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Symposium on Colour Vision and Colour Measurement

The Visual Laboratory
Department of Psychology
University of Edinburgh
1st April, 1966

Edinburgh was appropriately at its colourful best, with the sun shining from a cloudless blue sky, to welcome the participants to this first all-day meeting of The Colour Group in Scotland. About 130 people, including many Colour Group members from south of the border were present. After registration most people had a few minutes to look round some of the exhibits, which had been arranged by the Staff and students of The Visual Laboratory. These included demonstrations of apparatus used for studies on the visual functions, colour vision, colour measurement and photometry as well as several commercial firms' demonstrations of colour measuring instruments. Also on show was a unique display of over 300 books and pamphlets on all aspects of colour, and considerable interest was shown throughout the day in this display, particularly in the historical section which included books from as early as the 17th century by such famous names as Boyle, Newton, Young, Goethe, Hering, and Ostwald. This quick survey showed that there was plenty to keep our interest throughout the day.

The symposium was opened at 10 a.m. by the Chairman of The Colour Group, Dr. B. H. Crawford. He reviewed the development of the Group from its formation in 1941 and welcomed the extension of its activities to Scotland in this 25th anniversary year. Four papers on various aspects of colour vision were presented during the morning session, chaired by Dr. Crawford and Professor Pickford, and were each followed by an interesting discussion. Lunch followed, at which many of the discussions were continued, and where old friendships were renewed and many new ones made. Most people returned quickly from lunch to take the opportunity to look further at the interesting exhibits, displays and demonstrations. The afternoon session followed with three papers on Colour Measurement, chaired by Mr. R. S. Sinclair, and again the attendance and level of discussion, as throughout the day, indicated the interest shown in the papers presented.

The symposium was closed by Dr. Crawford who congratulated and thanked all those responsible for the organisation, in particular Dr. Lakowski and his staff and Mr. Sinclair, for all the effort which had gone to make the day the success it was.

A final cup of tea, supplied by the Students' Psychological Society, gave a further opportunity to meet or visit the exhibition or browse over some books, and the only regret was that we had to leave so soon to catch our transport.

The day was completed with an informal dinner at which the authors were the guests of the organising committee.

R. S. SINCLAIR.

Programme

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Acquired Colour Vision Defects

P. R. Kinnear

An acquired colour vision defect was defined as a colour visual anomaly occurring in a subject born with a potentially normal colour visual system, which either failed to reach maturity or has deteriorated since reaching maturity.

There is only space in this summary to mention some studies of the mode of occurrence of these defects, but before doing so, two points must be stressed :

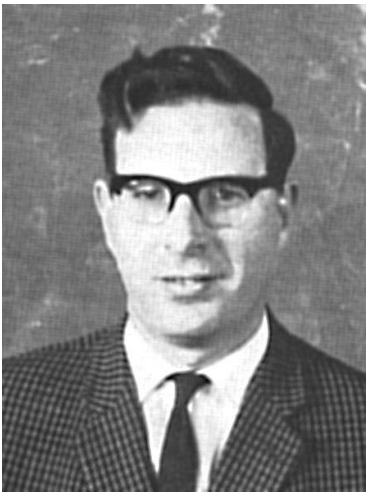
(a) Tests or instruments capable of detecting the presence or absence of the factor under investigation must beused—this may sound obvious,

butmany people still generalise from theMr. R. S. SinclairIshihara test being a detector of congenital defects to being a general test of colour discrimination.

A corollary is that if a test fails to differentiate subjects from controls, it cannot be concluded that there is no difference between the subjects and controls but only that the test used was unable to detect a difference.

(b) In surveys of colour vision as opposed to individual clinical cases, samples tend to be inadequate or the conclusions too general. For example, in some of the studies on age and colour vision, only a small part of the age spectrum was sampled.

Thus it is vital to ascertain the properties of a colour vision test before incorporating it into a testing procedure.



Mr R. S. Sinclair

AGEING

Ageing is not a disease, but it cannot be denied that certain irreversible changes occur in the body as it becomes older. In this, topic especially, the first point about what a test measures is apropos. Chapanis[1] found no age changes with pseudo -isochromatic plates on 574 subjects aged from 5-79, nor did Kleemeier[6] with the Orthorater colour test on 128 men aged from 67-85.

However, more sensitive tests of colour discrimination did reveal losses, although the age at which these first start to occur is disputed. Smith[12] used Munsell samples on 199 subjects aged from 5-87 and found differential hue, saturation and lightness thresholds increased with age. Gilbert[4] used the colour aptitude test on 355 subjects aged 10-93, and concluded similarly. Lakowski[7] tested over 500 subjects aged from 5-91 on the PickfordNicolson Anomaloscope and found a progressive deterioration with age. Ruddock[10] found with 400 preselected subjects aged from 16-70 that colour-matching and the relative luminous efficiency of selected spectral wave-lengths were significantly correlated with age.

Verriest[13] used the 100-Hue test on 480 subjects aged from 10-64 and noted a gradual deterioration after the age of 25. Kinnear[5] also found a similar trend with age on the 100-Hue test with 508 diabetics aged from 10-72. Incidentally, the mean deviations of the diabetics were much greater than those of Verriest's population, but this will be considered again later.

Summing up, it would appear that the development of an acquired defect with increasing age is highly probable.

