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The new physiology of vision—Chapter XIV. The red end of the spectrum

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In the present chapter, we shall concern ourselves with the visual sensations excited by light of wavelengths between 579 mμ and the long-wave limit of the visible spectrum. Some of the features of this region which are evident to simple inspection may first be mentioned. The yellow at 579 mμ is followed by the region in which the hue passes from yellow to red through various intermediate colours usually termed as orange. This region extends up to about 630 mμ and it is highly luminous. From 630 to 660 mμ the colour is red, but the luminosity of the spectrum falls off. This is followed by a region in which there is a further rapid diminution in brightness. Beyond 690 mμ, the spectrum becomes excessively feeble.

It is a remarkable and indeed significant fact that it is not possible by observation to fix a definite wavelength as that beyond which the red of the spectrum ceases to be observable. It is found, for example, that an observer who views the highly luminous part of the sky in the vicinity of the sun through a pocket spectroscope would be inclined to place the limit at 700 mμ. But if, on the other hand, he directs the same instrument towards the blue sky far away from the sun, he would find that nothing can be seen of the spectrum beyond 670 mμ. Likewise, if inside a room illuminated by diffuse daylight, the same instrument is directed towards a whitewashed wall, he would decide that the spectrum terminates at 650 mμ, but also exhibits a rapid fall of intensity between 630 and 650 mμ.

The experiences set forth above become intelligible when we consider the spectroscopic behaviour of the visual pigments functioning in the long-wave region of the spectrum. The data regarding their properties were already set out in an earlier chapter, but are here reproduced again as figure 1 covering the spectral range between 500 and 800 mμ. The graphs have been copied from the chart appearing at the end of the volume by Lemberg and Legge entitled *Hematin Compounds* (Interscience, New York and London, 1949). The most conspicuous feature noticeable in the figure is the rapid diminution in the molecular extinction coefficient of all the three pigments which exhibits itself as we proceed towards longer wavelengths. But as between the three, there are noteworthy differences.

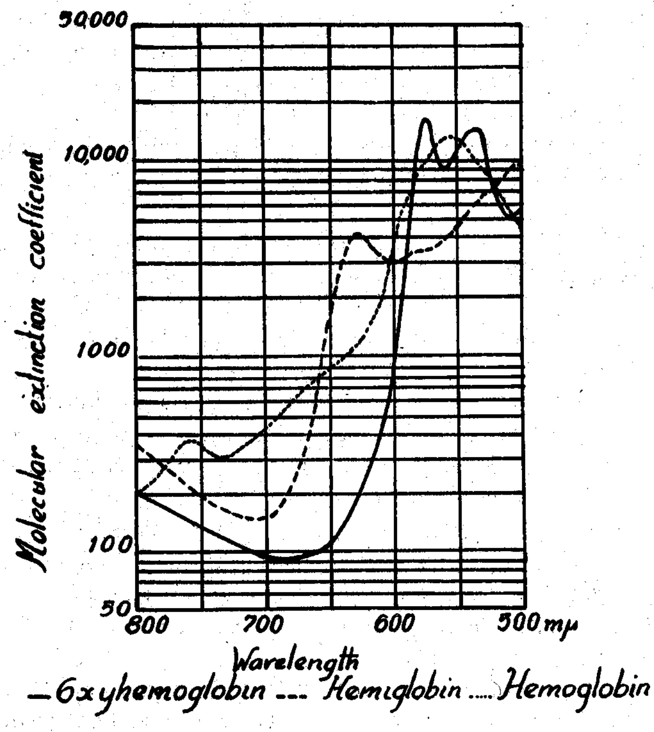

Figure 1. Light absorption curves.

The ferrous form of the heme pigment exhibits a wide-band maximum located at about 560 mμ, its absorption falling off to a small fraction of that value for wavelengths greater than 650 mμ. The oxygenated form of the heme pigment exhibits a sharply defined peak at 579 mμ coinciding with the yellow of the spectrum; following this, there is an extremely rapid fall of the molecular extinction coefficient, its value becoming quite small at 600 mμ and entirely negligible at 650 mμ. The ferric form of the heme pigment has high values of the extinction coefficient in the spectral range between 600 mμ and 630 mμ, in other words, in the range of wavelengths in which the perceived colour exhibits the transition from red to orange. There is a well-defined maximum at 630 mμ. Beyond 630 mμ the extinction coefficient drops off very rapidly and becomes quite negligible at 700 mμ.

