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The new physiology of vision—Chapter XX. Superposition and masking of colours

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The following questions of a fundamental nature arise in the theory of colour. If two beams of monochromatic light of different colours are perceived by our eyes simultaneously, what would be the resulting sensation and how would it depend on the relative brightness of the two beams? An answer to these questions is needed for every possible pair of colours in the spectrum. If it is forthcoming, it would furnish material for a fuller understanding of the phenomena we are confronted with in the synthesis of colour, a subject which has been dealt with in the two preceding chapters. Observational studies are necessary which would enable the questions raised above to be answered. They will be described and the results obtained will be discussed in the present chapter.

The method of superposed spectra: A very simple technique by which the effect of superposing monochromatic light from two different parts of the spectrum can be ascertained is to use two linear light sources held parallel to each other and for the observer to view the diffraction spectra of the two sources simultaneously with a replica grating held in front of his eye. The two sources may be two similar lamps or two illuminated slits held at a convenient distance apart which can be varied as desired. The first-order diffraction spectra of the two sources are then seen superposed but in displaced positions with respect to each other. If one of the sources is placed at a slightly higher elevation than the other, the superposition is effective over the greater part of the width of the two spectra, but a little of each spectrum would project beyond the other, thereby enabling the observer to notice the two colours which are superposed at any point in his field of view. By appropriate methods, viz., by varying the electric current through the tubular lamps or by varying the width of the illuminated slits, the relative brightness of the two sources can be altered. By changing the separation between the two sources or by the observer moving towards or away from them, the displacement of the spectra with respect to each other can be varied to any desired extent. The colours seen in the overlapping parts of the two spectra can then be readily compared with those in the non-overlapping regions.

Observations made in the manner described make it evident that the visible spectrum extending over the range of wavelengths from 7000 to 4000 A.U. falls into two divisions. The first division from 7000 to 5000 A.U. covers the red, yellow and green sectors of the spectrum, while the second division from 5000 to 4000 A.U. is the blue sector, including in this term the regions where blue, indigo and violet are observed either in different parts or at different levels of brightness, as the case may be. Each of these two divisions of the spectrum has the property that any two monochromatic radiations selected from different parts of it when superposed result in a chromatic sensation of the same nature as is to be found within that division, its position, however, being dependent on the relative brightness of the two superposed radiations. If, for example, we superpose monochromatic light which exhibits a red colour upon another which appears green, the resultant would be one or another of the intermediate colours in the spectrum, the position of which would be determined by the relative intensity of the two superposed radiations as indicated by the formula:

$$n_1 h\nu_1 + n_2 h\nu_2 = (n_1 + n_2) h\nu_3.$$

The formula states that the energy as well as the number of corpuscles perceived is a summation of their respective values for the superposed radiations. It follows from this assumption that the resultant would be perceived as light of frequency ν_3 which is intermediate between ν_1 and ν_2 and is nearer one or the other according as n_1 is greater or less than n_2. The formula assumes that the more intense radiation does not mask the weaker radiation thereby preventing its influence being felt in the final result. There is observational evidence, however, that such masking does occur when one of the superposed radiations is much more intense than the other.

The reason why the spectrum falls into two chromatic divisions in the manner indicated above is not far to seek. In the first division, as has been set out in earlier chapters, the visual pigments are chemically of the same nature, viz., heme, but in different states of oxidation and their absorption spectra overlap. In these circumstances, it is to be expected that they would co-operate in the reception of polychromatic radiation and enable it to be perceived as a monochromatic sensation. The position is entirely different when the radiations which are superposed belong to the two different divisions of the spectrum. The visual pigment in the second division is of a different nature, viz., a carotenoid. Further, the two divisions of the spectrum represent light-corpuscles of widely different energies. It could scarcely be expected in these circumstances that the chromatic sensations associated with monochromatic radiations from the two different divisions should be coherent and be perceived as a single monochromatic sensation.

The foregoing remarks indicate that the superposition of a monochromatic radiation selected from the blue sector of the spectrum upon a radiation selected from the red, yellow or green sector would result in the production of colour sensations of a distinctive character. This is found to be actually the case when the matter is investigated by the method of superposed spectra described above. As the blue sector of one spectrum successfully traverses the red, yellow and green sectors of the other spectrum, beautiful and striking changes are noticeable in the colours of the superposed spectra, the colours observed being quite different from the monochromatic sensations which are superposed on each other. We shall later return to a detailed description of these effects. Presently, we shall proceed to consider from first principles the phenomena which may be expected to manifest themselves in such cases.

Theoretical considerations: The most natural assumption to make regarding the sensation excited by two monochromatic radiations of widely different frequencies v_1 and v_2 when superposed is that it can be represented by a formula of the type

$$n_1 hv_1 + n_2 hv_2 = n_1 hv_3 + n_2 hv_4.$$

The formula assumes that both the energy and the number of light-corpuscles perceived when the radiations are superposed is a simple summation of these quantities for the two radiations considered separately. It is postulated, however, that the superposition can result in an alteration of the frequencies of the perceived radiations. The equation contains two unknowns, viz., v_3 and v_4, with only one equation connecting them. It follows that the values of v_3 and v_4 are not exactly definable, but that they can range over wide tracts in the spectrum. If the ranges of variation of v_3 and v_4 are sufficiently large to cover the entire visible spectrum, the resulting sensation would be more or less perfectly achromatic, in other words, it would resemble white light. Whether this result actually manifests itself would depend on the particular circumstances of the case. Of special importance in this respect would be the relative intensity of the two superposed beams. If for example, n_1 is very large compared with n_2, the resultant sensation would evidently approach the monochromatic colour of v_1. Vice-versa, if n_2 is large compared with n_1, the perceived sensation would resemble the colour of v_2. More generally, however, the sensation would resemble neither the one nor the other and would largely be determined by the continuous spectrum of perceived frequencies.

