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The perception of light and colour and the physiology of vision—Part V. The colour triangle

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1. Introduction

So far, in this memoir, we have concerned ourselves exclusively with the sensations excited by monochromatic radiations of different wavelengths appearing in the spectrum. The reason for this, as has already been explained in the first part of the memoir, is that only by such an approach is it possible to reach a correct understanding of the nature of the retinal processes which enable us to perceive light and colour. We shall now turn to the consideration of the more complex field which offers itself in the study of the sensations excited by heterogeneous light. Here again, the visual sensations resulting from monochromatic light necessarily form the starting-point of our approach to the subject. Indeed, the outstanding result which has emerged from all investigations in this field is the relation that all observed colours bear to the colours of monochromatic radiation. These latter stand in a category by themselves and form a kind of upper limit to the visual manifestations of colour.

The functioning of the three visual pigments present in the retina in their respective spectral regions will form the basis of our considerations. It will be shown that they enable a satisfactory elucidation to be given of the observed facts of the subject including especially those which in the past have been sought to be interpreted or explained in terms of the so-called trichromatic theory of vision. It is necessary here to emphasise that for a full understanding of the facts of heterochromatic vision, the role played by the central parts of the organ of sight is no less important than the functioning of the retina which is only the periphery of that organ. The function of the retina is to receive, absorb and pass on the energy of the incident radiation. But the synthesis which enables composite radiation consisting of energy quanta of different magnitudes to be perceived as a visual sensation can only take place in the central part of the visual organ. This is indeed very clear from the facts of binocular vision. There is no colour sensation which can be produced by mixing two lights and presenting them to one eye which cannot be duplicated by supplying the two lights independently, one to each eye.

As an example of this general principle, it will suffice to mention the familiar techniques employed in colour stereoscopy.

2. The chromatic sensations

As we proceed, it will emerge that the sensations which result from the superposition of radiations appearing in different parts of the spectrum fall into two categories which we shall term the *chromatic* and *achromatic* sensations respectively. We shall commence with a consideration of the chromatic sensations. The colours of the spectrum which represent the effect of monochromatic radiations on our visual organs are, of course, the chromatic sensations of the first order. In certain circumstances, however, the superposition of different monochromatic radiations may result in colour sensations which may be included in that category. We shall now consider these cases in order.

A group of cases of particular importance is that in which two radiations appearing respectively at the two ends of the spectrum, viz., violet and red, are superposed. The observations described in the second part of this memoir show that the visual pigments which function at the two ends of the spectrum are *exclusively* the first and the third respectively. The energy-quanta at the red and violet ends of the spectrum also differ widely. There is no reason, therefore, to anticipate that the spectral components of the incident radiation would be confused with each other when the signals originating at the retina reach the cerebrum. Indeed, in this case, human vision very nearly succeeds in recognising the composite nature of the incident radiation. That the so-called purples are a mixture of red and violet is fairly obvious even to an inexperienced observer. The relative intensities of the two components make themselves felt in the hues perceived which form a complete sequence ranging from red at one end to violet at the other and rival the pure colours of the spectrum in their brilliance. It follows that the purples can be classed with the colours of monochromatic light as chromatic sensations of the first order. It is evident also that a mixture of two purples in any proportion would give us only another purple, in other words, nothing essentially different.

Another set of cases of special importance is that in which the two monochromatic radiations which are superposed both lie within the range of wavelengths between 530 and 780 mμ. Xanthophyll which is the visual pigment functioning in the violet and blue sectors of the spectrum does not absorb any light of wavelengths greater than 530 mμ. Hence, in the region between 530 and 780 mμ, only two visual pigments, viz., ferroheme and ferriheme function. The observations described in the second part of the memoir show clearly that there is a considerable overlap in their absorption spectra. It follows that when red and green radiations from the two ends of the range are superposed in any proportion, the resultant sensation would be one of the spectral colours falling within the same range. Indeed, two monochromatic radiations from anywhere between these wavelengths when superposed would reproduce a spectral colour lying elsewhere in the same range. These indeed are facts. They emerged quite clearly from Clerk Maxwell's investigations with his colour box and have been confirmed by all later investigations.

There is yet a third class of cases in which the superposition of monochromatic radiations gives rise to a chromatic sensation, viz., those in which the superposed radiations are close to each other anywhere in the spectrum. They may be sufficiently far apart to be perceived as different in colour when viewed separately or in adjacent fields. Yet, when they are superposed, the eye fails to recognise the composite nature of the light and perceives a colour which may be described as the colour of a spectral frequency which is the weighted average of the frequencies of the superposed radiations, the weightage being determined by their respective luminosities.

