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Colorimetric Analysis of Interference in Colour Television

by

K. HACKING, B.Sc.
(Research Department, BBC Engineering Division)

BRITISH BROADCASTING CORPORATION

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FOREWORD

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CONTENTS

PREVIOUS ISSUES IN THIS SERIES

COLORIMETRIC ANALYSIS OF INTERFERENCE IN COLOUR TELEVISION

SUMMARY

The monograph commences with a study of the effects of perturbing one or more of the primary stimuli in three-primary additive colour systems, and develops formulae for computing the magnitude of these effects. The interpretation of some fundamental relationships in terms of the geometrical configuration of the chromaticity co-ordinates of the primary stimuli on a colour diagram is shown to be useful. These methods are extended to deal with the analysis of colour television systems using the NTSC system* as an example and the concept of transmission primaries. A theoretical reconstruction of the well-known Bailey[1] experiment shows that recent measurements of the visual sensitivity ratio (luminance/chromaticity) for spatial colour variations of sinusoidal form are in substantial agreement with the earlier result obtained for coloured random noise. The method of obtaining these measurements is described in the Appendix.

The relative magnitudes of the luminance and chromaticity fluctuations resulting from two types of noise distribution encountered in picture-generating equipment is discussed. Finally, an attempt is made to assess the limits of failure of the 'constant-luminance' principle in the NTSC system.

1. Introduction

An important consideration in the formulation of any colour television system for broadcasting is its degree of immunity from the kinds of signal interference most likely to occur. Random noise generated by components within the system is often one major cause of picture impairment. Apart from employing the best available electronic devices for signal amplification and detection etc., much can be done to minimize the visual effects of interference by judicious choice of the form of signal coding and bandwidth tailoring in relation to the visual properties of the human eye. The NTSC compatible colour television system is an outstanding example of what can be achieved in this respect and, although perhaps imperfect in several ways, is regarded by many as a compromise solution which would be difficult to improve significantly.

One property of the eye which can be exploited in system design is the difference in visual sensitivity between small fluctuations of luminance and fluctuations of chromaticity. Generally, interference will perturb the luminance and the chromaticity together, so that to compare the degree of susceptibility to interference of one system with another it is essential to know, not only the magnitude of the interference relative to the signal but, also, the relative magnitudes of the luminance and chromaticity perturbations which result. It is the latter consideration which underlies the colorimetric analysis attempted in this monograph. We begin with the derivation of some general properties of three-colour additive systems.

2. Some Colorimetric Properties of Three-Primary Additive Systems

2.1 *Real Primaries*

To be specific in the first instance, suppose that we have a source of coloured light formed by the superposition of three component (primary) sources which we may denote in what follows by the subscripts 1, 2, and 3. The luminance and chromaticity of each of the primary stimuli may be specified in terms of three reference stimuli (U), (V), (W). Let the trichromatic amounts of the component sources be:

$$\left.\begin{aligned} \Sigma_1 &= U_1 + V_1 + W_1 \\ \Sigma_2 &= U_2 + V_2 + W_2 \\ \text{and}\qquad \Sigma_3 &= U_3 + V_3 + W_3 \end{aligned}\right\} \qquad (1)$$

U_j, V_j, and W_j are the trichromatic amounts of the chosen reference stimuli and Σ_j is their sum. It is convenient to choose the reference stimuli recently adopted by the C.I.E., having the property that the (u, v) chromaticity diagram associated with these reference stimuli is approximately uniform. However, all we need to note about this reference framework here is that the V_j value is directly proportional to the luminance of the colour and that U_j, V_j, and W_j have positive values for real colours.

Having specified the trichromatic amounts of the three component light sources, the trichromatic amount of the additive mixture of these components is clearly, from the relations (1) above

$$\Sigma_m = \Sigma_1 + \Sigma_2 + \Sigma_3$$

i.e.

$$\Sigma_m = (U_1 + U_2 + U_3) + (V_1 + V_2 + V_3) + (W_1 + W_2 + W_3)$$

or

$$\Sigma_m = U_m + V_m + W_m$$

where the subscript m denotes the mixture colour.

Suppose that the trichromatic amounts of the three components are altered by the small amounts $\triangle_1$, $\triangle_2$, and $\triangle_3$ respectively (thus Σ_1 becomes $\Sigma_1 + \triangle_1$, etc.), then it may be expected that the new mixture colour will, in general, differ in both luminance and chromaticity from

* The general results given in this monograph will apply also to the PAL modification of the NTSC system if the same transmission primaries are used.

the original mixture colour. Let the fractional change in luminance be $\delta V/V$ and the shift in chromaticity be $\delta(u, v)$, then by definition we have, where u and v are the normalized chromaticity co-ordinates:

$$\frac{\delta V}{V} = \frac{V_{m'} - V_m}{V_m} \tag{2}$$

and
$$\delta(u, v) = \{(u_{m'} - u_m)^2 + (v_{m'} - v_m)^2\}^{\frac{1}{2}} \tag{3}$$

where the subscript m′ refers to the new mixture colour.

Putting the expressions (2) and (3) in terms of the chromaticity co-ordinates of the primaries and their trichromatic increments we obtain:

$$\frac{\delta V}{V} = \frac{\Delta_1 v_1 + \Delta_2 v_2 + \Delta_3 v_3}{v_m \Sigma_m} \tag{4}$$

$$\delta(u, v) = \frac{1}{\Sigma_{m'}}\{[\,\Delta_1(u_1 - u_m) + \Delta_2(u_2 - u_m) + \Delta_3(u_3 - u_m)]^2 + [\,\Delta_1(v_1 - v_m) + \Delta_2(v_2 - v_m) + \Delta_3(v_3 - v_m)]^2\}^{\frac{1}{2}} \tag{5}$$

These general expressions become simplified in some special cases which it is instructive to consider.

(a) Perturbation of one Primary

To consider the simplest situation, suppose that the trichromatic amount of only one of the three components of the additive mixture is altered by an amount Δ_j. The expressions (4) and (5) then reduce to

$$\frac{\delta V}{V} = \frac{\Delta_j v_j}{v_m \Sigma_m}$$

and
$$\delta(u, v) = \frac{\Delta_j}{\Sigma_{m'}}\left[(u_j - u_m)^2 + (v_j - v_m)^2\right]^{\frac{1}{2}}$$

where the subscript j denotes the particular primary perturbed. The ratio of the relative change in luminance, $\delta V/V$, to the shift in chromaticity $\delta(u, v)$ is given by

$$\frac{\delta V/V}{\delta(u, v)} = \left(\frac{\Sigma_{m'}}{\Sigma_m}\right)\left\{\frac{v_j}{v_m[(u_j - u_m)^2 + (v_j - v_m)^2]^{\frac{1}{2}}}\right\} \tag{6}$$

Now if the trichromatic increment Δ_j is small compared with Σ_m the factor $(\Sigma_{m'}/\Sigma_m)$ in equation (6) is close to unity, whence we obtain the approximate relationship

$$\frac{\delta V/V}{\delta(u, v)} \simeq \frac{v_j}{v_m[(u_j - u_m)^2 + (v_j - v_m)^2]^{\frac{1}{2}}} \tag{7}$$

which is seen to be independent of Δ_j.

