The Colour Group

in collaboration with

The Institute of Physics and The Physical Society

and

The Inter-Society Colour Council of the U.S.A.

MAXWELL COLOUR CENTENARY

at

THE ROYAL INSTITUTION

and

THE IMPERIAL COLLEGE
LONDON

on

TUESDAY, WEDNESDAY and THURSDAY,

16th, 17th and 18th May 1961

Maxwell Colour Centenary

On 17 May 1861, James Clerk Maxwell gave his famous demonstration of trichromatic colour reproduction at the Royal Institution in London, and to mark the centenary of this event the Colour Group, in collaboration with The Institute of Physics and The Physical Society and the Inter-Society Colour Council of America, has arranged a three-day conference on 16, 17 and 18 May 1961. This will be held at the Imperial College of Science and Technology, South Kensington, London, S.W.7, with a centenary discourse at the Royal Institution on 17 May.

The subjects for discussion on the three days will be Trichromatic Principles, Colour Reproduction and Colour Appearance. Extended abstracts of the 18 papers to be presented at the conference are given in the following pages.

MAXWELL AND MODERN COLORIMETRY

*D. B. JUDD**

National Bureau of Standards, Washington, U.S.A.

ALL vision is colour vision, for it is only by observing differences of colour that one distinguishes the forms of objects. Among differences of colour are included differences of brightness.

All light is composed of the rays of the spectrum taken in different proportions. Objects which are called coloured when illuminated by daylight make a selection of these rays, and our eyes receive from them only a part of the light which falls on them. This is the optical explanation of the colours of bodies when illuminated by daylight. They separate the daylight into its component parts absorbing some and scattering others.

To bring a quality (such as colour) within the grasp of exact science one must conceive it as depending on the values of one or more variable quantities, and the first step is to determine the number of these variables which are necessary and sufficient to determine the quality of a colour. Elaborate experiments are not required to prove that the quality of colour can vary in three and only in three independent ways.

Now colour depends on three things. If one calls these the amounts of the three primary colours, and if one is able in any way to measure these three amounts (tristimulus values) one may consider the colour as specified by these three measurements. If it is wished to specify the position of a point in a (usual) room, it may be done by giving the measurements of three distances—namely, the height above the floor, and the distances from any two touching walls. If the amounts of the primary colours are taken as these distances, it may be said, by a useful geometrical convention, that the colour is represented to our mathematical imagination by the point so found in the room; and if there are several colours, represented by several points, the chromatic relations of the colours will be represented by the geometrical relations of the points.

There is a still more convenient method of representing the relations of colours by means of (what Maxwell called) Young's colour triangle (now known as the Maxwell triangle). It is impossible to represent on a plane of paper every conceivable colour; to do this requires space of three dimensions. If, however, one considers only colours of the same total amount—that is, colours in which the sum of the tristimulus values is the same, then the variations in chromaticity of all such colours may be represented by points on a plane. For this purpose one must draw a plane cutting off equal lengths from the three lines representing the primary colours. The part of this plane within the space in which our colours have been distributed will be an equilateral triangle. The three primary colours will be at the three angles, white or grey will be in the middle, the degree of purity of any colour will be expressed by its distance from the middle point, and its hue (dominant or complementary wavelength) will depend on the angular position of the line which joins it with the middle point.

*Except for parenthetical expressions and substitution of modern terminology, this summary of colorimetry is composed entirely of quotations from the writings of James Clerk Maxwell.

Thus the ideas of purity and hue can be expressed geometrically on the (Maxwell) triangle. To understand what is meant by brightness (luminance) one has only to suppose the illumination of the whole triangle increased or diminished, so that by means of this adjustment of illumination the triangle may be made to exhibit every variety of colour. If any two colours in the triangle are taken and mixed in any proportions, the resultant colour will be found in the line joining the component colours at the point corresponding to their centre of gravity.

Nothing has been said about the nature of the three primary colours. In order to lay down on paper the relations between actual colours, it is not necessary to know what the primary colours are. Take any three colours, provisionally, as the angles of a triangle, and determine the position of any other observed colour with respect to these, so as to form a kind of chart of colours. In studying mixtures of colours, one must either mix the rays of light themselves, or combine the impressions of colours within the eye by the rotation of coloured papers on a disc (Maxwell disc).

One can make a mixture of any three of the colours of the spectrum, and vary the colour of the mixture by altering the amount of any of the three components. If the observer looks at a prism illuminated by daylight from each of three suitably disposed slits (with a lens to image the slits at the pupil of his eye) he sees (by Maxwellian view) this compound colour. If this compound colour is placed side by side with any other colour, the compound colour can be altered till it appears exactly similar to the other. When the match is pronounced perfect, the positions of the slits are registered, and the breadth of each slit is carefully measured by means of a gauge. The records of these breadths asserts that a mixture of three spectrum colours is, in the opinion of the observer, identical with the fourth colour. In order to make a survey of the spectrum three points are selected for purposes of comparison, and these are called the three standard colours. The standard colours are selected on the same principles as those which guide the engineer in selecting stations for a survey. They must be conspicuous and invariable and not in the same straight line. In the chart of the spectrum colours one may see the relations of the various colours of the spectrum to the three (working) standard colours and to each other.

Experiments on colour indicate very considerable differences between the vision of different persons, all of whom are of the ordinary type. These differences are exactly of the same kind as would be observed if one of the persons wore yellow spectacles. In fact, most of us have near the middle of the retina a yellow spot through which the rays must pass before they reach the sensitive organ. When a mixture of red and bluish-green light falls on the ordinary surface of the retina, it is of a neutral tint, but when it falls on the yellow spot only the red light reaches the optic nerve, and we see a red spot (Maxwell spot) floating like a rosy cloud over the illuminated field.

COUNTING METAMERIC OBJECT COLOURS

W. S. STILES
National Physical Laboratory, Teddington
and
G. W. WYSZECKI
National Research Council, Ottawa, Canada

THE defining characteristic of a diffusely reflecting surface, regarded as an object colour, is its spectral reflectance function ρ_λ ($0 \leqslant \rho_\lambda \leqslant 1$) over the visible spectrum. Given the three colour-matching functions $\bar{x}_\lambda$, $\bar{y}_\lambda$, $\bar{z}_\lambda$ of a trichromatic system (e.g., the C.I.E. System) and an object illumination of fixed intensity and spectral energy distribution ($E_\lambda \, d\lambda$), the corresponding tristimulus values X, Y, Z, of the light reflected from any object colour define a point of the colour solid, in XYZ-space, that is associated with the combination ($\bar{x}_\lambda$, $\bar{y}_\lambda$, $\bar{z}_\lambda$, E_λ). This solid is bounded by a closed surface (which is nowhere concave) containing the representative points of the familiar "optimal colours" (object colours of given chromaticity having the highest luminance). Except where they lie on plane parts of the surface, optimal colours have no metamers—there is just one object colour or spectral reflectance function which will generate them. On the other hand, to all points within the colour solid belong many metamers—in fact infinitely many. Qualitative considerations suggest that, in some sense, the "number" of metamers belonging to a point increases in going inwards from the surface of the colour solid. By introducing elementary statistical concepts, the "counting" of metameric object colours is made precise and the process is shown to have several colorimetric applications in problems such as the assessment of degree of metamerism, or of the difference of colour-rendering properties of different object illuminations.

The starting point is a basic collection of object colours, and main interest attaches to basic collections containing indefinitely many object colours extending over a continuous range of ρ_λ functions. Counting has a meaning only if the frequency with which different ρ_λ functions occur in the basic collection can be specified. Of the innumerable forms in which a basic collection could be specified, probably the simplest—and the one mainly used here—approximates every spectral reflectance ρ_λ by a step function having constant values in M small wavelength intervals into which the visible spectrum is divided. The basic collection is then completely specified by some function $F(\rho_1 \ldots \rho_M)$ where $F(\rho_1 \ldots \rho_M)\, d\rho_1 \ldots d\rho_M$ is the chance that a random member of the collection has its respective interval reflexion factors between ρ_i and $\rho_i + d\rho_i$ ($i=1$ to M). An important restriction on the basic collections specifiable in this way is imposed by assuming that ρ_i varies independently in each wavelength interval, i.e., it is assumed that $F(\rho_1 \ldots \rho_M)$ reduces to a product of M functions each dependent on one ρ_i only: $F(\rho_1 \ldots \rho_M) = F_1(\rho_1) \ldots F_M(\rho_M)$. This assumption greatly facilitates further analysis and all basic collections that conform to it can be represented by proper choice of the functions $F_i(\rho_i)$. It is adopted in what follows, but ways in which it can be relaxed, in some degree, to conform better to practical basic collections, are touched on in the paper.

A particular tristimulus value, X say, of the members of a basic collection takes the form

$$X = \sum_{i=1}^{M} \rho_i\, (E_i\bar{x}_i)$$

where $(E_i\bar{x}_i)$ is the average value of $E_\lambda\bar{x}_\lambda$ in the i^{th} interval. Since the ρ_i's are independent random variables—although not in general normally distributed—the central limit theorem of statistics can be invoked to show that the sum X will approximate to a random variable *distributed normally* about its average value for the collection, X_M, provided M is sufficiently large and some other acceptable conditions are satisfied. The normal distribution according to which $G(X)\, dX$ (chance that X lies between $X + dX$ and X) is proportional to $e^{-(\frac{1}{2}\sigma^2)(X-X_m)^2}$ where

$$\sigma^2 = \sum_{i=1}^{M} (E_i\bar{x}_i)^2 \left[\int_0^1 \rho^2 F_i(\rho) d\rho - \left\{ \int_0^1 \rho F_i(\rho) d\rho \right\}^2 \right],$$

is an approximation that must obviously break down when $X - X_m$ exceeds a certain limit because X has finite maximum and minimum values beyond which the actual probability G(X) must be strictly zero. However, computations indicate that for a large proportion of the object colours of the collection the normal distribution is an adequate approximation to the true distribution.

When the three tristimulus values are considered together, the generalized central limit theorem shows that, subject to approximations already mentioned, the metamer distribution is again a normal one but, of course, in three dimensions. The analysis is conveniently carried out by making an initial linear transformation of the tristimulus variables, which, in effect, replaces the functions $E_\lambda\, \bar{x}_\lambda$, $E_\lambda\, \bar{y}_\lambda$, $E_\lambda\, \bar{z}_\lambda$ by three equivalent but normal orthogonal functions. Finally, the inverse transformation is applied, to G(X, Y, Z), the distribution function in X, Y, Z space. G(X, Y, Z) has a maximum value at the point X_m, Y_m, Z_m, and assumes each constant value below the maximum on the surface of an ellipsoid, all these ellipsoids being similar and centred on X_m, Y_m, Z_m but of increasing size as the constant G value diminishes. The absolute size of all these ellipsoids—but not their common shape and orientation—is reduced and by the same factor if the original subdivision of the spectrum is made finer, i.e., if M is increased. But the finer the subdivision the less acceptable is the assumption that the reflexion factor values ρ_i in different—and in particular adjoining—wavelength intervals, vary independently among the members of the basic collection. Thus when the absolute size of the ellipsoids of constant G value is in question, the proper choice of M is critical and not easy.