The considerations set forth above give us an intelligible explanation of a well-known fact of experience, viz., the existence of what are known as complementary colours in the visible spectrum. The complementarity manifests itself as between two regions in the spectrum widely separated from each other, one in the region between 700 and 560 mμ, in other words, in the red and yellow sectors of the spectrum and the other in the blue sector of the spectrum between 500 and 400 mμ. If radiations suitably selected from these two regions and having the appropriate relative intensities are superposed, the resulting sensation is that of white light. Such complementarity is exhibited when the two superposed beams have comparable luminosities, if one of them is located in the orange-yellow at about 600 mμ and the other in the blue-green region at about 490 mμ. In these circumstances, it would evidently be possible for the spread-out of the perceived frequencies of the two components to result in the entire visible spectrum being covered, and hence to result in the perception of an achromatic sensation.

Confirmatory observations: A convincing demonstration can be given that the process envisaged in the preceding theoretical discussion actually occurs, viz., that the superposition of two monochromatic radiations of widely different frequencies results in each of them being perceived spread out into a spectral band of frequencies. For this purpose, two highly monochromatic light-sources of which the colours are far apart in the spectrum may be selected. A suitable choice for one is the violet λ4358 radiation from a mercury vapour lamp. This may be readily isolated from its other radiations by using a fairly strong solution of cuprammonium as a light filter. For the other, a suitable choice is the orange-yellow light of wavelengths λ5890–5896 furnished by a sodium vapour lamp. Light from these two sources may be projected with the aid of apertures and lenses to appear as luminous circles on a white screen. The region where the two circles overlap is observed to exhibit a vivid rose-red colour, in striking contrast with the violet and orange-yellow colours of the non-overlapping regions.

As has been shown by several examples in earlier chapters, a rose-red colour results from the removal of the green sector ranging from 500 to 560 mμ from white light, while the rest of the spectrum including especially the blue sector from 400 to 500 mμ remains of undiminished brightness. Thus, what is actually observed in the experiment indicates that the superposition of the violet and orange-yellow radiations has resulted in the former being perceived as a spectral band covering the blue sector and of the latter being perceived as a spectral band covering the red and yellow sectors of the spectrum. This interpretation of what is observed receives confirmation from the observed result of projecting on the same screen, the λ5461 radiations of another mercury arc isolated with the aid of colour filters of disulphine-blue and acridene-orange. Where the circle of green light thus obtained overlaps the rose-red region, the area appears achromatic. On the other hand, in the region of overlap of the green and violet, the perceived colour is a pale bluish-white. Where the green circle overlaps the circle of orange-yellow light, we perceive a bright lemon-yellow colour.

In the experiment described above, we may use, instead of the orange-yellow light from a sodium lamp, red light from the extreme end of the spectrum at 700 mμ which may be isolated from white light by passing it through a dense filter of methyl-violet and another filter of acridene-orange. It is then noticed that where the circle of red light obtained in this fashion overlaps the circle of violet light from the mercury lamp, the colour observed in the region is *not a purple* but a rose-red similar to that obtained by the superposition of orange-yellow and violet. Likewise, in the present case, the rose-red colour of the region of overlap may be achromatised by the superposition of green light isolated from the radiations of a mercury lamp.

A similar experiment may also be performed using the violet λ4358 radiation from one mercury lamp and the yellow λ5770–5790 radiations from another mercury lamp isolated with the aid of colour filters of eosine and acridene-orange. When the circles of violet and yellow light thus obtained are projected on a white screen, the region of their overlap appears of a rose-red colour. But this does not present such a saturated hue as in the other cases.

The colours in superposed spectra: We now return to the subject of the colour sequences observed when two diffraction spectra are superposed upon each other in displaced positions as in the manner explained earlier. This technique is particularly useful in the study of colour superposition, since it enables us to observe the entire region of overlap between the spectra at a glance and to compare the colours noticeable at different points in the region and also to observe how they alter as the spectra are progressively displaced with respect to each other. The influence of varying the relative intensities of the two spectra can be very conveniently studied.

Of particular significance and interest in the fact that the boundary at about 500 mμ between the green and the blue in the individual spectra manifests itself as a highly pronounced discontinuity in colour in the overlapping regions of the two spectra. Extremely conspicuous, for example, is this discontinuity when the blue sector of one spectrum overlaps the orange-red, orange and orange-yellow regions in the other spectrum. The overlapping region appears as a brilliant rose-red band of colour with a sharply defined edge on one side corresponding to the green-blue boundary of the first spectrum. The colour changes sharply from a rose-red to a bright greenish-yellow at the boundary. On the other side of the rose-red band, one can observe a narrow region of the spectrum which is nearly achromatic and corresponds to the point where the yellow of the second spectrum overlaps the blue of the first.

The discontinuity in the colour sequence persists when the two spectra are displaced with respect to each other from the position stated above, but the colours observed on either side of it are naturally then different. If, for example, the blue sector of one spectrum overlaps the green sector of the second, the region of such overlaps appears of a bluish-white colour, sharply differentiated from the orange-yellow on the other side of the discontinuity arising from the overlap of the green sector of the first spectrum with the red sector of the second.