The equation (7) has a simple geometrical interpretation on a (u, v) chromaticity diagram as may be seen from Fig. 1. On this chromaticity diagram are plotted the chromaticities of three real primaries P_1, P_2, and P_3 and that of an arbitrary mixture colour M (which may be anywhere within the triangle formed by joining P_1, P_2, and P_3). Let A be the ordinate of the primary whose trichromatic amount is altered (P_1 in Fig. 1), B be the chromatic separation between the mixture colour and the perturbed primary and C the ordinate of the mixture colour. Then from equation

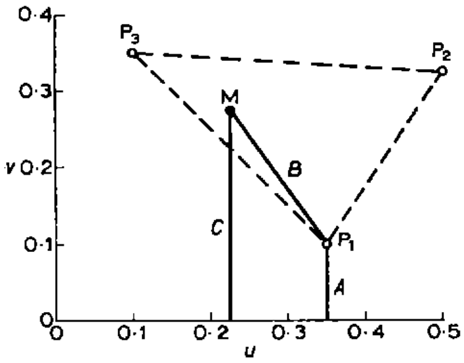

Fig. 1 — Geometrical interpretation on a (u, v) chromaticity diagram of the approximate formula for the ratio $\frac{\delta V/V}{\delta(u, v)}$ when one primary (P_1) is perturbed.

(7) and Fig. 1 ($v_j = A, V_m = C, [(u_j - u_m)^2 + (v_j - v_m)^2]^{\frac{1}{2}} = B$),

$$\frac{\delta V/V}{\delta(u, v)} \simeq \frac{A}{BC} \tag{8}$$

This simple geometrical relationship is useful for calculating the value of the ratio for any position of M within the triangle.

(b) Perturbations of two Primaries

If the trichromatic amounts of two of the primaries are altered by the increments Δ_j and Δ_k respectively we obtain, from the general equations (4) and (5),

$$\frac{\delta V/V}{\delta(u, v)} \simeq \frac{\Delta_j v_j + \Delta_k v_k}{v_m\{[\,\Delta_j(u_j - u_m) + \Delta_k(u_k - u_m)]^2 + [\,\Delta_j(v_j - v_m) + \Delta_k(v_k - v_m)]^2\}^{\frac{1}{2}}} \tag{9}$$

for small Δ_j and Δ_k.

Further, if $\Delta_j = \Delta_k = \Delta$ i.e. if the increments are of equal magnitude and sign, then

$$\frac{\delta V/V}{\delta(u, v)} \simeq \frac{(v_j + v_k)}{[v_m(u_j + u_k - 2u_m)^2 + (v_j + v_k - 2v_m)^2]^{\frac{1}{2}}} \tag{10}$$

which is again independent of Δ. The geometrical interpretation of this situation is similar to that outlined above for the perturbation of one primary if the two primaries perturbed are regarded as being replaced by an effective primary whose chromaticity bisects the line joining the two primaries. This is illustrated in Fig. 2, where it is assumed that P_1 and P_2 are perturbed by equal trichromatic amounts of the same sign: P′ then represents the effective primary for calculating the ratio of $\delta V/V$ to $\delta(u, v)$ using the relation (8).

A slightly different relation arises if the trichromatic increments Δ_j and Δ_k are of equal magnitude but opposite sign, i.e. if $\Delta_j = -\Delta_k = \Delta$. The ratio then becomes

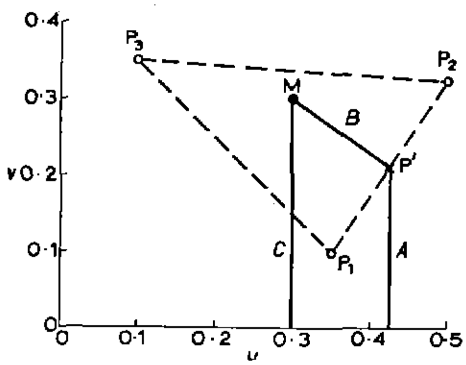

Fig. 2 — Geometrical interpretation on a (u, v) chromaticity diagram of the formula for the ratio $\frac{\delta V/V}{\delta(u, v)}$ when two primaries (P_1 and P_2) are increased or decreased by equal trichromatic amounts.

$$\frac{\delta V/V}{\delta(u, v)} \simeq \frac{(v_j - v_k)}{v_m[(u_j - u_k)^2 + (v_j - v_k)^2]^{\frac{1}{2}}} \qquad (11)$$

Here the second factor in the denominator is the chromatic separation between the primaries perturbed and is thus constant. The ratio is inversely proportional to the v co-ordinate of the mixture colour, but now independent of its u co-ordinate.

2.2 *Transmission Primaries*

Although the relations obtained in Section 2.1 were developed from an example based on the additive mixture of three real primaries they are, in fact, quite general and equally applicable to non-real primaries. The colorimetric properties of a colour television system can often be seen in a simple manner by using the concept of 'transmission primaries' put forward by Howells.[2] As is well known the R, G, and B decoded signal voltages applied to the display tube in a colour receiver control, respectively, the amounts of red, green, and blue (phosphor) primaries synthesizing the reproduced colour. At some earlier stage in the transmission process the three independent signals necessary to specify the reproduced colour may not control, respectively, the amounts of the reproducer primaries. Thus at this stage a perturbation of one of the signals may perturb the amounts of all three reproducer primaries. One can derive, however, an artificial set of primaries termed 'transmission primaries' such that each one of the three signals at that stage in the transmission controls one and only one of the transmission primaries. The transmission primaries obey the same laws of colour mixture as do real primaries. The chromaticities of the transmission primaries, which may be unreal, can be derived from the three equations relating the amounts of the reproducer primaries to the signal voltages at the transmission stage under consideration. If these equations are linear then the chromaticities of the transmission primaries are independent of the reproduced chromaticity. If the equations are non-linear then the chromaticities of the transmission primaries vary with the reproduced colour. To illustrate the above statements consider the transmission primaries of the NTSC colour television system for

(*a*) an ideal system (linear display tube) and
(*b*) the practical system (non-linear display tube).