DRUGS

Recently Siegel[11] spoke about drugs and colour vision and found that the anti-bacterial drug Altafur was associated with irreversible changes which he estimated were due to cone damage. The

patient had poor visual acuity and was dazzled in ordinary illumination. The anti-convulsive drug Tridione also created a dazzle phenomenon but, according to Siegel, the changes were reversible. Cox[3] also investigated Tridione by testing children who were taking the drug and found poor colour vision results with pseudo-isochromatic plates and the 100-Hue test but was unable to conclude positively owing to the unreliability of young observers.

The effects of Chloroquine have been investigated owing to the widespread use of the drug for relieving rheumatoid arthritis. In 1963 Okun et al.[9] reported eight cases giving the results of Dark Adaptation, the Farnsworth D-15 test and the HRR plates in addition to ophthalmological particulars. None of the subjects correctly read all the HRR plates and only three performed the D-15 test satisfactorily. However, all showed retinopathy to a varying degree. Carr et al.[1] found with eight subjects that there was a close relationship between Chloroquine dose and peripheral retinal thresholds for red and blue lights. Lakowski[8] tested 30 subjects suffering from rheumatoid-arthritis of whom 27 had been treated with Chloroquine. But in this last study very few of the subjects had any acuity loss or evidence of retinopathy, yet Lakowski still found considerable losses in colour-discrimination.

The significance of this last point is considerable: there is now a means of ascertaining whether a drug is affecting the visual system before pathological changes can be seen by the ophthalmoscopist.

PATHOLOGY AND LESIONS

Verriest[13] and Cox[3] have each published extensive surveys of the colour vision of patients suffering from various abnormal conditions of the visual system. They found that the defects fell into two groups, Red-Green or Yellow-Blue, and that on the whole Red-Green defects occurred with optic nerve and gross retinal lesions whereas Yellow-Blue occurred with moderate retinal lesions.

The diabetic results mentioned earlier were derived from a survey of over 500 patients of whom nearly 400 were aged under 50 with normal acuity and three-quarters of them had normal fundi and the remaining quarter only mild retinal disturbances. Yet about 30% could be classified as lying outside the 95th percentile of the normal population in the 100-Hue test and the Yellow-Blue equations of the Pickford-Nicolson anomaloscope. In some cases the colour loss was quite severe despite normal fundi and acuity.

Three points were presented in conclusion

(a) The 92% of the population with nonhereditary colour vision defects are not necessarily the possessors of normal colour vision.

(b) That people involved in occupations involving good colour discrimination should be assessed at intervals as they age for colour vision competence.

(c) Colour vision testing can provide a very sensitive test of visual function invaluable to ophthalmologists, neurologists and others as a means of diagnosing visual trouble and of assessing the effect of therapy.

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Colour, Colour Vision and Colour Blindness

R. W. Pickford

A complete consideration of colour vision must cover (1) The Phenomenology of Colour; (2) The Testing and Measurement of Colour Vision; (3) The Physiology of Colour Vision; (4) The Specification and Measurement of Colour; (5) The Inheritance of Colour Vision Defects and Variations.

COLOUR VISION TESTS

Conventional colour vision tests can be classed as (1) those utilising skeins of wool, coloured beads, chips or caps; (2) lantern tests; (3) pseudo-isochromatic charts and tables. Alternatively colour vision can be tested using an Anomaloscope. The Nagel anomaloscope, Model

I, uses spectral lights; red (670.8 nm) + green (546.0 nm) = yellow (589.3 nm). Model II also provides a blue and green equation; bluegreen (518.5 nm) + indigo (468.5 nm) = blue (486.1 nm). A number of filter anomaloscopes have been devised, and the writer has made one which uses neither lenses nor prisms and is readily portable, Fig. 1. It can be used in diffused daylight.

With this instrument it is suggested that three colour equations should be used as shown in Fig. 2. They are obtained with Chance's Optical Glass Filters, of which the dominant wave lengths are given in brackets.

(1) Red (OR1; 642 nm) + Green (OGrl; 555 nm) = Yellow (OY 3; 585 nm).

(2) Green (OGr1; 555 nm) + Blue (OB 10; 470 nm) = Bluegreen (OB 2; 495 nm).

(3) Blue (OB 10; 470 nm) + Yellow (OY 3; 585 nm) = Neutral (near Illuminant A).

CLASSIFICATION OF DEFECTS

The following classification of types and degrees of colour vision defects and variations is widely accepted.

I. Major Defects.

Total Colour Blindness (Achromatic): "Rod" Achromatopsia; "Cone" Achromatopsia.

Yellow-Blue Blindness: Tritanopia (Dichromatic); Tritanomaly (Trichromatic); Tetranopia (Dichromatic); Tetranomaly (Trichromatic).

Red-Green Blindness: Protanopia (Dichromatic); Extreme Protanomaly (Trichromatic); Simple Protanomaly (Trichromatic).

Deuteranopia (Dichromatic); Extreme Deuteranomaly (Trichromatic); Simple Deuteranomaly (Trichromatic).