The most interesting application of the method so far is to the determination of the distribution of the tristimulus values in a second trichromatic system $\bar{x}'_\lambda$, $\bar{y}'_\lambda$, $\bar{z}'_\lambda$ and for another object illumination $E'_\lambda d\lambda$, of all those object colours that are approximately metameric for the original trichromatic system and object illumination. This case is handled by treating the two pairs of three tristimulus values as a six-variable system and deriving the normal distribution function $G(X_1\, Y_1\, Z_1\, X'\, Y'\, Z')$. The form of G shows that the ellipsoid of constant G, in $X'\, Y'\, Z'$ space, which encloses some fixed proportion of all the metamers (in the original system) of a given reference colour X_o, Y_o, Z_o, is the same in shape, orientation and volume whatever the reference colour selected: it is merely the location of the centre of the ellipsoid that varies with X_o, Y_o, Z_o. While this result is valid only in the domain of the colour solid in which the conditions for the approximate normal distribution hold good, it suggests that one interesting aspect of the difference in the colour-rendering of two illuminants, or the difference between two sets of colour-matching functions can be characterized, for a given basic collection, by a single ellipsoid.

An earlier method of treating the problem just discussed was developed by one of the authors (G. W. W.) using the device of metameric blacks (hypothetical functions that go negative at some wavelengths in such a way that their tristimulus values are all zero), and employing Monte Carlo computations, in contrast to the "deterministic" procedure used here. Comparison of the results by the two methods illustrates certain differences in the underlying assumptions.

THE CURRENT POSITION IN THE PHYSIOLOGY OF COLOUR VISION

W. A. H. RUSHTON
Trinity College, Cambridge

THE physiology of 100 years ago had yet to arrive at many of the concepts which seem basic to-day. Hormones were not suspected, and there was little direct evidence as to what went on in nerves—especially sensory nerves. Yet in the lecture-demonstration which is being commemorated on this occasion, Clerk-Maxwell clearly saw that the laws of colour mixture are laws of human physiology, and his treatment was essentially correct by present day physiological standards.

He verified Newton's centre-of-gravity rule for colour mixture and enunciated what Newton must have seen, that this implied trichromacy. He rejected Lomonosov's and Brewster's idea that there were three different kinds of light, and adopted Thomas Young's suggestion that there were three different kinds of nerve distributed over the retina.

Maxwell accepted the important generalization of Johannes Müller that the quality of a sensation depends upon the particular nerve fibres excited, not upon the quality of stimulus which excites them. Thus the observed trichromacy of vision implies three types of nerve and is explained if we postulate them. Though colour-vision theory provokes many people—even physiologists—to remarkable intellectual acrobatics and staggering attitudes of unstable equilibrium, the majority have accepted Maxwell's views, and subsequent physiological research has done little to undermine them.

What physiologists have begun to do is to fill in two details of mechanism. (*a*) What is it at the sensitive terminal's of Young's three nerves that can resonate to undulations of 500 billions of vibrations in a second? (*b*) What sort of message is sent up the optic nerve fibres to the brain centres?

(*a*) **Visual Pigments.** The specific molecular resonnance of visual pigments was seen as soon as Kühne studied the bleaching of rhodopsin in lights of various wavelengths. Kühne's famous investigations upon rhodopsin have been followed by a series of distinguished workers including Lythgoe, Morton and Dartnall in this country and Bliss and Wald, Hubbard and their colleagues in the U.S.A. Though rhodopsin is the pigment of the rods and probably plays no part in colour vision, it is much easier to investigate than the very inaccessible cone pigments, and it probably behaves in a way closely similar.

Visual pigments may be studied objectively by three methods.

(i) They may be brought into solution by extracting with e.g., digitonin (Tansley).

(ii) The retina may be excised and mounted in a transparent cell with the receptors still maintaining their structural organization (Denton).

(iii) The reflectivity of the intact (e.g., living) eye may be measured in an ophthalmoscopic arrangement and changes in visual pigments inferred from changes in reflectivity.

Dartnall, Crescitelli, Wald with their colleagues and also others have obtained extracts from a great variety of animal eyes (mainly from rods) and found that these may be divided sharply into the compounds of Vitamin A_1 and Vitamin A_2. All the pigments have much the same spectral absorption curve but the peaks occur at various wave lengths.

Perhaps the most important result in recent years is Wald and Hubbard's success first in synthesizing rhodopsin from the rod protein, opsin and retinene, the aldehyde of Vitamin A (Morton). Then their discovery that only the 11–*cis* isomer of retinene was effective, and that the retinene liberated on bleaching in the form of indicator yellow (Lythgoe) was the all-*trans* form. Thus isomerization of retinene (or Vitamin A) is an essential step in the bleaching $\longrightarrow$ regeneration cycle. The 11–*cis* isomer appears in nature only in eyes, but it is there in a wide range of animals including invertebrates.

The method of retinal densitometry (iii) is much inferior in accuracy to methods (i) and (ii), but it has three advantages: (*a*) the conditions of bleaching and regeneration may be measured in the living eye, (*b*) measurements may be made on man and correlated with psychophysics, (*c*) measurements upon the human fovea give objective information about cone pigments which is hard to get any other way.

But so far results are slight. They amount merely to this. On the fovea of the protanope there is one visual pigment detectable in the red-green range. Its action spectrum coincides pretty well with its difference spectrum and with the protanope visibility curve (Pitt). This is therefore the principal cone pigment of of the protanope. He can see blue and presumably has a blue-sensitive pigment, but it cannot be measured with a technique which measures the green pigment, chlorolabe, correct to about 10 per cent.

The normal fovea contains a red-sensitive pigment erythrolabe lacking in the protanope. So does the fovea of the deuteranope. Erythrolabe behaves in a misleading manner which cannot be explained until a new deuteranope is found to work on. They come to Imperial College at the rate of 12/1000 but they come to the Cambridge Mecidal School at about 12/10,000!

(*b*) **Nerve Messages.** Hartline, Granit and many others following them have obtained electrical records from optic nerves and ganglion cells in various vertebrates.

These nerve fibres are clearly connected to cones since their photoreceptors exhibit not only the photopic spectral sensitivity (Granit) but also a marked Stiles-Crawford effect (Donner and Rushton). But they certainly do not correspond in any simple way with one or other of Young's three types. This is probably for two reasons: (*a*) It is very hard to isolate a single cell or fibre for detailed study unless it is exceptionally large, and large ganglia are connected to very many receptors, probably of different kinds. So the fibres studied are not likely to be concerned mainly with colour. (*b*) The idea that Young's three colour nerves run to the *brain* for the assessment of their relative outputs seems to be wrong. The first stage in the assessment probably occurs in the middle layers of the retina, and "colour" messages in the optic nerve encode such things as the red/green *ratio*. Hubel and Weisel have recently found a few optic nerve fibres in the monkey which gave "on"-discharges to a red flash, "off"-discharges to a green flash and no discharge to a white flash!

This is analagous to the remarkable records that Svaetichin and MacNichol have obtained from horizontal cells in the excised but surviving retina of some fish. Micro-pipette recordings show, not the explosive "all or none" response of the nerve spike, but a sudden maintained potential change like the output of a photocell. A red light caused hyperpolarization, a green light, depolarization, a yellow light, no change. Some fish have this red-green antagonism, some a yellow-blue, some have different cells which show each.

Though no mammal has yet been shown to have antagonistic horizontal cells it seems very likely that there may be some such mechanism in our own eyes and that Young's trichromacy is established at the pigment level, and Hering's opponent colour process at the horizontal cell layer.

But retinal interaction is enormously complex. There is inhibition between centre and periphery of each tiny area supplied by one optic nerve fibre, there are spatial and temporal interactions on a much wider scale, and there is likely to be an elaborate organization in brain centres before a level is reached where we may suppose the activity is connected with consciousness.

De Valois and others have recorded the spectral sensitivity of various cells in the monkey's visual cortex. The results show much variation from cell to cell, and a good deal of this skilled and exacting work will be needed before clear generalizations can emerge. But these are the lines which eventually will tell us how the brain organizes its messages into colour vision.

THE PHYSIOLOGICAL BASIS OF POLYCHROMATISM

Y. LeGRAND

Natural History Museum, Paris

THE existence of three photosensitive pigments in the retinal cones provides an adequate basis for colorimetry; that is to say, for the laws of metamerism of the eye functioning merely as a colour-matching apparatus. But the phenomena of colour vision in general require additional hypotheses concerning the receptor mechanisms of the retina and their interactions, and concerning the functions of the various nerve cells which occur in the visual path (bipolar, ganglion, geniculate body, and the cortex itself). Various classes of facts serve as a basis for these hypotheses.

First of all, the generalization of colorimetry to include general matching and threshold phenomena. For example the colorimetry of point sources and measurements of visual acuity in monochromatic light (especially after strong coloured adaptation) provide data on the topographical distribution and density of the retinal receptors. A form of interaction between these receptors can be obtained by the additivity of luminances (Abney's law) and the departures from this additivity; and various luminous efficiency curves can be interpreted by the synthesis of the activities of the mechanisms of colour vision. Finally, the differential colour threshold is the result of an interaction between receptor mechanisms, but the analysis of this interaction is difficult; in particular the considerable variations in threshold with the dimensions of the test object show that the co-operation of a large number of receptors seems necessary for good colour discrimination.

Secondly, subjective effects greatly affect colour sensations. Thus the classical laws of colour vision constitute a body of knowledge which greatly exceeds the trichromatic scheme: the character of simplicity of certain radiations, the Bezold-Brücke effect, neutralization of saturation in complementary mixtures, etc. The effects of adaptation on the appearance of colours and the exceptions to the Von Kries coefficient law also provide several facts difficult to interpret; the same is true of the variations in intensity in the Stiles-Crawford effect.

Thirdly, the objective results of electrophysiological studies must be considered. The electro-retinogram, even with techniques in which micro-electrodes are used, has as yet only given meagre results at the level of the retinal receptors themselves; but the subsequent nerve cells (bi-polar, and perhaps also horizontal and amacrine cells) in fishes have given interesting results which in one sense provide arguments in favour of Herings' opponent pairs. With regard to the well-known response of the ganglion cells, they provide a lot of material but it is difficult to interpret: the modulators seem to result in complex interactions between the signals produced by the preceding cells, and perhaps thus provide the physiological basis for polychromatic sensations. With regard to tests made on animals at the levels of the geniculate body, they have not so far taught us much, and this organ does not seem to modify the messages which are responsible for colour vision. With regard to the cortex, colour phenomena only occur there in a manner still sufficiently uncertain for one to conclude anything precise.

In spite of the enormous mass of experimental data which the ingenuity of investigators has accumulated, it seems premature to settle on a coherent physiological scheme for colour vision; the only certainty which emerges from these studies is the complication of the mechanisms and their interactions at all stages, except those of the photosensitive pigments themselves; if Thomas Young's brilliant hypothesis remains exact at this stage, it is highly improbable that "each nerve fibre consists of three sections, one for each principal colour." Subjective techniques have nearly exhausted their possibilities, but electro-physiology is still very rich in promise and it is here that one can hope in the not too distant future for a fitting crowning of the work of Young and Maxwell.