2.2.1 *Linear System*

In the NTSC system the transmitted signals E_Y, E_I, and E_Q are related to the signals applied to the display tube E_R, E_G, and E_B by the linear transformation (normalized so that if $E_Y = 1$, $E_I = 0$, $E_Q = 0$ then $E_R = E_G = E_B = 1$).

$$\begin{bmatrix} E_R \\ E_G \\ E_B \end{bmatrix} = \begin{bmatrix} 1 & 0{\cdot}956 & 0{\cdot}621 \\ 1 & -0{\cdot}272 & -0{\cdot}647 \\ 1 & -1{\cdot}106 & 1{\cdot}703 \end{bmatrix} \begin{bmatrix} E_Y \\ E_I \\ E_Q \end{bmatrix} \qquad (12)$$

In the ideal case, with a linear display tube transfer characteristic, the signals E_R, E_G, and E_B will be related to the tristimulus values of the reproduced colour by the linear transformation

$$\begin{bmatrix} U_m \\ V_m \\ W_m \end{bmatrix} = k \begin{bmatrix} 0{\cdot}407 & 0{\cdot}116 & 0{\cdot}134 \\ 0{\cdot}299 & 0{\cdot}587 & 0{\cdot}114 \\ 0{\cdot}145 & 0{\cdot}827 & 0{\cdot}629 \end{bmatrix} \begin{bmatrix} E_R \\ E_G \\ E_B \end{bmatrix} \qquad (13)$$

where U_m, V_m, and W_m are the amounts of the C.I.E.–U.C.S.* reference stimuli, respectively, specifying the reproduced colour and k is a constant of proportionality.

Substituting equation (12) in equation (13) gives the relation

$$\begin{bmatrix} U_m \\ V_m \\ W_m \end{bmatrix} = k \begin{bmatrix} 0{\cdot}657 & 0{\cdot}209 & 0{\cdot}406 \\ 1 & 0 & 0 \\ 1{\cdot}601 & -0{\cdot}782 & 0{\cdot}628 \end{bmatrix} \begin{bmatrix} E_Y \\ E_I \\ E_Q \end{bmatrix} \qquad (14)$$

Denoting the transmission primaries by (Y), (I), and (Q) respectively we can obtain their relation to the C.I.E. reference primaries from equation (14) by substituting the values (1, 0, 0), (0, 1, 0), and (0, 0, 1) for the column matrix on the R.H.S. in turn. This leads to†

$$\begin{bmatrix} (Y) \\ (I) \\ (Q) \end{bmatrix} = k \begin{bmatrix} 0{\cdot}657 & 1 & 1{\cdot}601 \\ 0{\cdot}209 & 0 & -0{\cdot}782 \\ 0{\cdot}406 & 0 & 0{\cdot}628 \end{bmatrix} \begin{bmatrix} (U) \\ (V) \\ (W) \end{bmatrix} \qquad (15)$$

The (u, v) chromaticities of the transmission primaries are thus

	u	v
(Y)	0·201	0·307
(I)	−0·364	0
(Q)	0·393	0

Fig. 3 shows the chromaticities of the NTSC transmission primaries plotted on a C.I.E.–U.C. diagram: also plotted are the chromaticities of the reproducer primaries. It will

* Uniform Chromaticity Scale.

† Note that the 3 × 3 matrix in equation (15) is simply the transpose of that in equation (14).

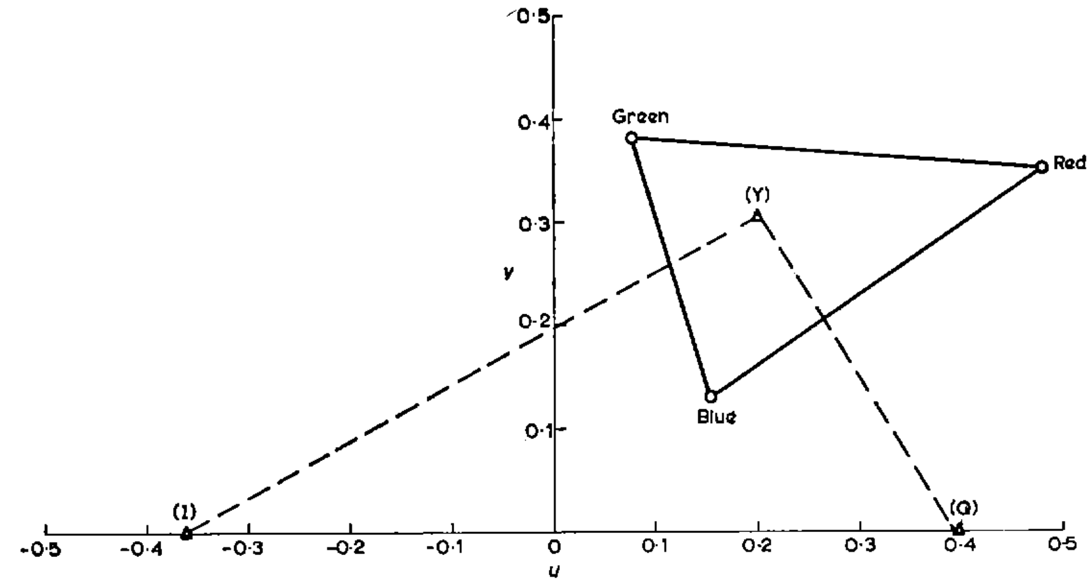

Fig. 3 — Chromaticities of the NTSC transmission primaries and the reproducer primaries plotted on a (u, v) diagram.

be noted that the (I) and (Q) transmission primaries lie on the alychne (i.e. the $v = 0$ axis) and the (Y) primary has the chromaticity of the standard Illuminant C, i.e. the reference white on which the NTSC system is balanced.

Consider now the effect of a perturbation of the (Y), (I), and (Q) primaries, such as may arise from signal interference in the transmission stage for example. If the interference is confined to the chrominance channel so that the amounts of the (I) and (Q) primaries are perturbed, we see from the relation (9) in Section 2.1 that,

$$\frac{\delta V/V}{\delta(u, v)} = 0$$

since the v co-ordinates of the (I) and (Q) transmission primaries respectively are both zero and the denominator in equation (9) is non-zero for all real colours. Consequently, the effect of the interference on the reproduced colour can only be to perturb its chromaticity. This, of course, simply demonstrates the constant-luminance principle on which the NTSC signal formulation is based. One may conclude, therefore, that the only colorimetric condition necessary to achieve a truly constant luminance system is that the chrominance transmission primaries must lie on the alychne for all reproducible colours.

If the interference is confined to the luminance channel, so that only the amount of the (Y) primary is perturbed, then the effect on the reproduced colour will be, in general, to perturb both its luminance and chromaticity. This may be seen from the relation (7) (and Fig. 1), since the numerator is finite and non-zero. An exception occurs when the chromaticity of the reproduced colour coincides with that of the (Y) transmission primary (Illuminant C in the NTSC system). Here the denominator in the relation (7) is zero, hence

$$\frac{\delta V/V}{\delta(u, v)} \to \infty$$

and the interference will affect only the luminance of the reproduced (white) colour.