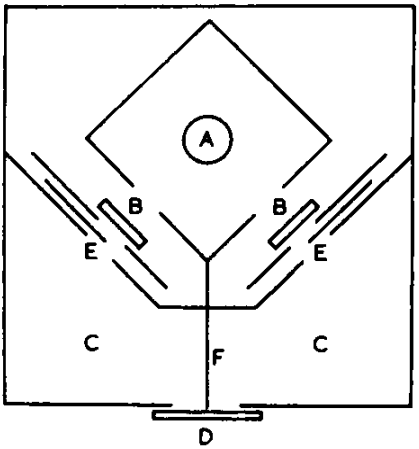

Fig 1. Plan of Pickford Anomaloscope. A; Lamp. B; Colour Filters. C; Integrating boxes. D; Viewing aperture. E; Shutters. F; Partition.

II. Minor Variations.

Deviants in the anomaloscope tests may be defined as those subjects, excluding major defectives, who show deviations of matching point, in any equation, greater than twice the standard deviation (sigma) for the normal group (Trichromatic).

Colour Weak subjects in the anomaloscope tests may be defined as those subjects, excluding major defectives, who have matching ranges of more than twice the modal matching range of the normal group (Trichromatic). Deviation and colour weakness may go together but are not necessarily correlated.

The criteria of more than twice the standard deviation of matching point, and more than twice the modal matching range, were chosen because subjects with such variations tended to show some difficulties with colours in everyday life.

Total colour blindness is satisfactorily diagnosed with the anomaloscope. No colour differences are found in any of the standard tests.

The matching points for deuteranomalous or protanomalous subjects are beyond three times the standard deviation towards the green or red side. Their matching ranges are often not larger than those of some normal subjects, and do not include the normal average matching point. The matching ranges for extreme deuteranomalous and extreme protanomalous subjects are large or very large and include the normal average matching point, while the mid-matching point may be either more or less deviated than those of deuteranomalous or protanomalous subjects. The deuteranopic and protanopic subjects can match the red-green spot with the yellow throughout the whole scale if brightness is equalised, and are in consequence dichromats. Among protanomalous and deuteranomalous subjects the deviation of the matching point steadily increases until the extremest deviation is reached, with little increase in matching range, while, for most of the protanomalous subjects there is a marked reduction in the brightness of the red end of the spectrum. All protanomalous and deuteranomalous subjects have moderately or quite

good red-green discrimination, but on a scale of colours or shades of colour widely different from the normal.

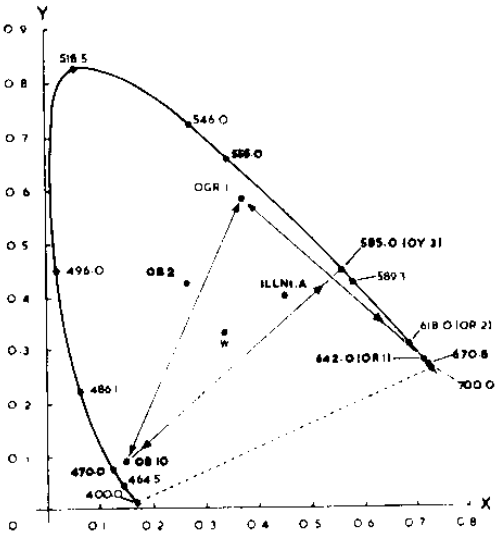

Fig. 2. Locations of Pickford anomaloscope tests on chromaticity diagram

The best anomaloscope techniques are those in which we proceed step by step from one end of the scale to the other end and back, several times, or in which we first establish the ends of the matching range and then take points along it at random but in such a way as to be sure that it has been properly filled in. It is easy to start by offering the subject possible matches at the ends of the scale, to find out whether he is a dichromat or nearly a dichromat, and then to proceed accordingly. As soon as we find that he is not a protanope or deuteranope, and find roughly where his matching range will be, we can make a systematic sequence of steps to establish its size and position precisely, taking account ofchanges of brightness as we proceed, because no claim of a colour difference should be accepted unless the brightness of two hues are equal for the subject in question.

For all dichromats the matching range runs from one end of the scale to the other. For most anomalous subjects and all ordinary trichromats we must proceed from a perceptible difference through equality of hue to a perceptible difference at the other end of the matching range. Since all points in the matching range are points of equality of hue there is no object in trying to find a so-called "midpoint" otherwise than as the middle of the matching range.

RETINAL PIGMENTS

It seems reasonably established by the work of Rushton, Wald, MacNicol and others that three retinal pigments are concerned with colour vision. The work of Hurvich and Jameson, Svaetichin and others, however, supports the results of many "behavioural" rather than physiological experiments, that the three primary cone responses are transformed into a general light response and two opponent colour responses, probably red/green and yellow/blue. This would imply a synthesis of the Young-Helmholtz and Hering types of theoretical treatment of colour vision. Many problems, especially those of the response mechanism of the protanomalous, deuteranomalous and tritanomalous subjects, require fuller treatment.

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Colour Vision Tests : What Do They Test ?

R. Lakowski

In the past the validity of a given colour vision test was evaluated in relation to certain diagnostic criteria. Now, however, colour measurement techniques and the theory of colour vision have advanced sufficiently for a theoretical approach to be made. Spectrophotometric and colorimetric data on certain tests have been analysed (measurements were made on the Pretema Spectromat). Only tests in common use for vocational purposes such as the Colour Aptitude Test (CAT), the Farnsworth-Munsell 100-Hue test, four pseudoisochromatic tests (PIC), and the Willmer and Farnsworth plates for detecting yellow-blue losses are discussed here.