EYE MOVEMENTS IN RELATION TO COLOUR DISCRIMINATION

R. W. DITCHBURN
University of Reading

EYE movements produce movements of the retinal image with respect to the retina. By methods which have previously been described[1-6] it is possible to produce a *stabilized retinal image* (i.e., an image which remains on the same retinal receptors even when the eye moves). It has been shown that involuntary eye movements remain during fixation[7-10]. These involuntary movements include a tremor which vibrates the retinal image with an amplitude of the same order as the intercone separation. There are also involuntary saccadic movements of up to 20 min. arc (and occasionally much more) and slow drift movements. It is found that when all movements of the retinal image are annulled (completely stabilized image) visual discriminations fail and the field goes dark. This failure is intermittent; normal vision returns from time to time provided that the illumination is sufficiently strong. Normal discrimination of contrast (in white light or in monochromatic light) is restored by a small imposed vibration in the frequency range 4–14 c.p.s. It is also restored by imposed saccadic movements[11]. Intermittent illumination of the stabilized image (in the frequency range 2–15 c.p.s.) also restores normal discrimination of differences of luminance[12].

If two parts of a bipartite field (of about $1\frac{1}{2}$ deg. in all) are illuminated by light of different hue and saturation but about the same luminance and retinal image movements are restricted, a phenomenon called *colour fusion* occurs[13]. If the two halves of the fields are on the long wave-side of 5,900Å, the boundary line disappears and the whole field appears orange (unsaturated). Similarly pairs of colours whose hues are on the short wavelength side fuse to a pale blue. Red and green never fuse and if blue and red are juxtaposed the former appears to "veil" the latter without extinguishing it. These phenomena are best seen with a moderately well stabilized image but McCree[14] has shown that they can be obtained by observers who are trained to fixate very well. Tests have shown that these observers are able to suppress the saccadic movements but not the tremor.

Hue discrimination is restored if the two parts of the field are separated by a black bar.

The remaining discriminations in the above-mentioned experiments are similar to those of a tritanope. It has not, so far, been found possible to produce any condition in which either red–green or blue–yellow discrimination fails while any other kind of hue discrimination remains. This is of interest in relation to opponent-colour theories and to the electrophysiological observations of MacNichol and Svaetchin[15] and of Wagner, MacNichol and Wolbarsht[16]. With a well stabilized image and a wide field, a condition has sometimes been observed in which the subject behaves as a cone-monochromat[12]. This condition is difficult to study because the remaining discrimination (of luminance) is only available from time to time. The experiments so far described indicate that discrimination of hue is specifically dependent on eye-movements. They suggest that the main information for this discrimination is derived from retinal receptors lying near the boundaries (in the retinal image) between areas of different colours. The following results, some of which are previously well known, indicate that this information is time-coded at some stage in the transmission from retina to visual cortex.

(*a*) When an observer views a well stabilized image in light which is flickering at 12 c.p.s., discrimination of luminance is obtained but not discrimination of hue. This result may be compared with those observations which are the basis of heterochromatic comparisons in the flicker photometer.

(*b*) In the above situation normal colour discrimination is obtained when a flicker of 4–6 c.p.s. is used[12].

(*c*) When an observer views a stabilized field in which there is a difference of luminance, but no difference of hue, normal vision may be obtained by imposing a modulation of the luminance. The amplitude of modulation required is lowest for a certain frequency and this frequency is different for red, green and blue[12].

(*d*) In the visual illusion known as Benham's top, a variation of illumination with time produces the subjective observation of colours when the whole field is illuminated with white light or with monochromatic light.

(*e*) The electrophysiological observations of Donner and of Granit[17] show a time variation of the signals which differs according to the hue of the light used as a stimulus.

The relations between these results will be discussed and it will be suggested that, taken together, they indicate time-coding with frequencies in the range 4–8 c.p.s.

References

(1) Ditchburn, R. W. and Ginsborg, B. L. *Nature*, **170**, 36. 1952.
(2) Ditchburn, R. W. *Opt. Acta*, **1**, No. 4, 171-6. 1955.
(3) Ditchburn, R. W. and Pritchard, R. M. *Nature*, **177**, 434. 1956.
(4) Ratliff, F. *J. Exptl. Psych.*, **43**, 163. 1952.
(5) Riggs, L. A., Ratliff, F., Cornsweet, J. C. and Cornsweet, T. N. *J.O.S.A.*, **43**, 495. 1953.
(6) Clowes, M. B. and Ditchburn, R. W. *Opt. Acta*, **3**, 252. 1959.
(7) Lord, M. P. and Wright, W. D. *Prog. Rep. Phys.*, **13**, 1. 1950.
(8) Ditchburn, R. W. and Ginsborg, B. L. *J. Physiol*, **119**, 1-17. 1953.
(9) Fender, D. H. *Thesis* (Reading). 1956.
(10) Riggs, L. A., Armington, J. C. and Ratliff, F. *J.O.S.A.*, **44**, 315. 1954.
(11) Ditchburn, R. W., Fender, D. H. and Mayne, S. *J. Physiol.*, **145**, 98-107. 1959.
(12) Pritchard, R. M. *Thesis* (Reading). 1958.
(13) Clowes, M. B. *Thesis* (Reading). 1959.
(14) McCree, K. J. *Opt. Acta*, **7**, 281. 1960.
(15) MacNichol, E. F. and Svaetching. *Am. J. Ophth.*, **46**, No. 3, pt. 2, p. 26. 1958.
(16) Wagner, H. G., MacNichol, E. F., and Wolbarsht. *Journ. Gen. Physiol.*, **43**, 45. 1960.
(17) Granit, R. *Receptors and Sensory Perception* (Yale University Press), p. 287. 1955.

FUNDAMENTALS OF COLOUR REPRODUCTION

R. G. HORNER

Ilford Limited, Brentwood

JUST a hundred years ago James Clerk Maxwell demonstrated the first colour photograph by making three positive image records through red, green and blue filters and projecting them on to a screen with red, green and blue light. The principle behind this experiment still forms the basis of all commercially practicable processes of colour reproduction. It is unnecessary to try to reproduce exactly the particular spectral distribution of light in a colour, because a wide range of colours can be produced simply by the mixture of three suitably chosen stimuli.

In matching colours the eye appears to analyse them in terms of three responses derived from three sets of retinal receptors each with different spectral sensitivities. These sensitivities overlap over most of the spectrum but have peaks in the red, green and blue respectively. Red, green and blue lights centred on these peaks therefore each stimulate one of these responses preferentially. Mixtures of red, green and blue lights can therefore stimulate the three responses in a wide range of proportions just as do the different spectral distributions of various colours.

Considering additive processes first, it is clear that if the three image records using spectral sensitivities are made equivalent to those of the retinal receptors, then there should be perfect reproduction if each record could be viewed with light which stimulated only one of the three eye responses. This is impossible because the spectral sensitivities overlap so that, however well chosen, the light will stimulate to some extent one or both of the other responses as well, and result in de-saturation of the reproduced colour.

Subtractive processes in which the red, green and blue light in the reproduction is controlled by absorption in these regions by cyan, magenta and yellow dyes, suffer from the same loss in saturation, since the absorption of one dye image record necessarily affects all three of the eye responses. In addition, the proportion in which the other responses are affected is not fixed (as in additive processes) and changes with change in concentration of the dye because of the effective change in width of the absorption band. As a consequence it is necessary to choose the dyes carefully so that they are not dichroic and in particular that proportionate mixtures of the three dyes are not dichroic, and therefore do not change colour either with change of the viewing light or change in concentration. An even worse feature of the dyes used in subtractive processes is that they possess very appreciable absorptions in the parts of the spectrum they are not intended to control.

Some of these deficiencies can be countered by taking other measures whereby losses in one direction can be reduced by accepting some added distortion in another. Thus it is usual to counterbalance the loss in saturation previously mentioned by increasing the contrast of the reproduction and by using narrower spectral sensitivities for producing the records.

The degradations due to the unwanted absorptions of the dyes can be reduced or even eliminated over a certain range of colour by the use of masks. A negative image of one record is superimposed on the positive image of another record in such a way that it removes from that record an absorption equal to that introduced by the unwanted absorption of the first record. Masks can also be used to correct for the stimulation by each record of the wrong eye responses. Theoretically six masks are required to correct for the unwanted dye absorptions and six for the unwanted eye responses but the same six can do for both. In practice the strengths of some of the masks are too small to be worth while and never more than three are required while often one is sufficient. The masks may be produced as separate layers but are often incorporated in colour film in such a way that their action is automatic.

The duplicating and copying of colour reproductions introduces yet further errors. The second process includes all the sources of degradation present in the first process, but additional masks may be needed to correct for the enhanced contrast usually encountered and for the double loss of highlight contrast. On the other hand there is the possibility of further correcting for the dyes of the original as well as for the copy.

Colour television is essentially an additive process. Because the image information is translated into electrical signals, correction by masking is relatively easy to achieve by means of electronic matrixing. A special feature is that it is not necessary to transmit three full definition pictures. This is found to be wasteful of bandwidth because it provides more information than is required. The acuity of the eye to colour differences in the absence of luminance differences is less than to luminance differences alone. If the three signals are coded so that one carries the full luminance signal and the other two carry colour difference signals defining the colour only, the latter two can be of much reduced definition without the eye seeing any difference in the result.

It is interesting to speculate if advantage can be taken of this phenomenon to simplify colour photographic processes. Because the yellow image contributes so little to the luminance information it can, as is well known, have much less definition than the other two layers. But while a mixture of three dyestuffs is still needed to produce the full range of colours, three dye images will be needed and they may as well carry the luminance information as well. It would only complicate matters to provide a fourth image for this alone. It will be noted that even in colour television full luminance definition is restored to each of the three colour images presented to the eye.

The recent demonstration by Land of multicolour images produced merely by the mixture of red and white light (or almost any two differently coloured lights) raises the question of whether all this attention to detail and exact reproduction is really necessary. There is no doubt that the eye can be persuaded to see colours quite differently when related in certain ways to one another than when seen in quite unrelated situations. It seems that the eye appreciates directions of difference between colours rather than absolute colour. Nevertheless the need to reproduce any kind of subject in any form in which it is met and the need for covering diverse conditions of viewing make three colour reproduction a continuing necessity. The eye is very accommodating in many ways. It tries its best to see things as the brain thinks they should be seen. Provided certain relationships are reasonably satisfied it will accept the result as pleasing, even if the absolute reproduction is far from accurate. This at least is known to be true or there would not be any colour processes on the market today.

COLOUR REPRODUCTION TECHNIQUES IN COMPATIBLE COLOUR TELEVISION

J. W. WENTWORTH

Radio Corporation of America, Camden, New Jersey, U.S.A.