3. The achromatic sensation

A spectroscopist would define white light as a stream of radiation which comprises energy-quanta of all possible values ranging over the entire visible spectrum and with an energy distribution such as would be found in the radiation from a black body at very high temperatures. Since, however, the central organ of vision is incapable of resolving the incident radiation into its spectral components, there is no reason for assuming that only such a radiation would be perceived by the eye as white light. Indeed, much less stringent requirements might suffice. We may remark here that the light falling on the retina is absorbed by three visual pigments which between them cover the entire range of the visible spectrum. Hence, the minimum requirement for the perception of the incident heterogeneous radiation as white light could well be the following: *all the three visual pigments should function and should contribute to the observed luminosity in the same proportions as they would if the incident radiation were white light in the spectroscopic sense.* We shall provisionally accept this requirement as adequate and compare its consequences with the actual facts of observation.

The green light appearing in the wavelength region between 495 and 566 mμ stands in a category by itself. In this sector of the spectrum, vision is mediated almost exclusively by ferroheme though the other two visual pigments make sensible contributions respectively near the two ends of the sector. It follows that to achromatise green light, one would require the addition of radiations from both ends of the spectrum where xanthophyll and ferriheme respectively function. The complementaries to the green of the spectrum accordingly lie in the region of the purples; as we pass from the boundary between blue and green to the boundary between green and yellow, the location of the complementary colour would shift from the red to the violet end of the series of purples.

As has been remarked earlier, the yellow colour of the spectrum between 566 and 589 mμ and the orange colour between 589 and 627 mμ arise by reason of the circumstance that the absorption spectra of ferroheme and ferriheme overlap in these regions; in the yellow sector, their absorptions are of comparable strength, while in the orange, the third pigment is distinctly the more effective. As a consequence of this, the complementary colour to yellow would be at the violet end of the spectrum; as we move into the orange, the complementary colour would shift into the blue. A further shift towards the red would result in the complementary colour being located at the boundary between the green and blue sectors in the spectrum. The remarkable fact of observation that in a whole series of cases the superposition of only two monochromatic radiations with appropriate intensities results in a complete suppression of colour thus finds a simple and satisfactory elucidation on the basis of the present approach to colour theory.

4. Superposition of the chromatic and achromatic sensations

We have seen that in certain cases, non-homogeneous light excites chromatic sensations identical with the colours of the spectrum or the purples derived therefrom, while in other cases the resulting sensation is achromatic. We may therefore assume that, in general, both of these effects would be manifested but to different extents depending on the particular circumstance of each case. In other words, the sensation excited by non-homogeneous light could, in general, be described as a superposition of the chromatic and achromatic sensations. The colours of the spectrum and the purples accordingly set an upper limit to the visual manifestations of colour. We infer that non-homogeneous light exhibits a third attribute besides luminosity and colour, namely, the purity or degree of saturation of the colour. The highest purity is that of the pure spectral colours and the purples derived therefrom, while the lowest purity represents the case in which the achromatic part is relatively so large that no colour is discernible. Hand in hand with the concept of purity enters also the concept of dominant wavelength, which is the particular wavelength in the spectrum the colour of which the composite radiation under study most nearly resembles.

An interesting question arises here. Should the chromatic and achromatic sensations associated with non-homogeneous light be regarded as distinct effects or as inseparable from each other? If one thinks in physical terms, there is clearly a fundamental difference between them. An achromatic sensation would correspond to a chaotic and characterless disturbance; on the other hand, a pure spectral colour is associated with specifiable quanta of radiational energy. There is no reason why sensations so different in their nature and origin should be placed in the same category. It seems more appropriate to regard them as quite distinct attributes of the sensations excited by non-homogeneous light.

The very interesting results obtained by E.P.T. Tyndall and by G. Haase in their studies on colour discrimination with admixtures of monochromatic and white light have a bearing on the issue raised above. Measurements were made by these authors of the smallest change in wavelength of monochromatic light necessary to produce a detectable change of colour. The determinations were then repeated when white light was added in equal amounts to the two monochromatic fields of slightly different wavelength under comparison, the purity or degree of saturation of the colour in these fields being thus varied in different observations over a wide range. The remarkable result emerged that the chromatic sensibility of the eye to wavelength differences is not significantly diminished even when the white light added represents a 50% dilution of the visible colour. A result of this nature could scarcely have been anticipated unless the chromatic and achromatic sensations are distinct and unrelated effects.