Dr. R. Lakowski

The objective *spectrophotometric* data show that isomerically identical or only slightly different stimuli are presented in each task in the two colour discrimination tests, whereas in the PIC tests, it is possible that metameric relationship may exist for some subjects. In addition, broad band stimuli with frequent secondary peaks are used in the PIC tests, and this makes for a less distinct stimulus situation.

There are similarities in the design of the qualitative plates in the PIC tests, but the differences between the test plates indicated by the reflectance curves are great enough to make us cautious about expecting anyone but an outright dichromat to respond equally to them all. Eight distinct reflectance curves can be identified in most of the PIC plates, except for the Dvorine, where only four are employed. In yellow-blue tests the number varies more - 6 (for plate F2) to 15 (in the W11). There are two distinct types of curve for the bluish figures, those with peaks of 460μ, and those of 490μ, and their difference if unintentional is a significant variation in design, especially if people who use them treat them as tritan plates.

Colorimetric data correspond more closely to sensory experiences, therefore more definite inferences can be made from them. One type of information is quantitative, that is, it tells us the difficulty of a test in terms of the colour differences present (ΔE), and the other type is qualitative, that is, it tells us how well a test measures up to the tenets of colour confusion theory.

The 100–Hue test, though primarily a test of colour discrimination, is also a test of colour confusion, since certain consecutive caps follow the confusion lines for all known dichromats, but it is also a sensitive measure of defects other than the well-known congenital ones, for example colour losses

due to general reduction in the luminosity efficiency of the visual system gives rise to the scotopic axis.[1] Colour differences between adjacent caps are very small, with an average ΔE of 2.2 NBS units. The order of difficulty between the series is not uniform. It is least for series 85-22 and greatest for 43-64.

Theoretically, it might be expected that dichromats would show slightly lower scores on the CAT than those with normal colour vision, as only one of each of the four colour series corresponds to the confusion lines for any given defect (e.g. only the pink series lies on the protan lines). Colour differences are very small, the maximum being 4 NBS units—e.g. ΔE between board chip no. 11 and acceptable chips of the yellow series is one NBS unit with 13; 2.5 with 38, and 2.6 with 19.

In the Dvorine and Ishihara tests colour dots of individual plates tend to be grouped *only roughly* along the deutan and protan confusion lines in the centre of the CIE space. In the Tokyo test, on the other hand, two distinct areas are used, one in the centre for the qualitatively diagnostic plates, the other near the spectrum locus (between 570 and 590μ) for the quantitative and screening plates. In this test the deutan and protan elements correspond exactly to the isochromatic lines for the defects, but the yellow-blue plates follow the tetartan instead of the tritan lines.

All HRR plates have a grey background, and the colours in the symbols are arranged along the axes for red-green defects and the axes for yellow-blue, so theoretically it can test all known defects. Colorimetric measurements indicate surprisingly that in this very modern test none of the axes exactly follows the confusion lines.

The qualitative plates in the PIC tests (excepting the Tokyo) have a common fault. The figure to be confused by deutans contains a few colour dots which lie along the protan confusion lines. Thus, theoretically, it could be inferred that those plates would diagnose deutan better than protan defects, and this is borne out by experimental evidence, since fewer protans than deutans give the expected responses.[2]

The Farnsworth and Willmer plates are not all tritan plates. F 5 was designed specifically to detect the effect of macular pigmentation (with an apparent copunctal point of 460μ), and the F 2 follows the tritan confusion lines for the green square and purple background. It is insensitive to age variations, but can be used to verify outright red-green dichromats, who never see the blue square, as it and the purple background lie on the protan and deutan confusion lines. The Willmer W 2 plate best fulfils the requirements of colour confusion theory, as both figure and background lie exactly on the tritan confusion line. Kalmus[3] found this plate to be an almost perfect test for tritanopia. Plate no. 11 is of similar design to the Ishihara hidden digit series, and according to Kalmus is rather unsuccessful in detecting yellow-blue defects, and in an age study about half of 500 subjects of all ages could see the digit 11 at a distance of 2-3 feet.[4]

PIC tests are more than tests of colour confusion; they may also be tests of colour discrimination. In the HRR and TMC degrees of difficulty were deliberately introduced, but in the Ishihara and Dvorine these were accidental, as such tests were intended to be qualitatively diagnostic only. It is therefore relevant to know which of the plates are "simple" and which are more

difficult, since the plates may become difficult to those with no apparent congenital colour defect, if they are colour weak, or have acquired dyschromatopsias or are just growing old. In qualitatively diagnostic plates of the Ishihara, Dvorine and HRR the figure background colour difference is usually between 25 and 45 NBS units; in the quantitative plates of the HRR it is about 15 to 25, while in screening plates it is only about 12 NBS units. However, in the Ishihara there are plates (e.g. 9 and 17) with elements in the figure where ΔE is only 10 to 15 NBS units, and in the Dvorine four plates have ΔE of 10 to 15 NBS units.

