Light, Colour and Vision *

I must thank the organisers for the honour of the invitation to address this Congress. I shall use the time at my disposal to dwell on the fundamental aspects of ophthalmology. We seek answers to the following questions. Firstly, what is the process by which our eyes are enabled to perceive light and colour? Secondly, what are the respective roles played by the retina and by the visual cortex in that process? It is obvious that the right answers to these questions can only be given if we understand correctly the physical nature of light and the manner in which it interacts with material bodies.

The nineteenth century physicists, notably Thomas Young, Hermann Von Helmholtz and Clerk-Maxwell who were interested in the problems of physiological optics were also the leading exponents of the wave-theory of light. That theory had many notable successes to its credit. Quite naturally, therefore, it was thought it could also form the basis for an understanding of the phenomena of vision. But this is not actually the case, for the concepts of the wave-theory of light are altogether irrelevant in relation to the interaction of light with material bodies. These interactions can be successfully described and understood only if it is recognised at the very outset that light consists of discrete units or quanta of energy. The interplay of light and matter is a process in which the quanta or energy-units in the radiation are transferred from the field to the material body or *vice-versa*. Unquestionably, therefore,

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the quantum theory is the proper basis for the interpretation of the facts of visual experience.

The faculty that our eyes possess of perceiving colour brings the phenomena of vision into the closest relationship with the basic notions of the quantum theory. Light which appears as a sharply-defined line in the spectrum is composed of energy-quanta which are all equal. The quantum of energy varies with the position of the spectral line, being the lowest when it is at the red end and largest when it is at the violet end of the spectrum. Thus, the magnitude of the energy quantum varies *pari passu* with the colour of the perceived light. Every one of the different colours we can perceive in the spectrum - and, of course, they are very numerous - has thus an equal claim with the rest to be considered as a primary colour and as a fundamental visual sensation.

Colour discrimination, in other words, the ability to recognise closely adjacent regions of the spectrum as being different in colour is a noteworthy feature of our visual faculties. It may justifiably be described as the physiological perception of the difference in magnitude of the associated light quanta. Indeed, the precision exhibited by that faculty in various parts of the spectrum is so remarkable that it leads us to a very simple view of the role played by the retina in the perception of light and colour, namely that it absorbs the incident light-quantum and retransfers the absorbed energy through the nervous pathways to the optical cortex. We may then ask, what are the materials which enable the retina to function in the manner indicated, what are the spectral regions in which they are respectively operative and how are they distributed over its area ?

A technique of study of the visual process has been devised by me, the results of which are of great assistance in answering these questions. The observer holds a suitably chosen colour filter in front of his eye and views an extended source of light through it. After a little while, the filter is suddenly removed. The observer then sees projected against the source of light a highly magnified image of his own retina. The fovea and the central depression in it appear conspicuously in the picture by reason of their differing in colour and brightness from the surrounding regions.

It is significant that for the observer to see his own fovea in the manner explained, it is essential that the colour filter employed should absorb some part of the spectrum lying between 5600 A° and 6200 A°, though the absorption may also extend beyond these limits. It is equally significant that no effect whatever is observed in the experiment if the absorption by the colour filter lies between 4800 A° and 5600 A° and does not extend beyond these limits. On the other hand, if the absorption by the filter is located between 6200 A° and 7000 A°, a rose-red glow is seen over the whole visible area of the retina following the removal of the filter, but the foveal region is not distinguishable from the surrounding field. Likewise, if the absorption appears only between 4000 A° and 4800 A°, a blue glow covers the retina, but the fovea does not show up as distinct from the surrounding areas.

The observations thus enable us to demarcate the spectrum into four distinct sectors in which the visual mechanisms are markedly different. The sector between 4000 A° and 4800 A° is of low luminosity but vividly chromatic, the colours ranging from violet to blue. There is an abrupt change of colour from blue to green in passing from the first to the second sector. The luminosity also progressively increases and reaches its maximum at the boundary between the second and third sectors. In the third sector the perceived colour changes progressively from green to yellow, then to orange and finally to red, the luminosity falling off at the same time. The fourth and last sector is the red end of the spectrum in which the luminosity falls off and finally vanishes.

We now proceed to the identification of the materials present in the retina which function respectively in these four sectors. We shall take them in order.

Xanthophyll is the visual pigment which functions in the first sector and enables us to perceive the colours ranging from violet to blue. It is a yellow carotenoid pigment of vegetable origin which is present in all green plants and enters the human body through the medium of the food products consumed. It is present in the retina as the well-known yellow macular pigmentation. That it is indeed a visual pigment is indicated by the fact that the range of wave-lengths in which the perceived colour changes very rapidly from blue to green is precisely the same as that in which the absorptive power of xanthophyll drops suddenly from a large value to zero. A further demonstration that xanthophyll functions as a visual pigment is furnished by the effects seen by an observer who views an extended source of light through a polaroid and a colour filter transmitting only the blue part of the spectrum. The observer then sees an image of his own fovea projected against the source of light in which a bright brush and a dark brush appear crossing each other. This phenomenon is observed only when the illumination of the field is in the photopic levels and it disappears completely when the brightness is reduced to the scotopic level. The brushes appear as a consequence of the shape and optical properties of the xanthophyll molecules. These orientate themselves parallel to the nerve fibres and hence are arranged radially in the foveal area. They absorb light and function as a visual pigment only in respect of vibrations parallel to the chain of eleven double bonds contained in the molecule.

Various considerations which cannot here be set out in detail serve to exclude the possibility of the visual pigments functioning in the three other sectors of the spectrum being carotenoids. The pigment which actually functions in the second or green sector of the spectrum is heme in which the iron atom located at the centre of the tetrapyrrolic group is in the ferrous state. Heme in the ferrous state exhibits a powerful absorption of light between 5000 A° and 6000 A°, the maximum of absorption being located at 5600 A°. The wave-length of maximum visual luminosity in the spectrum is also 5600 A°. Thus, by reason of its structure and spectroscopic behaviour, heme in the ferrous state fits perfectly into the role of the principal visual pigment. One more function is thus added to the many important roles which heme plays in the field of biology.

When the iron atom at the centre of the tetrapyrrolic group in the molecules of heme is in the ferric state, the absorption spectrum undergoes a radical change, the principal feature being an extension towards greater wave-lengths and a greatly increased strength of absorption in the region between 6000 A° and 7000 A°. Thus, heme in the ferric state fits into the role of the visual pigment which functions in the fourth or red sector of the spectrum. The third sector in which the transitional colours of yellow and orange appear is clearly the part of the spectrum in which the ferrous and ferric states of heme function in co-operation with each other.

The time at my disposal does not permit of my dealing in detail with the problems of anomalous colour-vision. It will suffice here to state that the existence of such anomalies and their observed characteristics find a natural explanation on the basis of the present approach to the theory of vision. These and various other matters will be found discussed in detail in a memoir published by me two years ago.