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The new physiology of vision—Chapter XVIII. The visual synthesis of colour

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In the preceding chapters, we have been principally concerned with monochromatic light and the sensations excited by it. But in most cases of practical interest, the light which reaches the eye of an observer and enables him to perceive the objects around him is not monochromatic but is composite in character. As a consequence, the visual sensations result from the superposition of light appearing in various parts of the spectrum. The spectral nature of the light emitted by the original source and the optical properties of the objects on which it falls and from which it reaches the eyes of the observer determine its character. Hence, what the eye perceives is the integrated effect of light distributed over the visible spectrum, and a process which may be called the visual synthesis of colour is involved in the perception. This is evidently a subject which is highly important both from a practical point of view and from the standpoint of physiological theory. It will receive detailed consideration in this and the following chapters.

From the nature of the subject, it is evident that our understanding of it has to be based on the actual facts of experience in various cases, these being sufficiently numerous and representative to enable valid inferences to be drawn therefrom. What we wish to ascertain is the general nature of the relationship between the perceived colour and the spectral composition of the light which reaches the eyes of the observer. The latter can, of course, exhibit a wide range of variations and the question arises how it should be ascertained and specified. The further question arises how the perceived colour is to be characterised and described. The problems here stated indicate the complexity of the subject. The choice of the material utilized for such studies is evidently a matter of importance. It should be such as to minimize the difficulties of the investigation.

In the present chapter, we shall set out the results emerging from a study of the visual synthesis of colour made with material which is in a particularly suitable and convenient form, viz., colour filters which absorb a limited part of the spectrum more or less completely and freely transmit the rest of it. It will be recalled that a great many filters of gelatine-on-glass dyed with suitable colouring matters were specially fabricated and made use of for the studies described in earlier chapters. Such filters have been utilised also in the present studies. Colour filters can also be prepared by dissolving a small quantity of a dye-stuff or other material in distilled water contained in a rectangular glass cell of suitable dimensions ($10 \times 10 \times 2\,cm^3$). By varying the quantity of absorbing material put in, its effective thickness can be varied and the resulting changes in the colour and the spectral nature of the transmitted light can be conveniently followed.

Colour filters of cyanin: We shall now describe in detail, the observations made with a set of seven filters of gelatine-on-glass coloured by the well-known dye-stuff cyanin to different extents and thus exhibiting the effect in a regular sequence of an increasing measure of absorption, both on the colour of the transmitted light and on its spectral character.

To study the character of the spectrum of the light transmitted by a filter, a convenient plan is for the observer to hold a replica diffraction grating in front of his eye and to view the first-order diffraction spectrum of a linear tungsten filament in a tubular lamp glowing at a white heat. Introducing the filter in front of the diffraction grating, the change in the spectrum produced thereby can be quickly noted. It then becomes evident that absorption by the cyanin filters is limited to the yellow, orange and red sectors of the spectrum, while the blue and the green sectors are transmitted without any noticeable loss in intensity. The absorption in the red sector takes the form of a well-defined absorption band, which in the case of the weakest filter may be located in the wavelength range 620–650 mμ. In the other filters of the series, this band becomes more pronounced and also becomes wider, the spreading being asymmetrical and chiefly towards the lesser wavelengths. Even through the most heavily dyed filter, the red end of the spectrum in the region of 700 mμ continues to be freely transmitted.

Simultaneously with the increase of the absorption in the red, the absorption in the yellow and orange becomes intensified, until finally with the most heavily dyed filter, we have a continuous absorption commencing at 570 mμ covering the yellow and orange sectors and joining up with the absorption band in the red mentioned above. It is noteworthy that even with the most heavily dyed filter, there is no observable absorption in the region of wavelengths less than 570 mμ. In particular, the green of the spectrum comes through with full intensity.

The colour of the light transmitted by the filters as seen by holding them against a clouded sky may be described as blue in all cases. There is, however, an observable progression which can be described as an increase in the depth of the colour or alternatively as an increase in the degree of its fullness or saturation. These changes, it should be remarked, go hand in hand with the increase in the absorption in the yellow sector of the spectrum between 570 and 590 mμ. Indeed, it would be correct to say that the blue colour of the light transmitted by the filters exhibits fullness or saturation to an extent determined by the completeness of the absorption of the yellow.

With the disappearance of the yellow sector of the spectrum, and the extinction of the greater part of the red sector, we are still left with the blue and green sectors which are present in full strength. It is remarkable that there is scarcely any indication in the perceived colour of the green sector which is seen with great intensity on the spectrum of the light which passes through the filter.