As a practical example of a three-primary-colour additive process, compatible colour television is solidly based on the principles of tri-stimulus colorimetry set forth a century ago by James Clerk Maxwell. This paper summarizes some of the technical highlights of compatible colour television, with particular emphasis on those techniques of greatest interest to practitioners of colorimetry and the related arts and sciences.

The additive primaries adopted as standards in the United States for colour television purposes consists of highly-saturated red, green, and blue colours that can be obtained readily in the form of light-emitting phosphors for use in colour kinescopes. They provide a gamut which compares very favourably with all other practical colour-reproducing processes. The most popular type of colour kinescope employs three separate electron guns for separate control of the red, green, and blue images, which are produced in the form of intermingled dots too small to be resolved separately at normal viewing distances.

Colour television cameras usually employ three separate pickup tubes with a light-splitting registered optical system to generate the three signals required to control the three primary-colour images at the receiver. The ideal spectral-sensitivity curves for the camera tubes correspond to the colour-mixture curves for the receiver primaries. By appropriate combinations of optical filters and electronic cross-mixing circuits in colour television cameras, it is possible to achieve an almost perfect match to the idealized spectral-sensitivity curves, including the regions where *negative* response is theoretically required. As a practical matter, however, most cameras are designed to generate red, green, and blue signals directly through pickup tubes with spectral sensitivity curves adjusted to match only the positive lobes of the idealized curves.

As in colour photography, provision must be made in colour television systems for handling the "colour balance" problem resulting from the fact that cameras may be operated under a great variety of illumination conditions, ranging from the yellowish light of incandescent studio lamps to the strongly bluish light of the open shade out-of-doors. If these illumination differences were reproduced faithfully, the viewer would be acutely conscious of seemingly "unnatural" colour shifts. Fortunately, this colour balance problem is easily solved in colour television systems by simply adjusting the gain controls in the red, green and blue channels of the camera equipment in such a way that the signals produced by a non-selective reflecting surface (such as a black-and-white test pattern) always produce the same quality of *reference white* at the receiver. The particular reference white normally recommended as an operating standard has chromaticity coordinates matching those of CIE Standard Illuminant C. The use of such a constant reference white at the receiver may cause all colours to be shifted in *absolute* chromaticity but does not seriously distort their *relative* relationships.

A *gamma correction* technique is required in colour television to permit the system to operate with the linearity required for faithful colour reproduction. Colour kinescopes are nonlinear devices in that the luminance of each primary-colour image varies in proportion to the 2·2 power of the corresponding signal voltage. To compensate for this non-linearity at the viewing device, it is standard practice to pre-distort the signals at the transmitting end of the system to give them a complementary transfer characteristic.

Compatible colour television differs from the several other possible systems of colour television primarily in the choice of electronic techniques employed to "squeeze" red, green, and blue signals through a single transmission channel without losing their identity. The four techniques known as *matrixing*, *band-shaping*, *two-phase modulation*, and *frequency interlace* yield a colour television system which is compatible with older monochrome systems to the degree that colour signals produce excellent pictures on monochrome receivers and colour receivers can be used for monochrome as well as colour telecasts. While primarily electronic in nature, each of these techniques has features of colorimetric significance.

Matrixing, as employed in compatible colour television, is equivalent to the transformation of colorimetric data from one set of primary coordinates to another. Physically, the process involves passing the red, green, and blue camera signals through a circuit which cross-mixes them to form three different signals, usually designated M, I, and Q. The M, I, and Q signals are representative of the amounts of three new primaries needed to match the colours being transmitted, and the chromaticity coordinates of these primaries can actually be plotted on a chromaticity diagram. The M primary is found to have the same chromaticity coordinates as CIE Illuminant C, and the M signal is, for all practical purposes, equivalent to a conventional monochrome (or luminance) signal, capable of producing excellent images on monochrome receivers. Both the I and Q primaries fall on the zero-luminance line, and the term "chrominance" has been coined to designate the type of information they convey. The I and Q signals show how the colours being transmitted differ from the "white" or neutral condition along two different axes passing through the reference white point.

Band-shaping refers to the process of adjusting the bandwidths of the M, I, and Q signals in proportion to the resolving power of the human eye for the different types of information conveyed by the signals. The I and Q signals are reduced in bandwidth to values of approximately 40 per cent and 12 per cent, respectively, of the bandwidth allotted to the M signal. These bandwidth savings are of major importance in the "squeezing" process needed to fit chrominance information into the same transmission channel previously occupied exclusively by luminance information. Compatible colour images lack colour resolution in the finer details, but at normal viewing distances they are indistinguishable from full-resolution colour images.

In the *two-phase modulation* process, the I and Q signals are modulated on two carriers of the same frequency but with a 90-degree phase separation, forming a single two-variable signal. The technique is used primarily as a highly efficient means of transmitting the two signals in a minimum of spectrum space, but it turns out to be colorimetrically significant in that the *phase* of the two-phase-modulated wave is representative of the *hue* of the colours being transmitted and the *amplitude* of the same wave (relative to the amplitude of the signal existing simultaneously in the M channel) is representative of *saturation*. These properties of the two-phase modulated wave make it possible to employ very convenient *hue* and *saturation* controls in colour television receivers.

The *frequency interlace* is essentially a means for combining the two-phase-modulated chrominance signal with the unmodulated luminance (or M) signal in such a way that there is no objectionable interference between the two, even though they are forced to share the same transmission channel. From a psycho-physical point of view, it can be shown that the frequency interlace technique is actually a practical means for exploiting the persistence-of-vision effect in small image areas.

In summary, compatible colour television provides a number of excellent examples of effective utilization of the information about colour vision and colour reproduction discovered through research stimulated by the pioneering efforts of Maxwell.

THE PRODUCTION OF COLOUR PHOTOGRAPHIC PRINTS ON PAPER

R. W. G. HUNT

Kodak Limited, Harrow

THE colour transparency, both as a motion picture film and as a single frame or sheet, has been an established medium of colour reproduction for about twenty-five years; and in some fields, for example amateur kine-photography, it has almost entirely replaced black and white. But it is only recently that colour photographic prints on paper have begun to make similar headway, and it is the purpose of this paper to review some of the difficulties which have obstructed progress in this field.

In the first place, all reflexion print processes, whether black and white or colour, suffer from the restriction that the range of tones is limited by the whitest white and the blackest black which can be obtained on the paper being used. Thus the luminosity of the white in a print cannot be appreciably greater than that of other white surfaces in the field of view; but when a transparency is projected in a dark room, or viewed on an illuminator of high luminosity, its lightest areas can appear considerably more luminous than white surfaces, and hence the sparkle of sunlight shining on the sea, for instance, can be reproduced much more faithfully on a transparency than on a print. At the other end of the scale, the blackest black obtainable on a print depends not only on the absorption of light by the image, but also on the nature of the surface and the type of illumination, and usually the reflectance of blacks is controlled by the latter factors more than by the former; thus, unless the surface has a very high gloss and is viewed in specular illumination, its maximum density will generally not exceed 2·0, and may be much lower, whereas on transparencies it can be considerably higher than 2·0.

This more limited range of luminosities which can be exhibited by prints leads, in black and white photography, to the contrast level of the paper being chosen so as to accommodate the tone range of the original. With colour prints, however, if the contrast level is lowered to accommodate the tones, the colour saturation is also decreased and this is particularly undesirable because the inherent losses of colour saturation, which occur in all processes, are not offset by favourable viewing conditions, as tends to be the case for transparencies. These difficulties are present at their maximum when it is required to make colour prints from transparencies; but when the print is made from a colour negative the latter can be designed specially for the purpose, and special devices can be used to improve print quality: thus coloured couplers can be used to counteract the effects of the unwanted absorptions of the dyes in the negative, and hence excessive darkening of blues and greens can be avoided.

A further difficulty encountered in making colour prints on paper is that other objects in the field of view provide not only a reference brightness but also reference colours against which the print can be judged. The tolerances for the colour balance of prints are therefore considerably smaller than for transparencies.

The factors which can affect the colour balance of a photographic colour print include the following: the colour of the light illuminating the original scene, the colour composition of the original scene, the transmission colour of the camera lens, the relative sensitivities of the three layers of the film, the processing of the film, the colour of the light illuminating the negative or transparency in the printer, the transmission colour of the printer lens, the relative exposures given to the three layers of the paper, the relative sensitivities of the three layers of the paper, the processing of the paper, the colour of the light illuminating the print, and the colour composition of the field of view surrounding the print. The formidable nature of the above list stems in the main from the variabilities in the colour of illuminants together with the ensuing adaptation levels, and from the variabilities inherent in the manufacture and processing of colour photographic materials. Although progress is being made in reducing the latter type of variability, the former type is bound to remain.

Until recently the majority of prints were made entirely by trial and error methods, small test strips being printed through filters of various colours until a subjectively correct-looking result was obtained. This method was very time-consuming and therefore expensive, and the increasing popularity of colour prints today is due in no small measure to the increased use of photoelectric methods of controlling colour balance at the printing stage. This can take one of two forms. Either the red, green and blue transmissions of a small part of a negative of known subject matter, for example a face, or a neutral grey can be measured and then the print material exposed so as to give the required colour for that area; or the light from all or most of the negative can be integrated and the resulting red, green and blue contents used to regulate the exposure of the three layers of the paper so as to give prints the light reflected from which, if integrated, would appear approximately grey. The first method is applicable mainly to the production of high quality enlargements and the second, or "integrating to grey" method, to the mass production of colour prints.

The "integrating to grey" method is often criticized as leading to distortion of colour rendering if the average subject matter is not of neutral colour balance. This is perfectly true, and a white cat on a saturated red carpet, for instance, will exhibit "colour failure" by printing as a cyan cat on a pale red carpet. It is found in practice, however, that the method works very well for a remarkably high percentage of the colour negatives actually produced, and it is the adoption of this method that has largely contributed to the recent growth in colour print production for the public.

The incidence of colour failure can be to some extent reduced by making the exposure of the three layers of the print material vary somewhat less than that required for true "integration to grey"; if this is done, however, compensation for variations in illuminant colour will be incomplete and it may be necessary to discriminate between negatives exposed, for example, by daylight and by flash-light.

The first printers used for large scale automatic colour printing were of the additive successive type in which exposure with red, green and blue light were given successively; subsequently, additive simultaneous printers have been devised, and also subtractive printers in which the exposure of the three layers of the paper is terminated by the introduction of cyan, magenta, and yellow filters after time intervals which result in the desired colour balance. A simple enlarger has also been devised in which the paper is given a single exposure to coloured light, the required colour being obtained by the adjustment of subtractive filters in a light-scrambling device, monitoring being carried out by means of filtered barrier layer cells.

PROGRESS IN COLOUR PRINTING

D. C. GRESHAM

McCorquodale Limited, London

WHEREAS most of the practical systems of colour photography which have been developed have made use of three colours and have closely followed the Clerk Maxwell model, most colour printing has been done with a four-colour system in which a black printing has been added to the three-colour printings.