From the study of colour differences and colour confusion theory it looks as if some minimum ΔE should be employed in tests designed solely to diagnose colour defectives, if it is not also to become a test of colour discrimination for those with normal colour vision. If we introduce the concept of colour acuity into our thinking, we may say that depending on the task the following ΔE represent the limits of "colour resolution" (with an absolute threshold of 1/5 of an NBS unit). In tests of colour discrimination ΔE of one NBS will be considered to be difficult, and ΔE of 5 to 7 NBS to be easy. In PIC tests employing simple geometrical symbols the limit of "colour resolution" is probably around 6 NBS units, while in those using numerals the limit is about 8-10 NBS units. Thus plates to detect dichromats alone should be constructed not only along the confusion lines for that particular defect, but also should involve ΔE of the order of 20-40 NBS units.

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Some Uses of Flicker Photometry

A. W. Shirley

The term flicker photometry is taken here to cover the study of phenomena which arise as a result of stimulation of the eye by a series of variations in the intensity of one or more beams of light of one or more wavelengths respectively. The variations are usually regular and may be modulated to any form, e.g., they may be of square or sinusoidal, rectangular or saw-tooth form.

The aim of this paper is to present some of the uses to which flicker phenomena have been put in colour vision research and to demonstrate perhaps some of its advantages and disadvantages.

DETERMINATION OF RELATIVE RETINA SENSITIVITY

Retinal sensitivity for the full visual spectrum has been the subject of much careful scientific measurement for nearly a century and numerous methods have been employed to obtain valid and con-sistent data. Nevertheless, the experimenters admit that each method has weaknesses, and it would seem that what remains to be done is

to eliminate as many of these as possible. This can be done in one or two cases by a combination of methods using a new form of photometer which makes available three beams of any wavelength and a wide range of intensity, which can be conveniently presented to the eye in a suitable order for the particular investigation in hand.

SUMMARY OF EXISTING METHODS

There are at least five well tried methods.

(1) *Threshold of Vision*

This, very briefly, concerns the measuring of the minimum amounts of energy to produce luminous sensation at diferent wavelengths.

(2) *Visual Acuity*

By this method one's ability to distinguish fine print, etc., is used as a criterion with different amounts of coloured light.

(3) *Critical Frequency of Fusion (or persistence of vision)*

This involves determining the fusion frequency for various wavelengths and intensities.

(4) *Equality of Brightness (or cascade method)*

In this method the relative luminosity for an observer's eye is measured under given specified conditions of surround, etc., between two wavelengths of which the colour difference is minimal. The whole spectrum is covered in a step by step manner advancing first one colour then the other, in such a way that the colour difference between them affects the match for brightness as little as possible.

(5) *Flicker Photometry*

In this method the practice has been to illuminate the eye by alternative flashes of the colour under investigation and a standard light source, either a white or say a sodium yellow. It is found that by adjusting the flicker speed first the colours merge, then by brightness adjustment the flicker will disappear leaving a composite field of steady illumination. When this occurs the two colours are said to be at equal intensity or luminance. The method is based upon the fact that colour fusion occurs before brightness fusion.

APPRAISAL OF THE VARIOUS METHODS

The most intense rivalry for the centre of the stage has been between the two last : Equality of Brightness, or cascade method, and heterochronic Flicker Photometry.

Equality of Brightness is clearly direct and simple and, as Ferree and Rand point out, it has sureness of principle, but small differences in luminosity cannot be detected because colour differences interfere with the judgment, results cannot be reproduced in time with only small errors, and results cannot be reproduced from one observer to another. Houstoun found that considerable variations in the curve were obtained by varying the luminosity, the point of maximum sensitivity shifting from 502 to 644 millimicrons for illuminations of ½ and 1 /600th metre candles respectively.

Dow had found this a few years before and noted that red was decreased excessively in the equality method. He also discovered that field size was quite a critical parameter. Ives found that the only conditions which gave results comparable with flicker were at high luminances and small fields, when very small steps were taken round the spectrum, and even under these conditions it was difficult to avoid cumulative errors, and abandoned it on this account.

Flicker Photometry enables one to detect small differences in luminosity and to reproduce results for a given observer with a small mean variation. This is admitted by Ferree and Rand, the method's earlier most dogged critics, as is the fact that it has the further advantage of removing the difficulty caused by the colour differences. It is also quick and less susceptible to the effects of brightness and field size examined by Dow. Coblentz and Emerson, and Tufts, found that the readings were but little affected by fatigue. It was found also that the eye quickly adapts to the conditions of the experiment.

The most serious challenge is that, as different colours require different times to reach their maximum brightness effect in the observer and the time per flash does not permit of this being reached consistently for all colour pairs employed, the eye is being under-exposed and the method is thus unsatisfactorily established. There is conflicting evidence about this charge, but it is clearly desirable to avoid this possible source of error by having at least as small colour differences between the lights used as possible. Truss showed that persistence, the reciprocal of the critical colour fusion frequency (C.C.F.F.) increased as the colour difference diminished. The judgment of brightness equality is enhanced by reducing the fusion frequency and this can be achieved also in this way.

The method adopted by Ferree and Rand is to present a field in which one half consists of the colour being measured, and the other a fusion of this colour and a standard white light. These two are then matched for brightness. This certainly overcomes the colour differences problem but introduces a desaturation effect which may well he less but is still noticeable.