The cuprammonium filter: Dissolving copper sulphate in distilled water and adding ammonia in excess, we obtain a solution exhibiting a characteristic blue colour. When the concentration of the solution is high, the transmission by it is confined to the region of the shortest wavelengths and indeed, the cuprammonium filter is usually employed for isolating this part of the spectrum. When, however, the solution contained in a cell 2 cm thick is progressively diluted by addition of distilled water, striking changes may be observed in the spectrum of the light transmitted by it. The transmission, which at first is confined to the violet end of the spectrum, extends towards longer wavelengths. It ceases to be confined to the blue region of the spectrum and the green sector is also transmitted. This progressively gains in strength until as seen through the spectroscope, the green actually appears more luminous than the blue sector. With further dilution, the transmission extends into the orange and the red of the spectrum, but the yellow region remains faint, the orange and the red much exceeding it in brightness. Throughout this series of changes, the colour of the transmitted light is perceived as blue, the depth or saturation of the colour diminishing notably in the case of the very dilute solutions. The observations thus make it evident that the blue colour of the transmitted light and the extinction of the yellow in its spectrum are connected phenomena.

Solutions of potassium dichromate: Commencing with a concentrated aqueous solution of potassium dichromate and progressively diluting it with distilled water, we can readily follow the changes in the perceived colour of the light transmitted through a definite thickness of the solution in relation to its spectral character. The concentrated solution is of a deep orange hue and the spectrum exhibits a cut-off of all wavelengths less than 565 mμ. A considerable measure of dilution is needed before there is any marked change of colour or a noticeable shift in the position of the cut-off. Step by step, however, these changes may be effected and as the cut-off moves from 565 to 520 mμ the colour alters progressively from a deep orange to a rich golden-yellow. On further dilution, the cut-off becomes less sharply defined and moves from the green into the blue sector of the spectrum. The colour then alters to a bright yellow and then to paler and paler shades of yellow. So long, however, as even a tinge of yellow is observable in the colour of the transmitted light, the absorption at the short-wave end of the spectrum continues to be noticeable.

Solutions of cobalt sulphate: An absorption of light in the green of the spectrum covering the wavelength range between 500 and 550 mμ coupled with a free transmission of the longer wavelengths is manifested by moderately strong aqueous solutions of cobalt sulphate. Stronger solutions exhibit an absorption extending to about 575 mμ and appear of a deep orange colour by transmitted light, while weak solutions exhibit a colour varying from a rose-red to an orange-red depending on the extent of dilution. There is an observable transmission through the solutions of the shorter wavelengths in the spectrum. But such transmission does not appear to have any marked effect on the colour of the transmitted light.

Solutions of nickel chloride: Aqueous solutions of this crystalline salt exhibit notable variations in the brightness and colour of the transmitted light as the concentration of the salt is varied. These changes are most conveniently exhibited by filling a set of bottles of the same size with solutions of different concentrations and placing them side by side against the same white background so that their differences in appearance are evident at a glance. The relationship of the colour to the spectral character of the light transmitted through the solution can also be followed with the aid of a pocket spectroscope.

The green colour of solutions of nickel chloride is a consequence of an absorption of light which manifests itself at both ends of the spectrum, the intermediate parts being freely transmitted. When solutions of different concentrations are set side by side and compared with other, it is found that a very striking change occurs when the cut-off of the longer waves shifts its position from about 570 to 590 mμ. In the former case, the yellow of the spectrum is completely cut off, while in the latter case it is freely transmitted. As a result, the transmitted light notably gains in intensity and its colour changes from a clear green to a green tinged with yellow. Greater dilutions in which the cut-off shifts further into the red result in less noteworthy changes. The highly important role played by the yellow sector of the spectrum in determining the colour of the transmitted light is thus made apparent.

Solutions of chromium chloride: Strong solutions of the chloride of chromium exhibit a deep green colour which owes its origin to a transmission in the 500–550 mμ region of the spectrum. Holding up a cell containing such a solution against a strong light and examining the light coming through it with a pocket spectroscope, the transmission band in the green sector is found to be accompanied by another located near the red end of the spectrum. It is the intermediate region containing the yellow of the spectrum which is most strongly absorbed. Dilution by successive additions of distilled water results in a large increase in the brightness of light transmitted by the cell, but there is no very pronounced change in its colour. Spectroscopic examination in these circumstances reveals that the band of transmission in the green has broadened in either direction and that the red sector has also made its appearance in the transmitted light. When the dilution has been carried far enough, the red region of the spectrum is quite conspicuous and it is only a little less bright than it is normally.