2.2.2 *Non-linear System*

It is well known that the NTSC system is not a truly constant luminance system. It fails to be so because the transmitted signals are not, in fact, linearly related to the tristimulus values of the reproduced colour (except for neutral greys). If the display tube can be assumed to have a power-law transfer characteristic with an exponent γ, then the relation between the tristimulus values of the reproduced colour and the signals applied to the display tube is

$$\begin{bmatrix} U_m \\ V_m \\ W_m \end{bmatrix} = k \begin{bmatrix} 0{\cdot}407 & 0{\cdot}116 & 0{\cdot}134 \\ 0{\cdot}299 & 0{\cdot}587 & 0{\cdot}114 \\ 0{\cdot}145 & 0{\cdot}827 & 0{\cdot}629 \end{bmatrix} \begin{bmatrix} E_R{}^{\gamma} \\ E_G{}^{\gamma} \\ E_B{}^{\gamma} \end{bmatrix} \quad (16)$$

corresponding to equation (13) in the preceding section. Equation (16) can be restated as follows*

$$\begin{bmatrix} U_m \\ V_m \\ W_m \end{bmatrix} = k \begin{bmatrix} 0{\cdot}407A_R & 0{\cdot}116A_G & 0{\cdot}134A_B \\ 0{\cdot}299A_R & 0{\cdot}587A_G & 0{\cdot}114A_B \\ 0{\cdot}145A_R & 0{\cdot}827A_G & 0{\cdot}629A_B \end{bmatrix} \begin{bmatrix} E_R \\ E_G \\ E_B \end{bmatrix} \quad (17)$$

where $A_R = E_R{}^{(\gamma-1)}$, $A_G = E_G{}^{(\gamma-1)}$, and $A_B = E_B{}^{(\gamma-1)}$. The elements of the transformation matrix are now no longer constant values but functions of the applied signal voltages.

* This treatment is relevant only when the non-linear relationship is a simple power-law.

Substituting equation (12) into (17) leads to the relation

$$\begin{bmatrix} U_{m} \\ V_{m} \\ W_{m} \end{bmatrix} = k \begin{bmatrix} (0{\cdot}407A_{R}+0{\cdot}116A_{G}+0{\cdot}134A_{B}) & (0{\cdot}389A_{R}-0{\cdot}032A_{G}-0{\cdot}148A_{B}) & (0{\cdot}253A_{R}-0{\cdot}075A_{G}+0{\cdot}228A_{B}) \\ (0{\cdot}299A_{R}+0{\cdot}587A_{G}+0{\cdot}114A_{B}) & (0{\cdot}286A_{R}-0{\cdot}160A_{G}-0{\cdot}126A_{B}) & (0{\cdot}186A_{R}-0{\cdot}380A_{G}+0{\cdot}194A_{B}) \\ (0{\cdot}145A_{R}+0{\cdot}827A_{G}+0{\cdot}629A_{B}) & (0{\cdot}139A_{R}-0{\cdot}225A_{G}-0{\cdot}696A_{B}) & (0{\cdot}090A_{R}-0{\cdot}535A_{G}+1{\cdot}071A_{B}) \end{bmatrix} \begin{bmatrix} E_{Y} \\ E_{I} \\ E_{Q} \end{bmatrix} \tag{18}$$

from which we deduce, in the manner described earlier, the relation between the transmission primaries (Y), (I), and (Q) and C.I.E. reference primaries (U), (V), and (W) to be

$$\begin{bmatrix} (Y) \\ (I) \\ (Q) \end{bmatrix} = k \begin{bmatrix} (0{\cdot}407A_{R}+0{\cdot}116A_{G}+0{\cdot}134A_{B}) & (0{\cdot}299A_{R}+0{\cdot}587A_{G}+0{\cdot}114A_{B}) & (0{\cdot}145A_{R}+0{\cdot}827A_{G}+0{\cdot}629A_{B}) \\ (0{\cdot}389A_{R}-0{\cdot}032A_{G}-0{\cdot}148A_{B}) & (0{\cdot}286A_{R}-0{\cdot}160A_{G}-0{\cdot}126A_{B}) & (0{\cdot}139A_{R}-0{\cdot}225A_{G}-0{\cdot}696A_{B}) \\ (0{\cdot}253A_{R}-0{\cdot}075A_{G}+0{\cdot}228A_{B}) & (0{\cdot}186A_{R}-0{\cdot}380A_{G}+0{\cdot}194A_{B}) & (0{\cdot}090A_{R}-0{\cdot}535A_{G}+1{\cdot}071A_{B}) \end{bmatrix} \begin{bmatrix} (U) \\ (V) \\ (W) \end{bmatrix}$$

The chromaticity co-ordinates of the transmission primaries are:

$$\begin{array}{ccc} & u & v \\ (Y) & \left(\dfrac{0{\cdot}407A_{R}+0{\cdot}116A_{G}+0{\cdot}134A_{B}}{0{\cdot}851A_{R}+1{\cdot}530A_{G}+0{\cdot}877A_{B}}\right) & \left(\dfrac{0{\cdot}299A_{R}+0{\cdot}587A_{G}+0{\cdot}114A_{B}}{0{\cdot}851A_{R}+1{\cdot}530A_{G}+0{\cdot}877A_{B}}\right) \\ (I) & \left(\dfrac{0{\cdot}389A_{R}-0{\cdot}032A_{G}-0{\cdot}148A_{B}}{0{\cdot}814A_{R}-0{\cdot}417A_{G}-0{\cdot}970A_{B}}\right) & \left(\dfrac{0{\cdot}286A_{R}-0{\cdot}160A_{G}-0{\cdot}126A_{B}}{0{\cdot}814A_{R}-0{\cdot}417A_{G}-0{\cdot}970A_{B}}\right) \\ (Q) & \left(\dfrac{0{\cdot}253A_{R}-0{\cdot}075A_{G}+0{\cdot}228A_{B}}{0{\cdot}529A_{R}-0{\cdot}990A_{G}+1{\cdot}493A_{B}}\right) & \left(\dfrac{0{\cdot}186A_{R}-0{\cdot}380A_{G}+0{\cdot}194A_{B}}{0{\cdot}529A_{R}-0{\cdot}990A_{G}+1{\cdot}493A_{B}}\right) \end{array}$$

It will be seen, therefore, that when γ is other than unity, i.e. for all but the linear case, the chromaticities of the transmission primaries depend on the reproduced colour.

The chromaticity diagram shown in Fig. 4 illustrates the manner in which the chromaticities of the effective chrominance transmission primaries (I) and (Q) move as the reproduced chromaticity moves from that of the red primary (M_1 in Fig. 4) through the white point (M_w) to the complementary cyan (M_7). All the transmission primaries are coincident with the red primary at the chromaticity of the latter, including the (Y) primary not shown in the diagram. (In fact they are coincident with each of the three primaries, R, G, and B, at its own chromaticity.) As the reproduced colour moves towards the white point the effective transmission primaries move along straight lines towards the positions on the alychne which they occupy when the white point is reached (i.e. the same fixed positions as they occupy in the linear system). Note that the (I) primary reaches its white point position via infinity, and it appears that this is because the (I) and (Q) chromaticities each progress in one direction only but are forbidden to enter the chromaticity gamut of the real reproducer primaries, R, G, and B. As the reproduced colour moves from the white point towards the complementary cyan, the (I) and (Q) chromaticities carry on moving along the same straight lines until finally they are colinear with the cyan chromaticity and the green and blue primaries. Except for the extreme positions of the (I) and (Q) chromaticities, their positional distribution along their straight-line loci depends on the gamma of the system (providing $\gamma \neq 1$). The positions shown in Fig. 4 refer to $\gamma = 2{\cdot}2$. Similar diagrams are obtained for the green-magenta and blue-yellow colour axes.