6. The results of colour-mixing experiments

The simplest kind of experiment that could be made on the mixing of colours is to have only two monochromatic radiations, the spectral position and relative intensities of which could be varied, and to compare the sensation resulting from their superposition with another monochromatic radiation appearing in an intermediate position in the spectrum, the intensity of which can also be varied. The results of such comparison can be broadly indicated in the light of the remarks made above.

If both the selected radiations lie within the wavelength range between 530 and 780 mμ, there would be little difficulty in obtaining a perfect match. Likewise, if one of the selected radiations is near the extreme red end or near the extreme violet end, and the other also lies in the violet or red sector of the spectrum as the case may be, there should be no difficulty in matching the result with some intermediate radiation. The situation would however be different if one of the selected radiations lies in the wavelength range between 400 and 530 mμ and the other also lies in that range, but not in an adjacent position. Only when the two selected radiations are quite close to each other that it would be possible to obtain a good match. The further away they are, the less and less satisfactory would be the result, until finally when the two are sufficiently far apart, there could be no comparison at all. The position would be far worse if one of the radiations is in the wavelength range between 400 and 530 mμ and the other is in the range between 530 and 750 mμ. We would then be approaching a situation in which the result of mixing the two monochromatic colours would be to obtain an achromatic sensation.

Figures 1 and 2 represent the results of experiments of the same nature as that indicated above with the difference that three instead of two monochromatic radiations were chosen and employed and while their positions in the spectrum were kept fixed, their intensities were varied with a view to obtain a match with

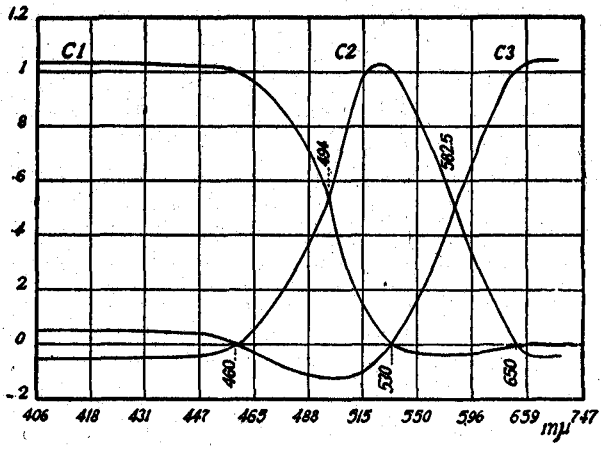

Figure 1. Results of mixing 460, 530 and 650 mμ.

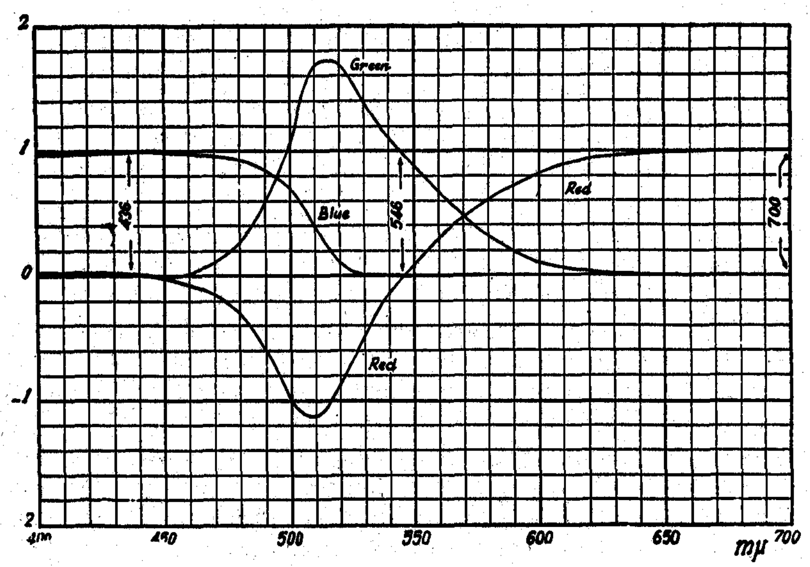

Figure 2. Results of mixing 436, 546 and 700 mμ.