It seems surprising that in the circumstances stated above, the colour of the transmitted light is not very different for the dilute solutions and for the stronger ones. The explanations for this feature is chiefly that in neither case does the yellow sector of the spectrum in the range of wavelengths between 570 and 590 mμ appear in the transmitted light. Indeed, the bands of transmission in the green and in the red come close to each other but the intervening yellow is scarcely visible. In the absence of the yellow sector, the transmission of the red sector has but little influence on the perceived colour. The only perceivable change is a diminution in the fullness or degree of saturation of the colour.

That the green solutions of chromium chloride powerfully absorb the yellow sector of the spectrum is strikingly illustrated by viewing a brightly illuminated screen through a cell containing such a solution and then suddenly removing the cell. The fovea of the observer's retina is then conspicuously visible projected on the screen as a bright yellow disk.

Solutions of methyl violet: Using a glass cell 2 cm deep containing distilled water, and adding to it drop by drop a strong solution of the well-known dye-stuff methyl violet, the changes resulting therefrom in the perceived colour of the transmitted light and their relation to the changes in its spectral character can both be followed step by step. The first noticeable change in the spectrum of the transmitted light is the manifestation of a powerful absorption in the wavelength range from 570 to 600 mμ. This becomes more and more pronounced and finally quite complete. Accompanying this change and evidently as the result of it, the transmitted light assumes a reddish-purple colour and this develops into a fully saturated hue. On further addition of the methyl violet, the absorption of the yellow extends into the orange up to about 620 mμ. A weak and rather ill-defined absorption also appears in the spectral range between 520 and 570 mμ. This ultimately joins up with the absorption in the yellow and orange and forms a continuous band of extinction extending from about 520 to 620 mμ. The final colour of the transmitted light is a reddish-purple, not noticeably different from that exhibited when the absorption of the green is weak and just noticeable.

The facts of observations stated above clearly indicate that it is the absorption of the yellow in the spectrum by the dye-stuff which results in the manifestation of a reddish-purple colour by its solution.

Solutions of crystal violet: Following the same procedure as that described above for the case of methyl violet, the behaviour of solutions of the closely related dye-stuff crystal violet can be studied. The detailed description of the observed effects given above may be repeated almost *verbatim*, except for the following differences. The strong absorption which first manifests itself now extends from 580 to 610 mμ instead of from 570 to 600 mμ as in the case of methyl violet and the colour of the transmitted light is a bluish-purple instead of a reddish-purple. The extinction band which is seen when a sufficient quantity of the dye-stuff has been added to the solution now extends from 530 to 630 mμ, and the colour of the transmitted light at this stage remains a bluish-purple.

Thus, the facts indicate that it is the absorption of the yellow in the spectrum by the dye-stuff which results in the manifestation of a bluish-purple colour by its solutions. That methyl violet yields reddish-purple solutions while crystal-violet yields solutions of a bluish-purple colour becomes intelligible when it is mentioned that the brightness of the red sector relatively to the blue sector as perceived in the spectrum of the transmitted light is manifestly greater for methyl violet than for crystal violet.

Solutions of bromo-cresol purple: An intense absorption of the yellow in the spectrum is a characteristic property of aqueous solutions of this dye-stuff. Dilute solutions of it exhibit a purple colour and spectroscopic examination of the transmitted light reveals that this is a consequence of the powerful absorption appearing as a dark band in the spectrum covering the spectral range from 570 to 610 mμ, while there is no noticeable absorption of either shorter or longer wavelengths. With further addition of the dye-stuff to the solution, the absorption band spreads in either direction, and covers the spectral range from 550 to 620 mμ. No noticeable change in the colour of the transmitted light however results therefrom.

Solutions of bromo-phenol blue: Dilute solutions of this dye-stuff exhibit a light bluish-purple colour associated with an intense absorption covering the spectral range from 580 to 610 mμ and perfect transparency to the rest of the spectrum. Less dilute solutions exhibit a somewhat deeper purple colour coupled with an absorption covering the spectral range from 550 to 620 mμ.

Solutions of chloro-phenol red: Dilute solutions of this dye-stuff exhibit a powerful absorption in the wavelength range 560 to 590 mμ which appears as a dark band in the spectrum. The colour of the solution as exhibited by a layer 2 cm thick is a purplish red. Less dilute solutions exhibit an absorption band covering the wider spectral range from 540 to 600 mμ and the same colour but somewhat more pronounced. There is also a distinct general absorption of the blue and the green in the spectrum and consequent weakening of those regions. This is evident on a comparison with the red part of the spectrum.