3. Reconstruction of the Bailey Experiment

An early subjective experiment designed to estimate the possible advantage to be obtained by adopting the constant-luminance principle in a colour television system was reported by Bailey.[1] It is appropriate, in the study of the colorimetric effects of interference in colour television, to examine this important experiment in some detail. The Appendix describes an optical experiment which the writer carried out recently to determine the relative sensitivity of the eye to spatial variations in luminance and chromaticity using a sinusoidal form of variation. The results of this latter experiment can be applied to predict the decrease in sensitivity to interference of the constant luminance system, measured in the same terms as in the Bailey experiment. It may, quite reasonably, be expected that the accuracy of such a prediction would be poor since data obtained from an experiment dealing exclusively with spatial variations are being applied to predict the result of a television experiment which also involves temporal variations. As demonstrated later, however, there is surprisingly good agreement between the predicted and measured results.

The type of interference used in the Bailey experiment was uniform-spectrum random noise and this was applied via an attenuator to the red and green tubes of a three-tube colour monitor, as shown in Fig. 5(a). The red and green tube beam currents were adjusted so that a uniform yellow (white minus blue) colour was displayed in the absence of the random noise. By means of a phase inverter and appropriate switching the noise signal could be applied to the red and green tubes with similar polarity or with opposite polarity. In the opposite-polarity condition the noise signal attenuator R_g in the green channel is adjusted for the minimum perceptibility of the displayed noise: the relative

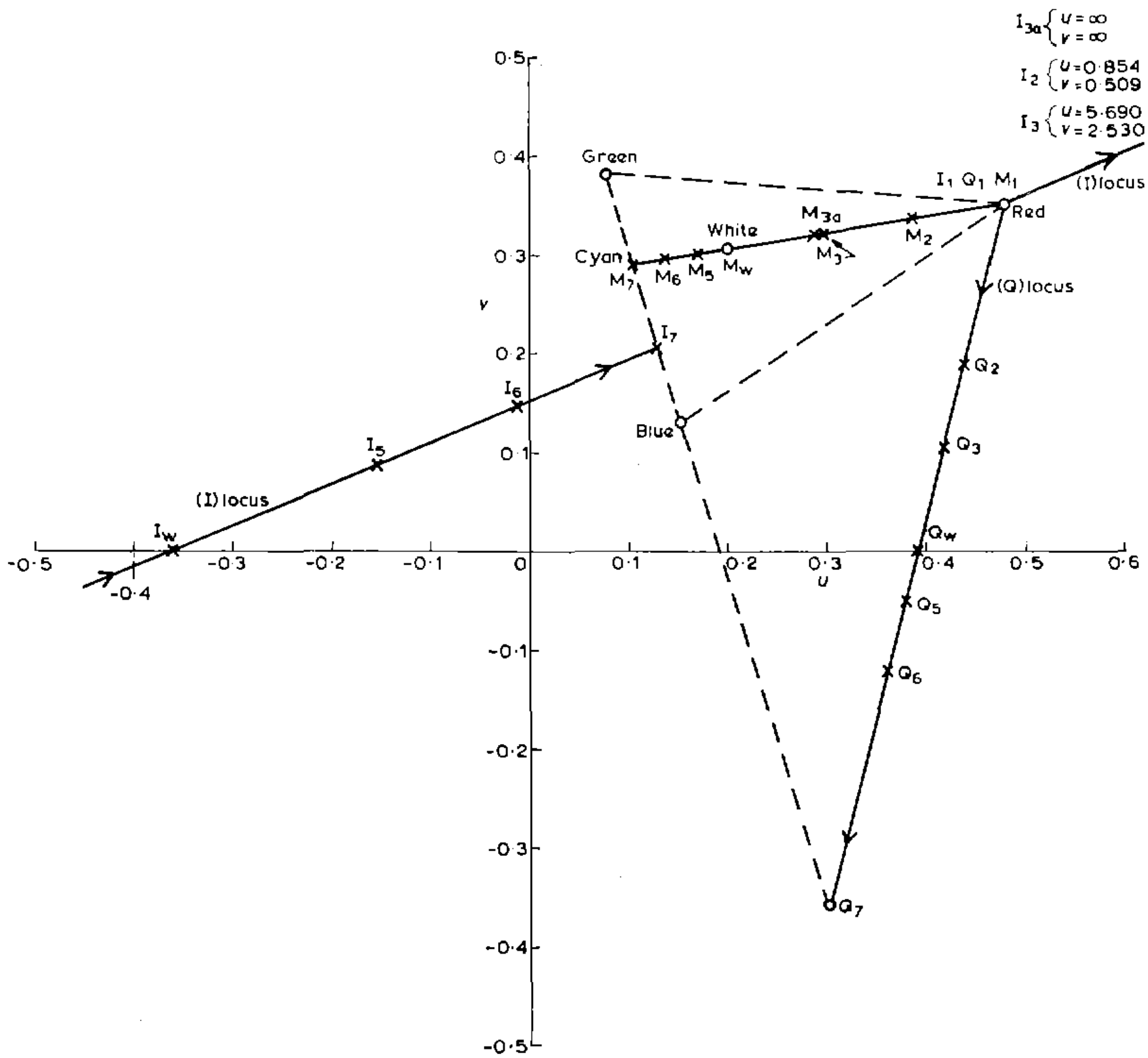

Fig. 4 — The chromatic loci of the NTSC chrominance transmission primaries (I and Q) respectively, for the reproduced colours lying on the red to cyan axis.

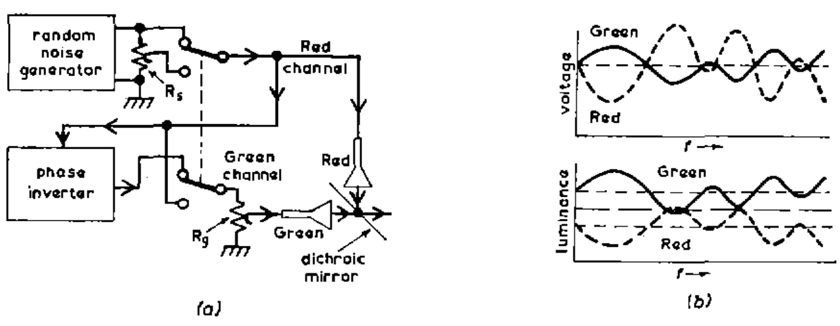

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Fig. 5 — The Bailey Experiment (Fig. 1 in Reference 1).

(*a*) Schematic arrangement of apparatus.