the spectral colours appearing over the whole range of the spectrum. In figure 1, the three chosen wavelengths were 460, 530 and 650 mμ and the results represented are those of W D Wright and collaborators. In figure 2, the chosen wavelengths were 436, 546 and 700 mμ, the two former being the strong lines in the mercury arc spectrum. The graphs appearing in the figure represent the values of the coefficients C_1 (blue), C_2 (green) and C_3 (red) which indicate the quantities of blue, green and red light necessary to obtain the match represented by the colour equation

$$C_1B + C_2G + C_3R = \text{Chosen spectral colour},$$

where

$$C_1 + C_2 + C_3 = 1.$$

Figures 1 and 2 show certain features in common and also some noteworthy differences. We shall first mention the former and remark on their significance in relation to the absorptive properties of the visual pigments. In both figures, the coefficient C_1 (blue) has a value of nearly unity in the violet sector of the spectrum and then drops down steeply in the wavelength range 480 to 530 mμ and is negligible or zero at all wavelengths greater than 530 mμ. The behaviour of C_1 thus clearly follows the absorption characteristics of xanthophyll. Then again, in both figures, the graphs for C_2 (green) and C_3(red) overlap in the wavelength region between 550 and 625 mμ; C_2 diminishes and C_3 increases in this range, the graphs crossing at 582 mμ in figure 1 and at 570 mμ in figure 2. C_2 becomes negligible in comparison with C_3 at all wavelengths greater than 625 mμ, while C_3 is dominant and practically unity in that region. Here, again, the behaviours of C_2 and C_3 recall the remarks made earlier regarding the overlapping of the absorption spectra of ferroheme and of ferriheme and its consequences.

The appearance of negative coefficients for C_3 in the spectral region between 460 and 530 mμ is a well-marked feature in both figures but far more so in figure 2 than in figure 1, evidently because the blue and green radiations superposed were farther apart in the spectrum in the case of figure 2 than of figure 1. The appearance of these negative coefficients indicates that the superposition of the two monochromatic radiations results in a strong achromatic component in the sensation. A good measure of the third component has therefore to be added to the spectral colour under study to obtain a colour match. The production of an achromatic sensation by the superposition of monochromatic radiations in certain circumstances is thus an important and indeed basic feature in colour theory. The circumstances in which the achromatic sensation appears have already been discussed in section 3 above and need not therefore be repeated here.

7. Geometric representations of colour

Figure 3 reproduces the so-called XYZ chromaticity diagram. This represents in geometric form certain empirically determined colour relationships which have been put into a shape convenient for practical use The diagram is reproduced here for the reason that the facts concerning colour vision elucidated in the preceding pages are evident on a simple inspection of it.

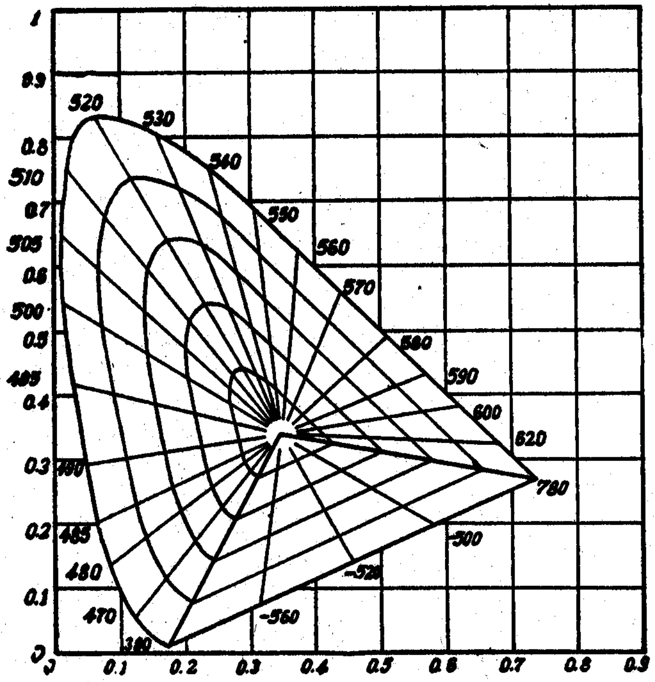

Figure 3. The XYZ chromaticity diagram.

1. All observable colours appear as points inside a closed figure at the periphery of which appear the colours of the spectrum and the line of purples. The latter is a straight line joining the violet and red ends of the spectrum.
2. The spectral colours in the range between 530 and 780 mμ appear on a line which is straight except very near 530 mμ where it exhibits a slight curvature.
3. Chromatic sensations complementary to each other are indicated by the two points on the periphery of the figure the straight line joining which passes through its white centre.
4. The degree of saturation or purity of any observed colour is indicated by its position in the figure on the line which joins the white centre with the point on the periphery representing the dominant wavelength.