It was to overcome these various objections that the following method was devised. In this, the field is divided into two. In one half is alternately flickered to fusion frequency two spectral colours as close in wavelength as one chooses. As before, colour fusion is achieved first, then brightness, but by virtue of the closeness of the colours this frequency is considerably reduced, and hence the precision of brightness judgment is enhanced. The advance around the spectrum is effected by a step by step method, the size of the step being as small as desired. To get the maximum advantage from the method it is desirable that it should be smallest in those areas where the colour difference is most acute, the near yellow region, although of course no colour difference is seen as in the equality of brightness method. At each position the other half of the field is matched to the first in colour and brightness. The purpose of this is to give an accurate and immediate assessment of the actual colour arising from the mixture and the brightness.

It is clear that this method overcomes the colour difference problems and avoids the denaturation effects. It is still liable in a straightforward run to accumulate errors in the unskilled observer. This can be rectified by a return run, the results of which can be used to fair the curve.

MEASUREMENT OF RELATIVE CONE DENSITY

Rushton and Baker have extended the use of Flicker Photometry to a research into the relative density of red/green cones in the foveas of subjects who have shown normal anomaloscope readings. The basis of the method employed is that of flickering a beam of red light of constant brightness with

a green the strength of which is varied to produce brightness fusion of the two. It was found that brightness values varying between 1 : 3 and 3 : 1 were needed by the two hundred subjects to obtain fusion. It is therefore concluded that the population proportion of red/green cones are also of this order (a conclusion supported by retinal densitometry). This is not made evident in the Rayleigh colour matching technique since this does notdepend upon the relative numbers present but upon the chemical constituents of each.

If the interpretation of the results is correct, and the present writer believes that it is, the method has clearly an important role to play in the research upon those who are defective in colour vision. Experiments along these lines are in progress at Glasgow.

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Colour Measurement with the Spectromat

G. W. Smith

The Spectromat FS 2 is a combination of an abridged spectrophotometer and a tristimulus colorimeter. It can be used for reflectance or transmission measurements between 390 and 710 mμ. Sampling of the spectrum is by means of 25 narrow band interference filters, each filter having a mean band width of 10mμ. Three separate measuring heads are available:

(1) with optical geometry 45/0/ for use with aperture diameters 5-20 mm.

(2) as (1) but for use with aperture diameters 20-70 mm.

(3) with optical geometry Diffuse /0/ for use with aperture diameters 10-60 mm.

Samples are illuminated directly by the light source and reflected (or transmitted) rays are collected by a collimator tube and directed towards a rotating filter disc on which the 25 interference filters are mounted. The filters pass successively through the collected light beam and divide it up into its various spectral parts. The individual spectral parts are converted into electrical impulses by the photomultiplier tube detector. These impulses are amplified before passing to an oscilloscope where they

appear as 25 vertical lines on the screen. The height of each line may be adjusted individually by means of potentiometers.

To operate for reflectance measurements a standard is placed under the aperture in the measuring head and the 25 impulses adjusted so that their heights all correspond to 100% on the scale on the oscilloscope tube. The standard is then exchanged for a sample and the heights of the impulses if plotted against the wavelength of the corresponding interference filter give the spectrophotometric curve of the sample as seen under an equal energy source. If the curve is required under Illuminants A or C the operation of a switch changes each impulse height by means.of built-in resistances to the correct energy distribution. When dealing with dark samples the impulse heights may be multiplied throughout by the factors 2. 4.9 or 9.8 for increased sensitivity.

The C.I.E. distribution functions &, & and & are obtained in the same way as Illuminants A and C and the curves corresponding to E_λ, R_λ, $\&_\lambda$ etc., are obtained on the screen. An integrator which sums the areas under these curves and gives a digital readout of the C.I.E. tristimulus values X. Y and Z is also incorporated.

VALIDITY AND REPRODUCIBILITY

Twenty-four Munsell samples having a gloss finish and measuring 7.5 × 13 cm. were used in the first part. Fourteen of the samples were chromatic and ten were achromatic. Of the 14 chromatic samples 10 had the same value and chroma, i.e. 6/6, and only differed in hue. The remaining four had the same hue and chroma, i.e. 5BG /4, but different value. The achromatic samples were the integer values N 1/ to N 9/ plus 9.5/. The chromaticity co-ordinates x and y of these samples as calculated by the Munsell Color Co. Inc. from reflectance curves obtained on their G. E. spectrophotometer, using 118 selected ordinates, were known.

Measurements were made on these samples with the Spectromat, with a Colormaster Mk. V colorimeter and with a Beckmann DK 2 recording spectrophotometer, and the chromaticity coordinates x and y calculated from these measurements. On the Spectromat the measurements were made under Illuminant C using 45/0/ geometry, a 10 mm. diameter aperture and with a pressed barium sulphate plaque as standard. Measurements were made over a period of 10 months. The reflectance curves on the Beckmann were drawn using a white tile standard and geometry 0/ Diffuse. The tristimulus values were calculated by the weighted ordinate method using 32 ordinates. Measurements with the Colormaster and the Beckmann were done once only on the chromatic samples.

The second part of the investigation was prompted by the paper of Robertson and Wright.2 The samples used were the four grey tiles corresponding to those used by Robertson, i.e. a near white (11572), a light grey (9862), a dark grey (9855) and a near black (11616) corresponding to Munsell samples N 9.5/, N 8/, N 6/ and N 3/, Measurements of the tristimulus values were made with the Spectromat on each tile over a period of 5 months. These measurements can be divided into four groups, all measured under Illuminant C:

(1) using 45/0/ geometry, a 10 mm. diameter aperture and with a pressed barium sulphate plaque as standard,

(2) as (1) but with magnesium oxide

powder pressed in a patent hand press as standard,

(3) as (2) but with a 30 mm. diameter aperture, and

(4) as (3) but with Diffuse /0/ geometry.