(*b*) Signal fluctuations corresponding to the opposite-polarity condition and minimum perceptibility of noise.

noise voltages applied to the tubes and the luminance perturbations of the display for this setting were found to be as illustrated in Fig. 5(b). In fact, the setting corresponded approximately to a condition of constant total luminance, the colour fluctuations being mainly chromaticity fluctuations.

The switch was then thrown to the similar-polarity condition whereby the displayed fluctuations are mainly luminance fluctuations, and it was found that the noise signal needed to be attenuated (by adjusting R_s) from 6 dB to 8 dB for equivalent visibility of the noise.*

We can deduce from the chromaticities of the red and green tube phosphors, and that of the yellow mixture colour, the relative magnitudes of the luminance-only variations and the chromaticity-only variations corresponding to the two conditions of the Bailey experiment respectively. This theoretical reconstruction of the experiment can be extended to include colours other than yellow.

In the equations which now follow in this section, those which refer to the similar-polarity condition of the experiment are labelled with the suffix A and those which refer to the opposite-polarity condition with the suffix B.

For the similar-polarity condition A of the applied noise signal we obtain, from equations (4) and (5) in Section 2.1

$$\left(\frac{\delta V}{V}\right)_A = \frac{\Delta_r v_r + \Delta_g v_g}{v_m \Sigma_m}$$

and

$$[\delta(u, v)]_A = \left(\frac{1}{\Sigma_m'}\right)\left\{\left[\Delta_r(u_r - u_m) + \Delta_g(u_g - u_m)\right]^2 + \left[\Delta_r(v_r - v_m) + \Delta_g(v_g - v_m)\right]^2\right\}^{\frac{1}{2}}$$

where the suffixes r and g denote the red and green primaries respectively and m that of the (yellow) mixture colour. The $\triangle$'s in these expressions are instantaneous increments in the trichromatic amounts of the primaries and for this condition they will have the same sign.

Similar expressions are obtained for the opposite-polarity noise condition B thus, assuming that the incremental magnitudes remain unchanged

$$\left(\frac{\delta V}{V}\right)_B = \frac{\Delta_r v_r - \Delta_g v_g}{v_m \Sigma_m}$$

and

$$[\delta(u, v)]_B = \left(\frac{1}{\Sigma_m'}\right)\left\{\left[\Delta_r(u_r - u_m) - \Delta_g(u_g - u_m)\right]^2 + \left[\Delta_r(v_r - v_m) - \Delta_g(v_g - v_m)\right]^2\right\}^{\frac{1}{2}}$$

While in condition B, the noise signal applied to the green tube was attenuated with respect to the red tube until approximately constant luminance in the display was obtained, i.e. until $\left(\frac{\delta V}{V}\right)_B \simeq 0$. This is achieved when

$$\Delta_g = \left(\frac{v_r}{v_g}\right)\Delta_r$$

Substituting this relation into the expression for $[\delta(u, v)]_B$ gives,

$$[\delta(u, v)]_B = \left(\frac{\Delta_r}{\Sigma_m'}\right)\left\{\left[(u_r - u_m) - \left(\frac{v_r}{v_g}\right)(u_g - u_m)\right]^2 + \left[v_m\left(\frac{v_r}{v_g} - 1\right)\right]^2\right\}^{\frac{1}{2}}$$

If the switch is now thrown to the similar-polarity condition (without attenuating the input noise voltage) we obtain

$$\left(\frac{\delta V}{V}\right)_A = \frac{2\Delta_r v_r}{\Sigma_m v_m}$$

and

$$[\delta u, v)]_A = \left(\frac{\Delta_r}{\Sigma_m'}\right)\left\{\left[(u_r - u_m) + \left(\frac{v_r}{v_g}\right)(u_g - u_m)\right]^2 + \left[2v_r - v_m\left(\frac{v_r}{v_g} + 1\right)\right]^2\right\}^{\frac{1}{2}}$$

In this condition it should be noted that both luminance and chromaticity perturbations will be produced in the display since $[\delta(u, v)]_A$ is not, in general, zero. However, for the two NTSC phosphor primaries (red and green) combining to give the yellow mixture colour used in the original Bailey experiment $[\delta(u, v)]_A$ is sufficiently small to be ignored in comparison with $(\delta V/V)_A$.

The above expressions refer to shifts in luminance and chromaticity for small instantaneous increments in the amounts of the primaries. Since random noise was used in the original experiment, the increments were, in fact, random functions of time. This presents no analytical difficulty if the root mean square value of the increments due to the applied noise signal is small compared to the trichromatic amount of the mixture colour. With this restriction $\triangle_r$ can be regarded as a time-averaged (r.m.s.) magnitude of the increments and directly proportional to the applied r.m.s. noise voltage. The relationship of interest in this analysis is the ratio of $(\delta V/V)_A$ to $[\delta(u, v)]_B$, since these are the major components of the colour fluctuations for the two conditions of the experiment respectively. From the expressions derived above, we have

$$\frac{(\delta V/V)_A}{[\delta u, v)]_B} \simeq \frac{2\left(\frac{v_r}{v_m}\right)}{\left\{\left[(u_r - u_m) - \left(\frac{v_r}{v_g}\right)(u_g - u_m)\right]^2 + \left[v_m\left(\frac{v_r}{v_g} - 1\right)\right]^2\right\}^{\frac{1}{2}}}$$

Substituting in this expression the values of the chromaticity co-ordinates for the red and green (NTSC) primaries and their mixture colour we obtain

$$\frac{(\delta V/V)_A}{[\delta(u, v)]_B} \simeq 4 \cdot 8$$

* A similar technique has been recently used by Schade[9] to measure the sine-wave frequency response of the eye to chromaticity-only variations.

Values of this ratio for several other combinations of the NTSC primaries and their complementaries yield the results shown in the first row of Table 1 below. It should be pointed out here that the calculated ratios quoted in the first row of Table 1 ignore the chromaticity component $[\delta(u, v)]_A$ which would accompany the luminance component $(\delta V/V)_A$ in condition A of the experiment. As already mentioned, the chromaticity component is negligible compared to the luminance component for the yellow mixture colour. For the other colours listed in Table 1 $[\delta(u, v)]_A$ is reasonably small except for the magenta (red and blue primaries). In the latter case it is expected that the effective ratio would be somewhat greater than that quoted in Table 1 because of the chromatic contribution to the noise. In the second row of this table are shown the corresponding values of the visual sensitivity ratio, expressed in the same terms, i.e. $(\delta V/V)/\delta(u, v)$, relating to the perception of spatial sinusoidal variations of luminance and chromaticity. These values are derived from the results of a recent investigation by the author, details of which are given in the Appendix. Assuming that these sensitivity ratios apply to random perturbations also, we can deduce the attenuation of the input noise in condition A of the Bailey experiment that would be required to produce equivalent visibility with condition B, for the various mixture colours (shown in Table1) respectively. The estimated attenuations required, for the various colours respectively, are shown in the third row of Table 1. These attenuations may be regarded as the maximum advantage of constant luminance working with respect to interference sensitivity.