In the early days of half-tone colour block-making, it was thought that the fourth printing could be dispensed with as soon as a few minor technical problems had been overcome. However, the black printer is still with us today and, indeed, is in some ways more important than ever. It is used almost universally in colour letterpress printing, in nearly all commercial colour photo-litho printing and in the majority of colour photogravure printing.

Some of the original reasons for introducing a black printing have to some extent disappeared. For instance, it is now possible to use inks which are more concentrated than those available in the early days and so to obtain a stronger print in three printings. Other factors involving the printing machinery and, particularly in the case of photo-litho, the printing plates make it possible to obtain a thicker ink film than was possible earlier. In photogravure it is quite possible to obtain excellent results in three colours and a great deal of high quality work is produced in this way, notably on the Continent of Europe.

However, in other respects the black printer has become more important than ever as effort has been directed towards ever higher printing speeds to cope with the demand for large quantities of colour printing of good quality at a reasonable price. The solution to the problem of bulk printing at high speeds obviously lies in the use of multicolour presses in which the successive printings are laid on the paper in a very short space of time. The problem of drying the ink between printings then becomes acute so that it is necessary to lay ink films on top of only partially set layers which may have been laid down only a few seconds earlier. This leads to what are known as "trapping" problems and at the present time in high-speed letterpress or photolitho printing on multicolour presses it is not possible satisfactorily to lay down a solid area of three coloured inks in the same place. This means that a black area cannot be produced by printing the three colours, and blacks and darker tones of the picture have to be reproduced by reducing the printing area of the plates in the three colours and making up with the black printing.

Quite drastic undercolour removal is required for high-speed letterpress printing, less is required for high-speed photo-litho and still less for photogravure. However, it is sometimes desirable to employ as much undercolour removal as practicable for economy reasons since it is cheaper to obtain a black with one layer of black ink than with three layers of colour ink.

There are other good reasons for using a black printing even when single-colour presses are used. These include the sharpening of fine detail and giving more latitude in colour balance which allows more tolerance in the printing of the colours.

The printer must have the black printer for the various reasons outlined above but it is this requirement which complicates the problems of the engraver and platemaker more than any other—particularly where drastic under-colour removal is required.

The engraver has to use much the same methods of colour separation as the colour photographer and therefore has most of the same problems to face—some of them in a more acute form. In particular, commercially available printing inks are generally less satisfactory in spectral reflectance and absorption characteristics than some of the equivalent dyes used in colour photography. This means that some form of colour correction for unwanted spectral absorptions of the inks must be introduced into the printing plates. In recent years more and more of this correction has been achieved by photographic "masking" techniques but usually a certain amount of handwork in the form of retouching or fine etching is still required to produce reproductions of commercially acceptable standard.

It is still difficult to make a satisfactory black printer by purely photographic means. Undercolour removal in the separation negatives is easy to achieve by masking but simultaneous masking for undercolour removal and colour correction is often difficult to achieve in correct proportions.

Theoretically, these problems are more easily overcome by electronic colour separation. Electronic scanners are already performing well in production. No doubt these machines are still capable of further improvement and it seems likely that we are on the threshold of automation of a large part of colour plate production.

Electronics are contributing in several other ways to the improvement of colour printing. Electronic register controls are now fitted to the majority of web-fed multi-colour printing presses and there is now equipment available for insetting pre-printed colour webs into newspapers on the news press. There is an automatic electronic control device for keeping each colour at correct printing strength on high-speed photogravure presses. A similar device is under development for offset and letterpress machines.

It has been possible to hold the price of colour printing at a reasonable level only by the use of faster and faster printing machines printing in larger and larger sizes. This has posed problems for the machine designer, paper maker, ink maker, plate maker and the printer. Nevertheless, it is fair to say the average quality of commercial colour printing has steadily improved and is still improving.

THE PHYSICAL BASIS OF COLOUR MATCHING WITH PIGMENTED SYSTEMS

D. R. DUNCAN

Paint Research Station, Teddington

A PIGMENTED system may be defined as one consisting of undissolved particles of a powder (the pigment) dispersed in another material (the medium) to confer on it the desired colour and in some cases to modify other properties such as opacity and durability. Typical pigmented systems include paints, distempers, pigmented lacquers, printing inks, linoleum and pigmented plastics, rubber, paper, concrete, putty, etc. They differ from clear solutions of coloured substances in that they scatter light as well as absorbing it. On this account, the colours of products containing mixtures of pigments do not follow the simple laws of subtractive mixture (resulting from the additivity of optical densities) which apply to clear solutions.

The optical properties of a pigmented system can be expressed in terms of two constants, the coefficient of absorption (α, sometimes designated k) and the coefficient of scatter (δ, sometimes designated S), the values of which usually vary with wavelength. In a well mixed sample, the values of these constants are a simple additive function of the values of the component pigments weighted in accordance with the proportions in which they are present. These constants must be determined in the medium in which the pigments are to be used (or in another medium of the same refractive index).

It is to be expected theoretically, and has been amply confirmed by experiment, that the reflectance of a pigmented composition at any particular wavelength is related to these constants by the expression

$$\theta = \frac{(a\alpha_A + b\alpha_B + c\alpha_C + \cdots)}{(a\delta_A + b\delta_B + c\delta_C + \cdots)}$$

where $\theta = (1 - R)^2/2R$, R being the reflectance (corrected, in cases where there is a continuous medium, for internal and external reflexion occurring at the air/medium interface) of a pigmented composition containing a parts of a pigment A, having a coefficient of absorption α_A and coefficient of scatter δ_A, the other symbols relating similarly to the other pigments present.

Having obtained δ and α values for a series of pigments, it is possible by means of this expression to calculate the reflectance values at different wavelengths, and hence the C.I.E. colour under any specified illuminant, for a product pigmented with any mixture of these pigments. Having calculated the colours of a wide range of pigment mixtures, it is possible to construct diagrams from which one can select at a glance a set of pigments or a number of alternative sets to produce any desired colour (it is never necessary to use more than four pigments in any one mixture) or alternatively to state definitely that the colour cannot be produced with any mixture of the available pigments, and, where required, by further graphs or calculations, to estimate the proportions in which the pigments must be mixed to produce the required colour.

The data obtained in this way also provide physical explanations of many empirically known facts about the colour-mixing properties of individual pigments (e.g., the mechanism by which certain yellow pigments, when mixed with black pigments, give bright greens), and lead to certain generalizations about colour-mixing properties which had apparently not been revealed by earlier purely empirical work.

As a method of reproducing colours, this approach has the disadvantage that many of the matches obtained may be metameric. This may be avoided by the use of alternative methods of calculation which lead to the production of a matching material having, as nearly as possible, the same reflectance curve as the original material. It is necessary to select pigments capable of giving a reflectance curve of the right form and to determine the proportions in which they must be mixed. A paper describing methods of doing this was presented by the speaker at a recent joint meeting of the Society for Analytical Chemistry and the Oil and Colour Chemists' Association and will appear in the Journal of the latter.

The general equation, applicable whatever pigments are present, to secure a given reflectance at any particular wavelength, is

$$at_A + bt_B + ct_C + \cdot \cdot \cdot = \theta,$$

where $t = \alpha - \theta\delta$. A series of simultaneous equations of this type may be solved to find the proportions of the different pigments required to secure the required reflectances at a number of wavelengths.

In favourable cases, simpler methods are available. One such method, which is applicable to materials pigmented with a white pigment tinted with small proportions of coloured pigments, makes use of the approximate formula

$$\theta = (a\alpha_A + b\alpha_B + \cdot \cdot \cdot) / \delta_W,$$

where δ_W is the coefficient of scatter of the white pigment.

An expression of this type, where δ_W is now the coefficient of scatter of the textile fibres, has been found to be applicable to textiles dyed with a mixture of dyestuffs.

LIMITATIONS OF THE PRINTING PROCESS

W. L. RHODES

Rochester Institute of Technology, Rochester, U.S.A.

At some time each of us has had occasion to be concerned with the limitations of the printing process. It is not unusual to find authors disclaiming responsibility for the appearance of reproductions of subjects or scenes in textbooks and in scientific journals by explaining that the incorrect appearance of the photographs or paintings is due to the limitations of the printing process.

Printing processes are much more limited than one ordinarily thinks. If it is assumed that the reproduction is to be a substitute for the original scene or object, then one can see just how limited printing really is. In the first place, the viewer of the reproduction is not exposed to all the stimuli of the original scene or object such as sound, smell, temperature, taste, etc. In this respect printing is limited indeed.

The printer, then, must rely entirely upon visual stimuli to represent the scene or object, except in a few extraordinary cases. The reproduction cannot even duplicate the visual stimuli of the original. The most serious limitation is that the reproduction is two dimensional and the scene is three dimensional. Other visual attributes such as gloss and texture probably could be achieved by printing but no economic way has yet been found.

Thus the problem is reduced to simple reproduction of the shapes and chromaticities of scenes or objects. If, in fact, the printer's problem were this simple, his lot would be a happier one.

The range of luminances in the scene is usually much greater than the range which the printer can produce with ink and paper. Finally, there may be colours in the scene which are more saturated than the colours available to the printer. The situation is further complicated because a reproduction which is a colorimetric match of the scene is unsatisfactory except in unusual cases. That we see around us so many beautiful and moving reproductions is a credit to our human capacity for developing complex responses from limited information, and a credit to the graphic arts technicians who can produce these beautiful reproductions in spite of the severe limitations imposed by the printing processes.

Fortunately the printer does not usually have to work directly with scenes or objects. He is usually concerned with the problems of reproducing originals such as photographs and paintings. This, of course, makes his task much simpler, because the original is already two dimensional, and only its visual characteristics are important. Photographic transparencies, however, pose some of the difficulties for the printer that scenes do. Both the lightness range and saturation of transparencies exceed that of the printing process; and like scenes, a reproduction which is a colorimetric match for the transparency is not acceptable.

The problem seems to defy simplification because even the simplest cases are complex. For example, the objective in reproducing photographic prints and paintings would seem to be simple. Surely here a colorimetric match is the most desirable reproduction. This is true, however, only if the original and reproduction are the same size, and are reproduced with the same gloss and sharpness. If the reproduction is larger or smaller, or if it has a different gloss or sharpness, then reproduction which looks like the original is not a colorimetric match.

Even when one considers the simplest possible case, the problems are not simple. When the reproduction is the same size, sharpness and gloss as the original then the best reproduction is a colorimetric match. The limitations of the printing processes now fall into sharp focus. Many of the saturated colours in photographs and paintings cannot be matched by the printer's colorant mixtures, and many of the whites and blacks in originals exceed the lightness range available to the printer.

Printers usually use only three colorants to produce all the colours in a reproduction. To evaluate these colorants and to compare colorant sets, the locus of maximum purity of colours obtainable with the set are plotted on the C.I.E. diagram. The maximum purity of the cyan-blue range of colour produced by commercially available sets have very low luminance. Since correlation between saturation and purity at low luminance is especially poor, it is preferable to evaluate colorant sets by using colour order systems which more closely approximate appearance. For this reason, the Munsell system is more useful than C.I.E. in evaluating ink sets.