What has been stated above enables us to arrive at certain conclusions. Firstly, it is the ferric form of the heme pigment which principally enables us to perceive the orange and the red sectors of the visible spectrum. The properties of that pigment also explain why the visible spectrum in the wavelength range between 600 and 630 mμ exhibits a high luminosity, why that luminosity diminishes rapidly in the range between 630 and 660 mμ, why the red of the spectrum becomes extremely weak in the spectral range between 660 and 700 mμ and why except at very high levels of illumination it ceases to be observable beyond 700 mμ. Further, since the observable extension of the spectrum depends on the level of illumination, we may expect that the entire red of the spectrum would disappear and cease to be visible and would be followed by the orange sector as well, when that level is lowered sufficiently.

The Purkinje phenomenon: The disappearance from sight of the red region in the spectrum has, in the past, been believed to be a characteristic feature of vision in dim light and to require the adaptation of the eye to low levels of illumination. That these beliefs are erroneous will be evident from what has been stated above. Actually, the Purkinje phenomenon arises by reason of the spectroscopic properties of the visual pigments which function in bright light and it is observed in circumstances that do not require the adaptation of the observer's vision to dim light. These inferences have been confirmed and firmly established by the author's studies using several different techniques which will presently be described. The essence of the matter is that the disappearance of red light from the visible spectrum is a progressive phenomenon. It commences at quite high levels of illumination for the longest waves and proceeds towards shorter wavelengths with diminishing illumination, till finally the entire spectrum of wavelengths greater than 600 mμ drops out of sight.

A simple and convenient procedure for demonstrating the real nature of the Purkinje phenomenon is to examine the spectrum of skylight visually using a pocket spectroscope. The most suitable time for such observations is either in the morning just before sunrise or in the evening just after sunset, when the illumination of the sky by the sun's rays traversing the higher levels of the atmosphere is sufficiently strong to enable the spectrum of every part of the sky to be seen through such an instrument clearly and without the least difficulty. Observations made under these conditions belong to the category of vision in bright light. Indeed, the spectrum itself exhibits features which distinguish it sharply from the spectrum of dim light. But it differs from the spectrum of skylight as seen at other hours by reason of the extreme weakness or total absence of the parts of the spectrum of which the wavelengths exceed 600 mμ.

The character of the spectrum as actually observed in the conditions stated above is determined by the luminosity of the part of the sky under view. Naturally, therefore, it varies with the direction of observation and alters as the sun comes up towards the horizon or goes down below it. The general sequence of the changes observed is however the same in all cases. Indeed, except in the areas close to the position of the sun, we observe the same effects almost simultaneously in all parts of the sky. In the first stage, there is a progressive shortening of the length of the spectrum, wavelengths greater than about 650 mμ ceasing to be visible. In the second stage, there is a progressive fall in the brightness of the spectrum between 600 and 650 mμ as compared with the spectrum between 500 and 600 mμ. In the final stage, the region of the spectrum beyond 600 mμ passes out of sight, while the region between 500 and 600 mμ continues to be conspicuously visible. The maximum brightness in the latter region appears at about 550 mμ; its colour is a bright green and quite different from the colour observable in the region of wavelengths less than 500 mμ. The latter regions are also much less luminous than the spectrum between 500 and 600 mμ. It is clear from these facts that the Purkinje phenomenon falls within the category of vision in bright light and is in no way related to the characteristics of vision in dim light.

That red light ceases to be visible at levels of illumination higher than those falling within the range of dim-light vision can be further demonstrated in the following simple fashion. A large plastic sheet of red colour with faces exhibiting a smooth polish is set up facing the observer at a distance of a few metres from him. Alongside of it and at the same distance from the observer, is placed a Snellen test-chart with printed rows of letters of the kind used by ophthalmologists. The illumination of the red plastic sheet and of the test-chart is controlled by varying the opening of a large iris-diaphragm through which skylight enters the otherwise darkened room. It is then found that the red screen becomes darker and finally turns black when the iris is closed down sufficiently, while on the other hand the printed types of the Snellen chart continue to be visible and can be read from a distance without difficulty. Spectroscopic examination shows that the light diffused by the plastic sheet appears in the spectral range between 580 and 700 mμ, while the rest of the spectrum is completely absorbed by the material of the screen. The Purkinje phenomenon thus extends over the entire range of wavelengths between the yellow and the extreme red of the spectrum.