Solutions of coomassie violet: When a few drops of a solution of this dye-stuff are put into a cell containing distilled water, the spectrum of the transmitted light exhibits a weak absorption in the wavelength range between 500 and 560 mμ, in other words of the green sector in the spectrum. Further additions increase the strength of this absorption till it becomes complete and appears as a dark band crossing the spectrum. There is, however, no noticeable spreading out of the band, nor is there any noticeable absorption in the other parts of the visible spectrum. The colour of the very dilute solutions is a pale rose red, and this deepens and becomes a bright rose red when the absorption in the green is complete.

Solutions of magenta: Very dilute aqueous solutions of this dye-stuff exhibit a well-defined absorption band covering the spectral range from 540 to 560 mμ in the green, while the colour of the transmitted light is a rose-red. Further additions of the dye-stuff result in this band extending up to 590 mμ, and also in a general absorption which weakens the transmission of the blue and green of the spectrum. The colour of the transmitted light then turns to a brilliant red.

Solutions of methul blue: This due-stuff exhibits a powerful absorption in the wavelength range 650 to 680 mμ which appears as a dark band crossing the spectrum of very dilute solutions. With successive additions of the dye-stuff this absorption spreads out in both directions. The transmitted light exhibits a full blue colour when the cut-off of the shorter wavelength extends up to 570 mμ, despite the fact that the green sector then appears with undiminished intensity along with the blue and there is also an observable transmission at the extreme red end of the spectrum. Further additions of the dye-stuff which shift the position of the cut-off to 550 mμ reduce the observed intensity of the transmitted light but have no noticeable effect on its colour.

Solutions of methyl green: Despite its name, a fairly strong solution of this dye-stuff in a cell 2 cm thick appears of a full blue colour, the spectrum of the transmitted light covering the wavelength range from 450 to 550 mμ, besides a narrow band in the red at 700 mμ; the intermediate region from 550 to 700 mμ exhibits a practically complete absorption. Dilution results in the absorption band becoming narrower, then covering the wavelength range from 570 to 680 mμ; and the transmission of the blue then extends to 440 mμ. In these circumstances, the green of the spectrum appears with full strength in the transmitted light; nevertheless, the perceived colour remains blue. Not until the dilution is carried much further and there is free transmission up to 590 mμ, does the colour change to a light greenish-blue.

Results of the study: We now proceed to state the conclusions which follow from the observations set forth above. The major result which emerges from the studies made with a variety of materials differing widely in their chromatic behaviour is the immense importance of the role played by the yellow sector of the spectrum and in particular, by the wavelength range between 570 and 590 mμ, in the perception of light and colour. The presence or absence of this range of wavelengths in the light received by the eye of the observer makes all the difference to the visual impressions produced by it.

First of all, we may refer to the most surprising result of all, viz., that the removal of the yellow sector from white light, other things remaining the same, results in producing the colour sensation familiarly known as purple. Numerous examples of this finding have been set out above. Many further illustrations that emerge from the studies of floral colour and of the hues exhibited by various natural and synthetic products will form the subject of later chapters.

If in the composite light under observation, the blue sector is stronger relatively to the red sector than is normally the case while the yellow sector is absent, the colour sensation would be a bluish-purple. The weaker the red sector is, the more nearly would the bluish-purple resemble blue in its characters. If the situation is reversed and the red sector is stronger relatively to the blue than it is normally, the colour perceived is a reddish-purple, tending more and more to resemble red in the limiting case when the blue is very weak.

More generally, the studies indicate that the presence in full strength of the part of the spectrum lying within the wavelength range 560 to 600 mμ is incompatible with the excitation by composite light of the highly chromatic sensations described by the terms blue, green or red. Only in the absence of the yellow sector of the spectrum can these colours be perceived at all, or at least without being modified to such an extent as to be unrecognisable.

The studies also furnish evidence of the existence of a physiological phenomenon which may be conveniently termed as the masking of one colour by another. An effect of this nature very clearly manifests itself when the composite light includes both the parts of the spectrum which we have referred to as the blue sector and the green sector. When the spectrum of white light is visually observed either through a prismatic spectroscope or through a diffraction grating, the green of the spectrum between 500 and 560 mμ appears far more luminous than the part of the spectrum between 400 and 500 mμ. Nevertheless the light transmitted by a filter which passes both of these regions freely but cuts out the light of greater wavelength appears of a blue colour without any indication appearing of its admixture with green light.