It might be possible to compare ink colorant sets by plotting the locus of their maximum chroma limits on chroma-hue charts and determining the area enclosed. The set with the greatest area would be considered best. This method has two disadvantages. First, it provides no information about the ability of the sets to reproduce light or dark saturated colours; and, second, it does not take into account that some colours may be more important than others.

In photography light colours are produced by varying the concentration or thickness of the colorant. In most printing, light colours are produced by varying the proportionate area covered by ink. Dots are printed close together (e.g. 22,500 per square inch) in a regular pattern. The number of dots in any given area does not vary, but the size of each dot may vary from zero to the point where no white paper remains. Light colours produced by these variable area processes are not as saturated as light colours produced by variable concentration or variable thickness systems. For this reason it is desirable to know something about the relationship between maximum saturation and lightness of colorant sets. This can be accomplished by plotting chroma-value graphs as well as chroma-hue charts. Thus, it is the volume of the colour solid representing the limits of a printing process rather than the area of its maximum saturation locus which is important in evaluation.

The volume alone is still not sufficient to assess the limits. Some parts of the solid are apparently more important than others. Many printers have four- and five-colour presses. One of the reasons for this is that printing is much easier if black ink is used in reproducing neutrals, and the use of black may extend the luminance range if the combination of the three colorants does not produce a black which is dark enough. The fifth printing unit is generally used to print a special colour. This special colour is frequently light blue or pink. That the printer would incur this extra expense is an indication that these light saturated colours are very important. To overcome this limitation some inventors have developed four- and five-colour reproduction systems.

Many authors have evaluated ink colorant sets using insufficient criteria. It has been common to rely upon the area enclosed by the locus of maximum purity colours on the C.I.E. diagram. Other workers evaluate systems on the basis of the amount of manipulation needed to make accurate reproductions of the colorants themselves.

Three changes need to be made to improve the evaluation of colorant sets and printing processes.

1. The evaluation needs to be made on the basis of the appearance.
2. Evaluation needs to be made on the basis of the volume of the colour solid rather than the area of maximum saturation.
3. Studies need to be made to determine the relative importance of various locations in the colour solid.

Doing this will not alter the limitations of the printing process, but it will enable workers to affect the best compromises and not work in a system which is more limited than it needs to be.

SCANNING METHODS IN PRINTING

V. C. HALL

Time Inc., Springdale, U.S.A.

SCANNING methods (electronic colour correction) represent one of the newest developments in graphic arts colour printing, and have had a varied history since their rather recent introduction into the printing industry. Scanning had definitely come of age, however, and most printers who have used scanning over the past years would not want to do without it, even though the number of colour prints seen which have come from scanned copy is less than 10 per cent of the total.

Colour scanners were invented in the mid 1930's and after 1945 the Kodak inventions were taken over by Time Incorporated, and the Interchemical scanner was taken over by Radio Corporation of America. Major scanners are listed in the table.

Table

	PDI	*Fairchild*	*Crosfield Scanatron*	*Hell Vario-Klischograph*	*Hell Colorgraph*	*Belin*	*HPK Autoscan*	*RCA*
Originals:								
Opaque Colour				X		X	X	
Transparencies	X	X			(4)		(3)	
Separations			X		X			X
Product:								
Continuous tone								
Negatives	X	X			X	X	X	X
Positives	(1)	X	X		X	X		X
Plates				X				
Size Change:								
On Scanner	(2)			X		X	X	
In Camera	X	X	X		X			X

(1) Now being added to scanners in field.
(2) Fixed enlargement of 6X from 35mm transparencies.
(3) Announced but not yet available.
(4) Recently made available.

Of the eight machines the RCA has been discontinued. The PDI scanner, the extension of the Kodak-Time Life development is operated in scanner studios, turning out separation negatives as a service. The other scanners are sold or leased to individual printers, or to organized groups for operation by their own trained personnel.

Scanner computers, for colour correcting between the scanning and the exposing or engraving mechanism, are all of the analog type, so far as is known all (except RCA) based on solving the masking equations, with modifications as required. All have been developed over considerable time and produce either 3-colour or 4-colour separations. Black printer exposures are computed as a function of the minimum of the 3-colour inks and masking circuits reduce the amounts of the 3-colour inks in an amount depending upon end result as to kind of printing.

Scanners which make separations the same size as the colour transparency original are limited as to the amount of subsequent enlargement which can be made from the continuous tone negatives, but it is possible to enlarge five diameters from transparencies which have been scanned at a pitch of 1,000 lines per inch, and experience has shown that most colour transparencies are not enlarged more than this value. PDI has recently introduced a means of making 6 diameter enlargements directly on the scanner and the definition then compares favourably with the best of camera work with conventional masking techniques. (Comparison samples will be distributed.) The sharpness of edges, or acutance, is extremely important, and the addition of unsharp masking has gone far to remove any criticism of the definition of printed results from scanned negatives. The amount of unsharpness is controlled so that there is no outlining in the final print, while still obtaining the maximum edge sharpness through the screening process.

It is necessary to compress the tone scale in any graphic arts reproduction process, and a smooth shouldering off of the tone scale in shadows, keeping the contrast in highlight and midtone areas near to that of the original has been found extremely successful.

With subjects of generally low key, however, the necessary shadow compression leads to an appearance of flatness, not peculiar to the scanner, and one of the major jobs of the retoucher is to increase the contrast in important shadow areas. On the PDI scanner a form of masking has been introduced which has the effect of increasing the detail in areas where edges occur, and the net effect of this opening up the shadows is sometimes very striking. (Exhibits showing this type of masking will be shown.)

Printers making use of scanning methods report that they are able to obtain a more faithful, natural rendition of the original copy, and can deliver colour plates on faster production schedules, frequently at some saving in cost. The future of scanning in the printing industry looks very bright, and the use of electronic colour correction methods in the next few years should rapidly increase.

FACTORS AFFECTING COLOUR APPEARANCE

W. D. WRIGHT
Imperial College, London

(*A*) ON the first day of the Maxwell Colour Centenary we shall be considering the principles of colour reproduction based on the equivalent trichromatic mixture of red, green and blue stimuli that matches each colour being reproduced. On the second day the application of this equivalence in terms of the mixture of dyes, pigments, printing inks and coloured phosphors is to be discussed. The practical success of three-colour photography, three-colour printing and three-colour television is evidence that the colour appearance of a scene can be effectively reproduced by the appropriate control of three stimuli. The quality of the stimulus defined in terms of its trichromatic specification is therefore one of the key factors determining colour appearance. It must be noted, however, that a trichromatic specification is only a meaningful way to describe a stimulus when the viewing conditions are such that Grassmann's laws of colour mixture apply. For example, if the level of illumination came within the Purkinje range between photopic and scotopic vision, these laws would not hold, while if small areas of colour are being considered, colour equivalence can be expressed in terms of a dichromatic instead of a trichromatic mixture. Therefore, the first of the factors affecting colour appearance is listed in purely physical terms as

1. Spectral composition of the Stimulus

This will embrace the general case, where one would normally simplify the stimulus description by giving it its C.I.E. specification, as well as the special cases mentioned above. In an illuminated scene the spectral composition is, of course, a function of both the spectral energy distribution of the illuminant and the spectral reflexion characteristics of the object being illuminated.

(*B*) It is well known that the response of the retina to light is not uniquely determined by the quality of the stimulus. Thus a patch of colour will have a different appearance if it is seen by peripheral vision than by foveal vision; its appearance will also be affected by the extent to which the sensitivity of the retina has been conditioned by previous light or colour adaptation or by stimulation of neighbouring retinal areas; there may also be significant differences in colour appearance between one observer and another on account of variations in ocular pigmentation or in the actual retinal processes responsible for discrimination. These factors may therefore be summarized as the second item in our list under the heading

2. The Light and Colour Sensitivity of the Retina

(*C*) Regarded as a neural structure, the retina can be considered to be an expansion of the brain, but from the visual point of view there is a major difference between the process responsible for the initial light reaction in the retinal receptors and the subsequent transmission of nerve impulses along the optic nerve to the brain and visual cortex. Regarding this as a separate stage in the process of visual perception is therefore justified. The pattern of neural information reaching the cortex is likely to be affected by summation and inhibition, by physiological spreading, by sensory "feedback" and by complex coding processes (whatever they may be) through which the brain is able to interpret the messages received from the peripheral sense organs. This group of factors may again be classified under the heading

3. Neural Transmission and Coding

(*D*) In the visual cortex itself, means must exist by which the subjective qualities of redness, greenness, etc. are generated to accord with the messages delivered along the visual paths. It may well be that quite specific types of activity in the cortex are associated with the primary colour sensations and that if they were inoperative then colour recognition would be impossible. Nevertheless, over and above any activities of this type, of which we are at the moment completely ignorant, the mental processes of interpretation and perception must act as the final arbiters of what we see. Here we may quote from Ragnar Granit's "Receptors and Sensory Perception":

"The apparent plasticity of the psychophysical interpretation is an adaptation to the organism's needs. The psychological datum which we try to trap in psychophysical experiments is an organized response to a large number of cues. If experience proves them unreliable a new and better system of interpretation is elaborated. The brain chooses and rejects, connects and disconnects. It is possible, even without elaborate experiments, to see something of these processes of purposeful integration in the many well-known visual and tactual illusions".

This final group of factors may be collected under the heading

4. Perceptual Interpretation

Under this heading should be included, for example, the ability of the observer to assess the nature of the illumination of a scene and to allow for its colour and distribution in judging the true colour of an object in the scene. One of the most remarkable properties of the visual process is the constancy in appearance of a scene or a colour reproduction of it, provided the objects in the scene retain to a reasonable approximation their correct relations to each other so far as their lightness and colour are concerned.

In our discussion on colour appearance, perhaps the most important thing will be to see the process as a whole. In the past there has been a tendency for one specialist to criticise another because he has treated his particular speciality in isolation. Whether or not the criticism is justified, detailed analysis of the individual effects occurring at each of the four stages is necessary but it should not be conducted at the expense of a proper integration with the other equally, or possibly more, important factors that are involved.

COLOUR AS LIGHT AND COLOUR AS DARKNESS

M. H. WILSON

Goethean Science Foundation, Stourbridge

RECENT investigations into the possibilities of two-colour projection have thrown into sharp relief the difference between the establishment of colorimetric values and the perception of colour-relationships in a meaningful context. In the latter, one of the essential factors is the discrimination between that element of a coloured appearance that is attributed to the illuminant, and that element that is attributed to the colorant, most probably a coloured object. This discrimination may take the form of assessing the various colours of objects in relation to a uniformly coloured illuminant, or more rarely, assessing the variation of the illumination in relation to a uniformly coloured or patterned surface, such as a printed textile. In a general sense this can be described as the discrimination between colour that belongs to the light and colour that belongs to the darkness. (Any influence that darkens the light is here called darkness for want of a better word.)