The tristimulus values were also measured on the Colormaster. The spectrophotometric curves of the tiles were measured three times on the Spectromat with conditions as in (2), (3) and (4) above. Spectrophotometric curves were also taken for the three darkest tiles using 11572 as standard and other conditions as before.

The Pretema Spectromat FS-2 82

RESULTS

The results obtained with the Munsell samples showed that the greatest differences in chromaticity co-ordinates between the Spectromat and the G.E. were for the darkest samples, 5BG 2/4 and N 1/ and were •0577 and •0386 in x and -0142 and •0252 in y respectively for the two samples. If the results for 5BG 2/4 and 5BG 3/4 are omitted the average differences in x and y are -0043 and •0074 for the chromatic samples. Similarly for the Colormaster and the Beckmann the differences from the G.E. in x and y are •0125 and -0085 and •0075 and •0088 respectively.

For the achromatic samples if the results for N 1/ are omitted the average differences between the Spectromat and the G.E. are •0020 and -0031 in x and y respectively. The maximum discrepancies between the results obtained on the Spectromat were -0211 and -0204 in x and y respectively. The average discrepancies from the mean Spectromat values were •0021 and -0020 in x and y for all 24 samples.

The reflectance curves of the tiles both with magnesium oxide and tile 11572 as standard fell well within the spread of Robertson's curves. The results obtained on the Colorimeter were basically the same as

Robertson's, except for 11616. The average discrepancies from the mean Spectromat results were •0012 and •0007 for x and y respectively for the 45/0/ results, and •0008 and •0003 for x and y respectively for the integrating sphere results.

VALIDITY OF THE RESULTS

The results obtained on the 14 Munsell chromatic samples show that the agreement of the Spectromat with the G.E. leaves much to be desired. However, the results from the Colormaster and the Beckmann show no better agreement with G.E. or in fact with the Spectromat or each other. Results published for other instruments show errors of similar magnitude.[3, 4]

The agreement on the Munsell achromatic samples is much better, as would be expected.

The chromaticity co-ordinates obtained for the tiles disagree with Robertson's results to the extent of more than two standard deviations. This is very surprising in view of the agreement of the reflectance curves. All the instruments used in Robertson's survey agree with one another within very fine limits, but not so the Spectromat.

Factors which could affect the validity of the Spectromat results are (1) the method of computing the tristimulus values,5 (2) differences in the optical geometry, (3) variability in the white standards used and (4) a fault in the tristimulus integrator.

REPRODUCIBILITY

The reproducibility of the results is fairly good compared with other instruments except when very dark samples are measured.[6]

Factors which could affect the reproducibility are: the difficulty in setting-up the impulses on the oscilloscope screen to exactly 100%, and difficulty in reproducibility of the surface of the barium sulphate plaque which is renewed by scraping.

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A Comparison of Adams Chromatic Value and 1964 C.I.E. Uniform Colour Space Co-ordinates

J. R. Bell

These two uniform colour space coordinate systems are defined from tristimulus values X, Y, Z as follows:

(1) *Adams Chromatic Value:*

Lightness $L=50\left(0\cdot 23V_y\right)$

$$\frac{X}{X_{MgO}}=f\left(V_x\right)$$

Chromaticity $\begin{cases} a=50\left(V_x-V_y\right) \\ b=50\left[0.4\left(V_z-V_y\right)\right] \end{cases}$

where $Y=f(V_y)$

$Z/Z_{MgO}=f(Vz)$

and $f(V)= 1.2219V-0.2311V^2+ 0.23951V^3-0.021009V^4+0.0008404V^5$; XMgO, ZMgO being the tristimulus value for MgO for the Illuminant under consideration.

Some workers have taken a factor other than 50 in defining L, a, b.

(2) *1964 C.I.E. System*

Lightness $W=25Y^{\frac{1}{3}}-17$

Chromaticity $\begin{cases} U=13W\left(u-u_0\right) \\ V=13W\left(v-v_0\right) \end{cases}$

where $$u=\frac{4X}{X+15Y+3Z}$$

and $$v=\frac{6Y}{X+15Y+3Z}$$

and (u.,v.) are the (u,v) co-ordinates of some achromatic colour placed at the origin of the (U,V) system.

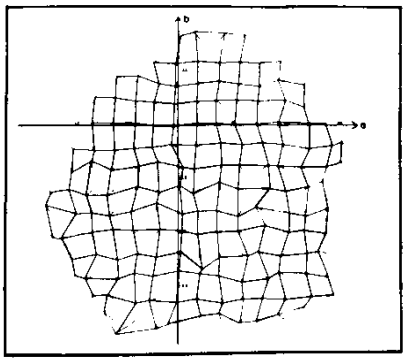

Fig 1. Dyeings 8 N.B.S. (Adams) units apart positioned in Adams a-b space.

The Adams co-ordinates have been used as the basis of the spacing for cubic lattices or grids of precalculated dye recipes on various classes of sewing threads[1] The 1964 C.I.E. system may become widely adopted and an examination of it was made, both from theoretical considerations and preparation of physical samples, to determine its characteristics and advantages, if any, relative to the Adams system.

