, the green $\lambda$ 5461 mercury line lies well within the region of the visible continuous spectrum. The yellow doublet $\lambda$ 5770–5790 of mercury appears just outside the long wavelength limit of the sky-spectrum, while the weak $\lambda$ 4916 of mercury appears close to its short-wave limit.

What is actually seen of the spectrum is thus confined to the wavelength range between 560 and 500 m$\mu$, the brightest part being at about 530 m$\mu$. These features are exhibited by the entire length of the spectrum covering the retina, irrespective of the particular part of it towards which the observer directs his vision.

The observations of the star-lit sky were made at various hours of the night when the sky was quite clear and free from haze or cloud, and the disturbing effects arising from the city-illumination were therefore at a minimum. The sky to the north of the Institute was made use of, since it was much better than the sky to the south in its freedom from such disturbance. No significant differences in the characters of the spectra could be noticed depending on the part of the sky under observation or on the time at which the observations were made.

*Observations with artificial light-sources*: The technique employed of such observations has already been described. It proved highly successful by reason of the fact that two dark rooms were available which were connected by a covered passage with two right-angle bends in it. It was possible, therefore, to place a brilliant source of light in one room without any light finding its way into the other room through the passage. The light diffused by a brilliantly illuminated screen placed in one room and then successively by two other diffusing screens placed at the two corners of the passage fell upon a slit placed near the entrance to the second room. This slit could be viewed by the observer through his diffraction grating.

The slit employed was 2 mm wide and 30 cm long and the observer could vary his distance from it to any extent desired. The observed luminosity of the spectrum could thus be varied over a great range of values. A further means of controlling the luminosity of the observed spectrum was by altering the illuminated area of the first diffusing screen. This area could be reduced from a circle of 40 cm diameter down to a circle of 6 cm diameter, thus allowing a reduction of luminosity by a factor of about 50.

The changes in the character of the observed spectra resulting from each step-down in the level of illumination could be made evident by replacing each diffusing screen by a reflecting mirror, thereby resulting in a great increase in the brightness of the illumination reaching the slit. The determination of the wavelength range in which the spectrum continues to be observable at the lower levels of illumination is effected with the aid of the discrete lines in comparison spectra of low intensity viewed through the same slit for a brief period of time sufficient to enable the observer to fix their positions.

*Results of the investigation*: The results of the study made with artificial light-sources are in full agreement with those described above using skylight at various levels of illumination. We may now sum up the conclusions reached. The spectrum of white light consists of four sectors, the wavelength ranges in which they appear being respectively from 400 to 500 m$\mu$ for the blue sector, from 500 to

560 m$\mu$ for the green sector, from 560 to 600 m$\mu$ for the yellow sector and from 600 to 700 m$\mu$ for the red sector. At high levels of illumination, the yellow sector is the most conspicuous, the red, green and blue sectors following it in that order. When the level of illumination is lowered sufficiently, the red sector is the first to pass out of sight, and is then followed by the yellow sector. At the lowest levels of illumination, the blue sector also disappears, till finally we are left only with the green sector covering the wavelength range from 500 to 560 m$\mu$. It then exhibits no observable colour, but the maximum of brightness is at about 530 m$\mu$. Thus, it is this restricted range of the spectrum which actually enables us to perceive and recognise the most dimly illuminated objects. This statement is valid alike for the fovea and for the outlying regions of the retina, there being no noteworthy differences between them at such levels of illumination.

Some remarks are here called for regarding the so-called "visual purple" which has in the past been identified as the material present in the retina that enables dim light to be perceived. The absorption spectrum of "visual purple" has been studied by several investigators. It exhibits a maximum of absorption at 500 m$\mu$, the absorption diminishing to smaller values both at higher and lower wavelengths. The absorption covers the entire range of wavelengths from 600 to 400 m$\mu$, and should therefore be effective in the perception of the yellow, green and the blue sector of the spectrum. The behaviour of "visual purple" thus inferred is wholly different from the characteristics of human vision at low levels of illumination established by the present investigation. It would seem, therefore, that the identification of the "visual purple" as the material which makes vision possible at such low levels is a misconceived idea.

One need not doubt that the "visual purple" is actually present in the living retina and that it subserves some physiological purpose. This prupose may be that of a protective material for preventing damage to the delicate structures of the retina by the incidence of strong light, especially in the region of shorter wavelengths. The photochemical decomposition of the material by strong light and its reconstitution in dim light may, in fact, be the means by which this protective action is brought into play.