Effects of simultaneous contrast with projected lights are partly dependent on the presence of light-dark relationships such that a mode of viewing similar to Object Mode can be evoked. Instances of this will be demonstrated, including conditions where the effect breaks down. This distinction between colour as light and colour as darkness is seen to be essential to our normal visual perception. Concepts of this kind are already in use by other workers in this field.

Our processes of three-colour reproduction are based on just this distinction. In photography, one records three kinds of coloured light in the darkness of the camera, and represent the result in terms of three kinds of coloured darkness (ink, dye) upon the lightness of the paper or film. Here it would be very inconvenient to have to do without the concept of Density, which implies essentially a darkening of the light.

The painter and the dyer have established their right over thousands of years to identify colour with their coloured materials. The yellowness which the artist's pigment exhibits is much more real to him than the blueness which the physicist tells him it absorbs. It is doubtful whether the physicist is really justified in attributing reality of colour to the light and not to the colorant. This difference of outlook and therefore of language has probably been responsible for more confusion in the teaching of colour than any other single factor. The suggestion is now made that this situation would be partly remedied by the use of such terms as the Mixing of Coloured Lights for additive mixture, and the Mixing of Coloured Darknesses for subtractive mixture.

In colour systems that refer to surface colours or filter colours the parameter of darkness is necessarily implied, and in some cases explicitly named (Ostwald's Black Content, and the recent DIN Dunkelstufen).

Much of our habit of attributing colour to the light only can be derived from Newton's assertion that the colours are already contained in the white light. But had he followed up his own "centre of gravity" method for calculating colour mixtures, and had he always been clear about the distinction between what we now call Luminance and Chromaticity, we might never have been asked to believe that all the colours are present in the white light whereas what we actually see is that they are all absent. The whole implication of Maxwell's Triangle and our present system that is built upon it, including the application to television is that whereas Luminance is additive, Chromaticity is not. When for instance yellow and blue lights are mixed, the luminances add up but the chromaticities do not. They become neutral. The colourednesses cancel out. In subtractive mixture it is the darknesses, the densities that are additive while the colourednesses may also cancel out in certain circumstances.

If the luminances of spectral colours were also commonly related to that of the total white, it would at once be evident how very dark all spectral colours become as their purity increases, and in this respect some of the popular misconceptions (as, for example, what kind of colour can be described as a "spectrum colour") might be avoided. Practical standards of colouredness would be readily provided by the Edge Spectra and their simple combinations in which the standard of whiteness is naturally preserved.

Finally, although colouredness may appear as an attribute of light or an attribute of darkness, it is not ultimately identifiable with either. It is a quality in itself, and the fact that we measure it by means of a system not unlike a triangle of forces should give one the clue to the dynamic nature of colour as a system of forces in its own right. It is suggested that the classical concepts of the nature of colour might well be replaced by concepts more in keeping with the practice of modern colour technology and that this could give us a language that is more comprehensible to everyone interested in colour, and a colour science that would be of help to the user of colour in every field, including the human sciences and the creative arts.

SOME COLORIMETRIC FACTORS IN COLOUR CHOICE

W. C. GRANVILLE

Granville Color Service, Libertyville, U.S.A.

THERE are two intents in colour choice which apply to our everyday living. These intents are to enhance objects and scenes so as to make them more beautiful and to provide a sensible impact simply to please. This paper will discuss some aspects of the design of colour systems for colour choice and will emphasize the need for accessibility of some colours in a more useful environment.

Those who practice colour choice use colour not as some abstract entity but in terms of people and how it affects them. In such uses, one is involved not only with intervals of visual colour difference illustrated by the basic co-ordinate scales in appearance colour systems but also with the emotional impact which certain colour regions carry. This attitude seems to require distinction between visual and sensible colour differences. Perhaps the best illustration of this conflict is the relation of the grey scale to the remainder of the colours in the colour world. It has been customary to assume that greys are terminal members of saturation series. There is no argument with the validity or usefulness of this concept for describing and specifying colour differences and for locating a colour in the colour world. However one gets two entirely different emotional impacts from the terminal members of the saturation series for at one end might be a bright red and at the other a neutral grey. The bright red makes a strong sensible impact, perhaps the most powerful in all the colour world. But how are we to think of the greys at the other end of the series? Do they have zero redness or chromatic negative infinity? Experience in colour usage does not lead us to this conclusion for greys have a sensory character of their own. Even the colours near to grey are referred to as being warm or cool as often as they are reddish or bluish grey.

This same type of conflict occurs within the grey scale itself. White, one of the terminal members, often is thought of as reflecting all colours in the spectrum while black, the other terminal member, is the nearly complete absence of reflexion. Is one to believe that because a continuum of visual difference intervals can be made between them that they are related to one another emotionally? Experience would have us believe otherwise for white has a completely different connotation emotionally than does black.

It is not hard to understand why nearly all colour systems have been designed with the idea of joining the grey scale with the colours of maximum chromaticness because this can be done by mixtures of colorants or lights—in fact by any method with which colour scales can be demonstrated including the disc mixture technique of Maxwell. These observations have encouraged the assumption that the two end-points were related also in terms of emotional character and it has led one to conclude that a warm near grey could be described as a desaturated red or yellow. Emotionally, the two have little relationship. They say different things.

An improvement in systems for colour choice could be made if one were to show the region of the grey scale as three distinct groups of colours, the whites, the blacks, and the neutrals and near greys, each to be shown on separate charts. This would encourage one to think about these three colour areas as having distinct emotional properties. Of course, there is one rather sticky problem in separating the grey scale range from the hue charts. At what saturation does one make the incision? It is thought, however, that this can be solved satisfactorily by means of an appearance appraisal using the scales in existing colour systems as references.

Another problem in using current colour systems is the lack of an adequate number of colours in the regions of primary sensible impact. Most have only a few vivid reds, yellows, greens, blues; whereas, in practice a larger assortment of colours in these regions is useful and necessary. If one is to build a colour system entirely on a uniform grid structure of equal or nearly equal visual colour differences, one is forced to represent these colour regions with too few colour samples if the total number of colours in the system is to contain a thousand or so. Some kind of supplementary sampling is needed to represent these colour regions adequately.

The lack of sufficient chips is most critical in the three regions of the grey scale. White usually is represented by one or two chips, whereas perceptually and industrially the existence of many whites is well known. The same may be said also for the blacks. In the case of the greys and near greys, the interval between the neutral axis and the lowest saturation series is too abrupt. This transition is an enigma—it is so small visually, yet so large emotionally. There also is a critical shortage of chips differing only in lightness or reflectance, especially in the lighter ranges. It would seem that the only way to make a more useful sampling of these regions is to provide separate arrays.

Up to now, only one of the principal intents in colour choice has been discussed—to please. There is another intent, however, that has been designated as enhancement. This is the intent to make an object or a scene more beautiful—to enhance its inherent character. A theory has been devised to show how classical contrast and adaptation effects can be used to enhance the appearance of natural materials such as wood and stone. Using wood as an illustration, enhancement is accomplished by choosing background colours to modify the wood in the same direction as it normally varies, called the *natural colour gamut*. Since lighter or darker variations of wood occur naturally, backgrounds which cause the wood colour to appear lighter or darker will enhance its appearance. Wood colour also appears to be improved if it is made to appear more saturated by using adjacent colours which modify the wood colour in the general direction of maximum saturation, using background colours that are grey or near grey or opposite hues including blues and greens. The reasoning in this case is that people prefer more saturated colours to those that are more neutral when the intent is on the object itself.

Application of this theory of enhancement requires the use of a colour system based on one of the classical grid structures such as Munsell, Ostwald or C.I.E. because here one is concerned with appearance colour difference rather than emotional impact. The theory will be diagramed and illustrated.

THE SPECIFICATION OF COLOUR APPEARANCE

D. NICKERSON

U.S. Department of Agriculture, Washington, U.S.A.

COLOUR appearance specification is a necessity for such problems as colour tolerances and colour rendering of light sources if they are to be solved with any real degree of accuracy or precision. The extensive use of the Munsell system of specification in both the United States and Japan and its growing use elsewhere has come about very logically in an attempt to solve these and other colour problems that require use of appearance, rather than colour mixtures specification.

Thirty years ago impetus was given to colorimetry by the resolutions passed at the 1931 meeting of the International Commission on Illumination (C.I.E.). The C.I.E. specifications and (x, y)-diagram that have resulted from these resolutions, have done many things to help advance the science of colorimetry, but the colour spacing on the diagram has little relation to uniform perceptual spacing, even for samples having negligibly different luminances. To obtain any real semblance of an appearance specification in three dimensions from C.I.E. data, it is necessary to use a conversion method such as the one provided by Adams' chromatic-value, a non-linear transformation of the C.I.E. space that is based on the Adams' theory of vision. The result yields chromaticity spacing that is a good first-approximation to Munsell spacing.

But let us try another road and approach colour as an aspect of the appearance of objects and light sources that may be described in terms derivable wholly from perception. Most conveniently this involves hue, brightness, and saturation for light sources, and hue, lightness, and saturation for objects.

The year 1905 saw the beginning of the Munsell system for specifying colours numerically on decimal scales of hue, value, and chroma, scales that are intended to be uniform for a normal observer, daylight viewing, and a neutral background of medium to high lightness. When these conditions are met the Munsell hue, value, and chroma specification for a colour sample will correlate closely with the hue, lightness, and saturation of the colour perception received from that sample. Under other conditions the correlation with the sample may be lost.

Munsell, as well as C.I.E. specifications can be assigned to any colour sample, but in either case it must be remembered that the specification refers to standard conditions only. For really accurate work it should concern us that the light source used in observations may be daylight, as from a moderately overcast north sky, while the source used in colorimetric computations may be C.I.E. Source C. Back in 1931 an approximation obtained in this way was far superior to anything previously available, but today it is not precise enough. A specification is needed that for standard conditions allows one to define the daylight colour of an object in terms of its appearance, and also needed is a method of computing its colour so that for one set of standard conditions the colour specification is the same, to a very high degree of accuracy, whether obtained by observation or by computation.

Use of the Munsell renotation specification, as defined in the 1943 O.S.A. subcommittee report by Newhall, Nickerson, and Judd, using "daylight" as a light source for observations, and using C.I.E. Source C as the light source for computation, provides an approximation that has proved very practical in much colour work over the past years. But the correlation between colour specification based on these appearance scales, and on colorimetric methods based on present C.I.E. standards, is not yet close enough to provide sufficiently accurate answers for many problems.

The goal should be that one is able to specify the colour appearance of a colour represented by any given C.I.E. specification. Today it is known how to transform C.I.E. data for no light source other than daylight to a Munsell specification. Once there is a method for obtaining an accurate daylight conversion from C.I.E. data for any light source, then through use of an appearance specification it would be possible to make increasingly precise judgments regarding the adequacy and applicability of results of studies such as those of chromatic adaptation and colour constancy.

On the basis of separate studies of chromatic adaptation made by Helson, Burnham, MacAdam and their associates, and in connexion with the work of the I.E.S. subcommittee on colour rendering of light sources, Judd and Howett in 1959 prepared formulas for converting C.I.E. data from any light source to Source C, or the reverse. These formulas are intended to allow prediction of equal-appearing colour with adaptation to Source C when the C.I.E. colour specification under another source is known.