The measured improvement in noise sensitivity for the yellow mixture colour reported by Bailey was 6 dB to 8 dB, which appears to be in agreement with that predicted by the above analysis. This is rather remarkable in that the present analysis is based on results obtained with spatial sinusoidal variations (6·7 cycles/degree, 2° field) in contradistinction to the random spatial and temporal variations which are characteristic of displayed noise. It is interesting to note from Table 1 that the improvement at the white point (Illuminant C) is estimated to be of the same degree, in fact 1 dB to 2 dB greater for the green-magenta axis, and this is the chromatic region where the constant luminance principle does not fail in the NTSC system, so that the full advantage can be obtained.

The somewhat reduced advantage seen for the magenta colour is more apparent than real because, as previously pointed out, in condition A of the reconstructed Bailey experiment there would exist a strong chromatic component in addition to the luminance component for this colour.

Optical studies of the visual sensitivity ratio* indicate that the benefit to be obtained from the adoption of the constant luminance principle increases as

(*a*) the level of the interference decreases;

(*b*) the absolute luminance level decreases for a given reproduced chromaticity;

(*c*) the viewing distance is increased for a given interference pattern, or alternatively, the frequency of the interference pattern is increased for a given viewing distance.

4. Interference in the NTSC System

4.1 *Random Noise at the Picture Source*

The inevitable random noise accompanying the three

* See Appendix.

TABLE 1

	Mixture colour and axis of chromatic variation				
	Yellow	*Cyan*	*Magenta*	*White (Illuminant C)*	
	Red to green	*Green to blue*	*Blue to red*	*Green to magenta*	*Red to cyan*
$\frac{(\delta V/V)_A}{[\delta(u, v)]_B}$	4·8	4·4	4·2	7·0	5·8
Visual sensitivity ratio*	JP 1·9	2·0	2·4	2·1	2·4
ϕ	DP 2·5	2·5	3·2	3·1	3·0
Estimated maximum advantage of constant luminance working	JP 8·0 dB	6·8 dB	4·9 dB	10·4 dB	7·7 dB
(decibels)	DP 5·7 dB	4·9 dB	2·4 dB	7·0 dB	5·7 dB

* Subjective results for spatial sinusoidal variation (6·7 cycles/degree, 2°field) where $\phi = \frac{\delta V/V}{\delta(u, v)}$ is the ratio obtained experimentally for equivalent visibility of luminance-only and chromaticity-only perturbations. (See Appendix, Section A3.)

JP – just perceptible level of visibility. DP – definitely perceptible level of visibility.

(or more) signal outputs from a colour camera or film scanner, may be of sufficient magnitude to perturb, visibly, all or part of the colour picture displayed. We will consider here only a triple-output picture-signal generating device in which the outputs are accompanied by random noise which is not correlated between any two outputs. The three signal outputs, or a linear transformation of them, will control the luminous outputs respectively of the fixed-colour phosphors in the reproducer, and be such as to give a visually acceptable synthesis of the particular colour being transmitted. The accompanying random noise will, in general, perturb the colour both in luminance and chromaticity. Ignoring, for simplicity, the effects of 'cross-colour' noise due to cross-talk within the system, we can estimate the relative subjective magnitudes of these two types of colour perturbation in the final display using the methods outlined earlier in Section 2 and the results of subjective measurements of the average-observer visual sensitivity ratios. In view of the apparent substantial agreement in magnitude between these ratios and that obtained by the foregoing analysis of the Bailey experiment, it seems reasonable to apply them to the noise and interference studies which follow.

4.1.1 *Colour Cameras*

In the most usual situation the three signal outputs from the camera tubes are E_R, E_G, and E_B, and are (approximately) directly proportional to the luminous outputs of the red, green, and blue reproducer phosphors respectively. Hence, considered as effective transmission primaries, these signals will have chromaticities coincident with those of the (real) reproducer primaries for all reproducible colours. In a colour camera using image orthicon tubes or Plumbicon tubes, each signal will be accompanied by random noise, which may be considered to be of constant power i.e. substantially independent of the signal level. By assuming that the signal-to-r.m.s. noise ratio is the same at each of the three camera outputs for the white-point (Illuminant C) (this is usually true for image orthicons, but not for Plumbicons), the relative distributions of the resulting luminance-noise and chromatic-noise with reproduced colour are shown in Fig. 6. In this figure the relative magnitude of each component is plotted against saturation* for the three primary colour-axes, green-magenta, red-cyan, and blue-yellow respectively: the full lines refer to the luminance-noise component and the dashed lines to the chromatic-noise component. In order to indicate, approximately, the relative visual magnitudes of the components by the ratio of their ordinates in the figure it has been assumed (for simplicity) that the average-observer visual sensitivity ratio $\frac{\delta V/V}{\delta(u, v)}$ is $2\cdot5:1$ for all chromaticities. Thus equal ordinate values would imply equal visibilities of the two components, viewed separately.

* Saturation is defined here as the ratio of the chromatic separation of the reproduced colour from Illuminant C to the maximum chromatic separation possible in the same direction, on the Uniform Chromaticity Scale. Thus all colours lying on the R, G, B triangle have unit saturation.

It should be pointed out that the visual sensitivity ratio does, in fact, increase with increasing magnitude of the perturbations.† Hence, referring to Fig. 6, toward the saturated blue and red colours, where the noise levels appear to increase markedly, too little weight has been given to the chromatic component in these regions by assuming a constant visual sensitivity ratio. Also, no account has been taken of variations of the ratio with luminance level. Hence the diagrams shown indicate the relative visibilities of the two components for noise levels of such magnitude that, for a given reproduced colour, the chromatic-noise alone would be in the just perceptible class. It should be mentioned also that the analysis refers to the lower-frequency spectral components of the random noise, i.e. within the chrominance bandwidth.

It will be seen from Fig. 6 that the luminance-noise is the visually-dominant component of the displayed noise. However, although this is true for the combined effect of the assumed equal-magnitude noise contributions from the three channels, it does not follow that it is true for each channel separately. For example, if the blue channel signal-to-r.m.s. noise ratio is very much worse than that of the other two channels, it can be shown that for saturated green, yellow, red, and magenta colours the dominant component is likely to be that of chromatic noise. Fig. 7, for example, shows the chromatic region (hatched area) where perturbations of the blue signal produce chromatic variations which are expected to be more visible than the luminance variations.

It is customary, when carrying out quantitative noise assessments of colour cameras, to weight the r.m.s. noise contributions of each channel corresponding to the relative luminosities of the reproducer phosphors which they control, namely $0\cdot3$, $0\cdot59$, $0\cdot11$ for the standard NTSC red, green, and blue phosphors respectively. This is a justifiable procedure when the luminance component of the displayed noise is in the just perceptible class since, as may be seen from Fig. 6, the chromatic component of the noise must be sub-threshold (with the possible exception of highly saturated red colours). However, for camera noise levels of greater magnitude the resulting chromatic perturbations may be visually significant, and the channel weighting coefficients need modification. Fig. 8 shows the degree of modification necessary when the chromatic component of the displayed noise is in the just perceptible class. The column of figures at various points around the two-thirds saturation locus of the NTSC chromaticity gamut and at the white point, represents the modified noise-weighting coefficients for the red, green, and blue channels respectively. It will be seen from the figure that the blue-channel noise should be accorded significantly greater weight than would be assumed from its relative luminosity coefficient) over most of the diagram, especially in areas remote from the blue. For instance, in the saturated red region the blue channel noise is not quite so insignificant as one usually imagines it to be.