From theoretical considerations, the following features are evident:

(1) Lightness scales L & W are to all practical purposes the same, differing only by a constant factor (L=1.15W).

(2) Neutral origins of the two systems coincide at Illuminant C.

(3) U axis (red—green) corresponds approximately to a

(4) V axis (blue—yellow) corresponds approximately to b, but with opposite sign.

(5) A change in V for positive V is equivalent to a much bigger change in b; by as much as a factor of 3 in the bright yellow region.

(6) A change in U is equivalent to a slightly smaller change in a.

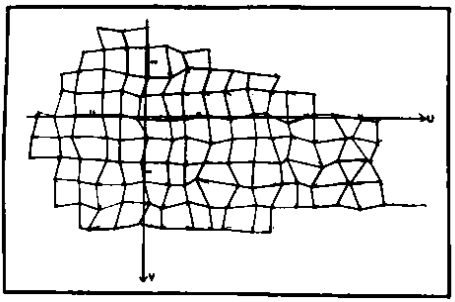

Fig. 2. Dye ngs 8 N.B.S. (1964 C.I.E.) units apart positioned in 1964 C.I.E. u, v space

Lattices of dye recipes for vat dyes on mercerised cotton sewing thread were calculated by digital computer, spaced at 8 units apart in the two co-ordinate systems, for constant lightness planes L=60 and W=52.[2] Such computer recipes are subject to various sources of error and, when measured and plotted in the two systems, there are distortions from the ideal square lattice. Recently these samples from computer recipes have been corrected so that each sample is within 3 N.B.S. units of its target value and the corrected samples are shown in figures 1 and 2. These graphs illustrate the relative spacing of the two systems in the various regions of colour and the general features (5) and (6) referred to previously, but the best impression is obtained from inspection of the samples. We are hoping to carry out some visual comparisons with these samples to assess the uniformity within each and between the two systems.

Using data taken from a paper by Wyszecki & Wright,[3] it can be shown that the Adams system correlates as well as the 1964 C.I.E. system in interpreting visual colour differences. However, the colour differences involved are large (mostly over 10 N.B.S. units and in the 20-60 N.B.S. unit region) and, I feel, not relevant to the order of colour difference of interest to us in grids of recipes and colour control in textiles.

Our opinion is that the 1964 C.I.E. system offers no advantage over the Adams and does not merit alteraf on of the basis of our grids of recipes.

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The Accuracy of Colour Measurement

J. M. Adams

The C.I.E. system for colour specification was issued in 1931, and within four years investigations into the accuracy of colorimetry were under way. Most of the early work concerned specifications calculated from spectrophotometric measurements, and investigated the effect of errors in measurement, and the number of ordinates required to achieve a given accuracy when using the weighted or selected ordinate methods for integrating the spectrophotometric curve.

With the introduction in the 1950s of photoelectric colorimeters, the effect of appreciable errors in the integration became important. The combination ofthe spectral emission of the colorimeter lamp, the spectral transmissions of the filters and the spectral sensitivity of the photocell forms effectively an analogue computer giving the tristimulus values from the reflectance readings. Owing to limitations of available components, the combination of spectral distributions is only an approximation to C.I.E. requirements, and the departures from C.I.E. requirements cause inaccuracy.

However, so long as the spectral distributions of the colorimeter components remain constant, the error will be constant. Thus although it may be difficult to make a colorimeter which will give a correct result it is possible to make one which will give its wrong answer with extreme consistency. It has been argued that for many applications this very high precision is adequate, and may be more important than fairly high accuracy.

All reflectometers give measurements relative to some standard, so the accuracy of the measurement will depend on the accuracy of the standard used. Traditionally the ultimate standard is taken as a freshly smoked magnesium oxide layer, and this is assumed to have a reflectance of 100% at all wavelengths. In fact, the reflectance of magnesium oxide depends on its method of preparation, and may vary by 2 or 3 per cent.

The effect of reference standards once again brings up the question of whether the requirement is for accuracy or precision. An incorrectly calibrated but stable reference standard will cause an error. But this error will be constant, and it is still possible to make colour difference measurements with a high degree of precision.

Most coloured materials scatter light in all directions, but the extent to which the light is scattered and the direction in which it is scattered varies with the texture of the material. A practical colour measurement is a sampling of this distribution, with the angles of illumination and viewing being fixed by the construction of the instrument used. The variation in optical geometry between instruments appears to be the biggest single factor contributing to the disagreement among them.

Inaccuracy has been considered above as departure from C.I.E. specifications. When we come to optical geometry, we are faced with imprecision in the C.I.E. specifications themselves. The C.I.E. recommendations are illumination at 45/ with normal viewing, or normal illumination with viewing at 45/, and infer that these two conditions are equivalent. This is not necessarily so. In any case samples are in practice not illuminated by single rays of light and there is no

mention by the C.I.E. of the limiting angular dimensions of the incident and reflected beams.

Most recent work has taken the form of direct comparisons between commercial instruments. If such an investigation is sufficiently comprehensive, the individual contributions to inaccuracy ofcomputation, geometry and reference standard can be inferred. But the main result has been the demonstration that accuracy will have to be improved by a factor of ten before colorimetry can be accepted as a practical method of interchanging colour standards.

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