These formulas have been applied to samples used in I.E.S. committee studies. If any one of them adequately represents the facts that must be taken into consideration in accounting for the everyday colour changes that take place when samples are viewed under A and C sources, then conversions should provide a C.I.E. specification for samples viewed under Source A that would be in terms of an equal-appearing colour under Source C. This C.I.E. specification for Source C, could in turn, be transformed to an appearance specification in terms of Munsell hue, value, and chroma. Putting the data into appearance terms would make it possible to judge the amount and direction of colour change that is involved. Once sufficiently accurate and appropriate formulas become available, the next step will be to tighten restrictions on observing conditions in order to obtain precision of reproducibility, as well as accuracy of results. This approach accords with work reported by Burnham (1959) on a comparison of Burnham-Evans-Newhall and Wassef experimental results, for which Source A to Source C prediction equations are developed. But, as Burnham says in a 1960 report ". . . there is at present no adequate . . . technique available for precise specification."

Wright has proposed that the immediate action required to establish a scale of subjective colour measurement is to agree on a standard set of viewing conditions for the comparison field. The subjective colour would then be expressed by the C.I.E. specification of the stimulus that had the same appearance, under standard conditions, as the test colour has in its particular environment. But before standard viewing conditions are adopted, it should be established that they are the sort that will provide results that agree, at least in a general way, with the important everyday colour situations that face us.

The problem of colour rendering of light sources is but one such situation, but for any similar practical need, the use of an adequate appearance specification, intelligently applied to results of a trial run, would soon tell whether any proposed set of standard conditions would give appropriate answers for the purposes of the experiment. The use of an accurate appearance specification that allows one to look at samples and judge immediately whether their colours accord with the appearance specification given them, is one of the great needs of colorimetry today. There are other phases of the appearance problem that one day will have to be considered, but long before that day we shall have to adopt some sort of standard conditions and standard methods for this complicated yet far simpler problem of appearance specification.

THE MEMORY ASSESSMENT OF COLOUR APPEARANCE

B. H. CRAWFORD

National Physical Laboratory, Teddington

THE human eye (and brain) can be adapted over a wide range of conditions, in particular in the sense of giving a constant response to what is seen. This is exemplified in the case of looking at white paper, which appears white over a certain range of conditions, or at a black object, which remains a black object in many circumstances. Coloured objects present greater complications and often smaller tolerances within which they preserve constancy of appearance, but in all cases there is a finite tolerance range within which no change is seen. Colour appearance, especially in popular parlance, usually implies a remembered appearance. The particular case of colour matching, the side-by-side comparison of colours, reduces memory to zero and measurement to its simplest and most precise terms. When memory is involved, precision suffers, but it does not *ipso facto* become zero, even if memory is operative over a long time interval. The present concern is with the degree of precision attainable in memory assessment and the structure of practical information which may be erected thereupon in the particular case of colour rendition.

When it comes to practical measurement involving memory, there are two general ways in which it can be carried out. Two conditions are to be compared and the answer required of the observer is whether they appear equal or unequal. The comparison may be made by looking first at one condition of affairs, then, after a suitable interval and suitable adaptation, at the other condition. Alternatively, the comparison may be made by looking first at the one condition, which then changes, gradually and continuously, into the other condition. It should be possible so to design the procedures in these two ways of measurement that they give the same, that is, the right result. Which method is chosen need only depend, therefore, on convenience and on the available experimental material. Considering the problem of colour rendering specification, the solution of which must be based upon colour appearance, the first method, which might be called the method of discrete changes, would be obligatory if experiments had to be confined to a number of fixed qualities of illumination. It is always possible, however, by exercise of a little ingenuity, to transform the conditions to those of the second method, the method of continuous change. One might ask, why bother? But further practical consideration shows that more information may be obtained in a given time by the method of continuous change, and this in a more convenient form, which justifies the endeavour to use this second method whenever possible. What follows will relate only to the method of continuous change, since no extensive work has been done by the other method.

The details of methods and apparatus used in our colour rendering investigations has been described in several papers[1,2,3], so that only the outlines need be described here. The basic requirement was a light source whose spectral composition could be continuously varied in any desired way while it was being used to illuminate a test object. The equivalent of this was actually obtained by using the optical system of a double, subtractive-dispersion monochromator as a filter, continuously variable by the gradual insertion of shutters in chosen parts of the central spectrum. It was inserted either between light source and test object, or between test object and eye. As a consequence of this continuous change in spectral composition there was a continuous change in the colour appearance of the test object.

Using a well-known object or type of object to avoid a long preliminary learning process, e.g., human face, food stuffs, scenery, it was possible to make a gradual change in spectral composition of the illuminant which eventually led to a noticeable change in appearance of the object. The more gradual the change in the illuminant, the more difficult to detect the change in appearance, but only up to a certain limit, ill-defined but real, beyond which the increase in difficulty was unimportant. In other words, beyond this limit we believe we have reached the same judgment as would be reached in long-term living with the modified illuminant. Some early results support this conclusion. Later work, in which colour rendering assessments on the basis of the laboratory experiments are confirmed in tests on a practical scale, also supports this conclusion indirectly.

Of interest at least equal to that of correspondence between the methods of discrete and of continuous change is the question of the validity of memory assessment as regards repeatability. Direct evidence of repeatability has been obtained at various stages during the experimental work. Repetition by the same small group of four or five observers who performed on each occasion a group of three or four tests, each repeated three or four times, is of the order of 7 per cent after an interval of four months or more. Repetition by a single observer is of the same order of precision under similar circumstances. Over a shorter time interval, consistency within a limited experiment may be even better. Taken all in all, there is a very satisfying numerical reality in these particular memory assessments which justifies their use in building up, for instance, a practical specification of colour rendering in terms of experimentally determined tolerances based on the memory assessment of colour. The technical details of how this has been done have been described in the references already given. Some of the results will be shown and discussed in relation to practical problems and experience.

References

(1) Crawford, B. H. *Die Farbe*, **4**, 168. 1955.
(2) Crawford, B. H. *J. Opt. Soc. Amer.*, **49**, 1147. 1959.
(3) Crawford, B. H. *Studies in Conservation*, **5**, 41. 1960.

A STUDY OF COLOURED SHADOWS

H. HELSON and C. SELF

University of Texas, U.S.A.

ALTHOUGH the phenomenon of coloured shadows has been known for centuries, it has not been subjected to systematic investigation. Coloured shadows are produced by interposing an opaque object between two sources of light illuminating a white surface. If one chromatic and one achromatic source is used, the shadow belonging to the chromatic source which might be expected to appear grey is strongly chromatic. Moreover, the shadow is as saturated in the centre as around the edges bordering the chromatic surround. The chromaticness of the shadows was determined by the binocular septum technique: six observers viewed the shadow with one eye and matched it with one of the chips in the Munsell Book of Colour viewed by the other eye. The Munsell chips were illuminated with Macbeth Daylight.

The method of limits was employed in making the matches. With fixed achromatic luminances, the chromatic luminance was varied in small steps, first in increasing amounts, then in decreasing amounts. The surround colour thus varied in purity as well as in luminance. The following ranges in chromatic luminance were employed:

Red:	0·71	to	·00059	ft. l.
Yellow:	5·0	to	·0044	ft. l.
Green:	0·52	to	·00043	ft. l.
Blue:	0·084	to	·000069	ft. l.

The achromatic luminance (Macbeth Daylight) varied from 13·8 to 0·31 ft. l. Thus the chromatic luminance had a range of 1,210 : 1 and the achromatic 44·5 : 1.

The design of the experiment is schematized in Table I.

Table I

Achromatic	*Chromatic*				
13·8	·71	·45	·29	·15	·00059
·31	·71	·45	·29	·15	·00059
·31	·00059	·00026	·013	·45	·71

Results and Discussion

Plots of Munsell chroma against luminance of the achromatic light in the shadowed area with luminance of the chromatic surround as the parameter show decreasing saturation of the coloured shadow as the amount of white light increases and/or as the amount of chromatic light decreases. The shapes of the curves for red, yellow, green and blue surrounds are very much alike and fairly linear with log luminance. The irregularities in the curves at low chromas are partly due to difficulty of matching weakly saturated areas and partly to the fact that the very weak chromas often could not be matched with the Munsell chips and therefore had to be estimated.

The following equation defines the relation between chroma and luminance of the chromatic surround:

$$C = K_1 \log L_c + K_2$$

where C stands for chroma, K_1 and K_2 are constants and L_c is the luminance of the chromatic surround. Owing to the breaks in the curves, the fitted equations do not include data for chromas less than 1·0.

The power of the eye to supply colours for which there are no dominant wavelength correlates is brought out by these data. Thus with as little as 0·006 ft. l. blue luminance the coloured shadow has a Munsell chroma of 6·0—one step higher than medium saturation.

Since chroma is a function of luminance of both shadow and chromatic surround it is natural to plot it as a function of the ratios of these values and this yields an equation similar to the first:

$$C = K_1 \log (L_a/L_c) + K_2$$

where the old symbols have the same meanings as above, and L_a is the luminance of the achromatic component. The values of K_1 and K_2 for the red, yellow and green hues are very similar, K_1 ranging from $-2{\cdot}6$ to $-3{\cdot}2$ and K_2 from 5·4 to 6·9. The values of K_1 and K_2 for blue luminance are larger, being $-4{\cdot}2$ and 11·1, probably due to the greater chromatic evoking power of blue compared with the other hues. This conclusion is supported by the fact that the blue luminance plots farthest from the spectral locus in the C.I.E. mixture diagram, and it was also the weakest of the four sources owing to the low transmittance for 2,848°K of the blue filter.

Conclusions

The results of this study may be summarized as follows:

(1) The saturation of the colour of the shadow increases as the purity of the colour in the surround increases (i.e., as less and less white light is mixed with the chromatic light) and it also increases with the log of the luminance of the chromatic light in the surround and inversely with the luminance of the achromatic component;

(2) The chromaticness of the shadow does not depend on absolute luminance of the surround or of the shadow but upon the ratio of luminances in the two areas;

(3) The hue of the shadow colour is unaffected by admixture of white light with the chromatic light in the surround but its saturation is affected as noted in (1);

(4) The hue of the coloured shadow is "complementary" to the colour of the surround as shown by the fact that the line connecting the surround points and the shadow points is a straight line passing through the white point of the C.I.E. diagram.

(5) Coloured shadows thus fall under the principle of colour conversion formulated by Helson (1938) for the colours of papers seen in strongly chromatic illuminants.

CENTENARY DISCOURSE

17 May 1961—On Wednesday evening at 9 p.m., a Centenary Discourse will be given by Dr. D. A. Spencer on "A Hundred Years of Colour Photography" at the Royal Institution.

Reprinted from The Journal of Photographic Science, Vol. 9, No. 2, 1961

Printed by RICHMOND HILL PRINTING WORKS, LTD., 23-25 Abbott Road, Winton, Bournemouth—19102