Other methods of observation: The conclusion thus reached is that in the familiar Newtonian sequence of colours exhibited by a continuous spectrum, the hues ranging from yellow to the deepest red disappear in the reverse order as the illumination reaching the eye is progressively reduced. It is evidently desirable that this result which is of fundamental importance in the physiology of vision is demonstrated with artificial light sources having a continuous spectrum and a controlled intensity under laboratory conditions. This can easily be arranged. A convenient technique is to use as the source of light a 100-watt tungsten filament-lamp with a frosted bulb. The spectrum seen when the pocket spectroscope is held close to the bulb is, of course, extremely brilliant. The yellow region is its most conspicuous feature and the orange and red which follow it can be seen extending up to 700 mμ. To obtain a controlled and progressive reduction of brightness, a useful device is to hold a sheet of opal glass 2·5 mm thick between the lamp and the observer. The spectrum of the light emerging through the sheet is viewed with the pocket spectroscope held behind it. The reduction of luminosity resulting from the insertion of the sheet of opal glass between the lamp and the observer is very striking. Indeed, the entire sequence of changes in the spectrum from one exhibiting the features characteristic of high illumination to one in which all wavelengths greater than 600 mμ have disappeared from sight can be followed merely by the observer holding the opal glass sheet and the spectroscope and moving away from the lamp to the further end of the laboratory a few metres away. To observe the same sequence without the aid of the opal glass sheet would require a movement which is far larger. Incidentally, it may be mentioned that the disappearance of the red end of the spectrum is well exhibited by distant street lights when they are viewed through a pocket spectroscope.

Another technique by which the real nature and characteristics of the Purkinje phenomenon can be effectively displayed requires the use of a straight metallic filament stretched along the axis of a tubular lamp and heated by an electric current. At a convenient distance from the lamp, the observer holds a replica diffraction grating before his eye and views the first-order diffraction spectrum of the luminous filament. When this is glowing at a white heat, the spectrum exhibits its greatest extension both towards the violet and towards the red; the spectrum is seen extending to 700 mμ or even a little beyond. A reduction of the heating current has the effect of weakening the entire spectrum, especially the region of shorter wavelengths and ultimately of extinguishing the latter. But the green sector of the spectrum continues to be visible, and the noteworthy feature is the progressive shortening of the red sector of the spectrum. As the heating current is reduced, the red in the spectrum then becomes weaker and weaker relatively to the green region and finally disappears, while the green continues to be visible. This, in fact, is the Purkinje phenomenon and proves that it is a progressive diminution in the visibility of the spectrum which commences at 700 mμ and ends up with the complete extinction of the spectrum beyond 600 mμ.

Observations with colour filters: The characteristic features of the Purkinjie phenomenon set forth above may be further demonstrated in a striking fashion by the aid of colour filters which transmit limited regions of the spectrum with the wavelength range between 600 and 750 mμ, but cut off the rest of that spectral range. Three such filters have been made use of by the author, prepared by staining gelatine plates respectively with the dye-stuffs (*i*) disulphine blue, (*ii*) Coomassie brilliant blue and (*iii*) methyl violet. The transmission bands of the three filters covered the following wavelength ranges (*i*) 700 to 730 mμ, (*ii*) 650 to 700 mμ and (*iii*) 630 to 670 mμ.

The luminosity of these strips of transmission in the red region of the spectrum relatively to the parts of the spectrum in the wavelength range between 500 and 600 mμ passed by the filters can be observed by viewing a continuous spectrum through the filters. It is found to depend to a very great extent on the brightness of the light source employed. It is also very different for the regions of the spectrum in the red transmitted respectively by the three filters.

Concluding remarks: We may sum up the results which have emerged by the statement that the Purkinje phenomenon owes its origin to the spectroscopic properties of the ferric form of the heme pigment. The observed characters of that phenomenon are a demonstration of the correctness of the identification of the ferric form of heme as the visual pigment which functions in the red sector of the spectrum.