† See Appendix: footnote to Section A3.2.

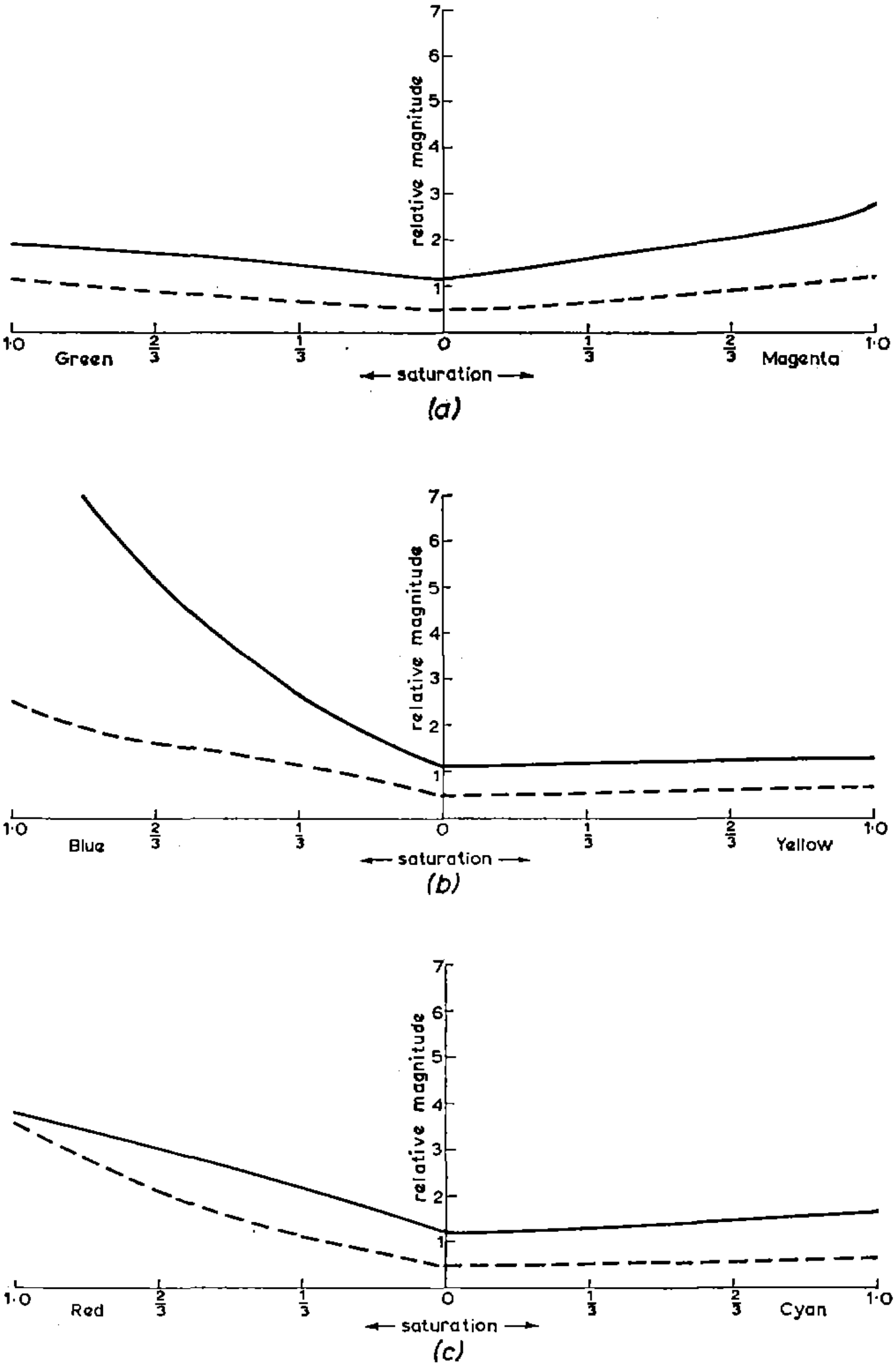

Fig. 6 — Colour camera noise: the relative distributions of the displayed noise with reproduced colour.

(——) luminance-noise component.
(– – –) chromatic-noise component.
(*a*) Green-magenta axis.
(*b*) Blue-yellow axis.
(*c*) Red-cyan axis.

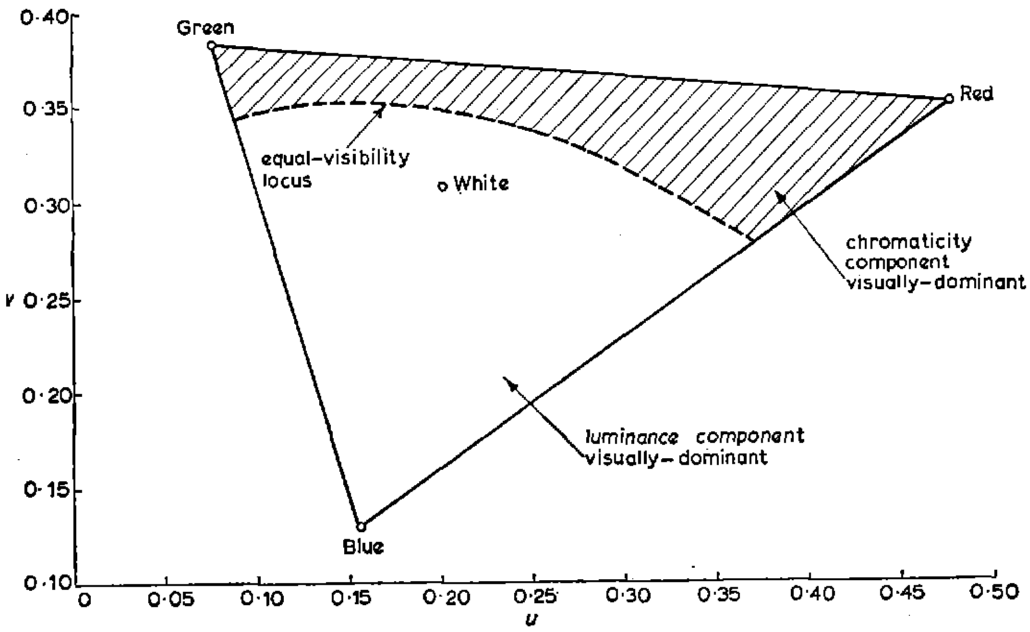

Fig. 7 — Chromaticity diagram showing the equal-visibility locus for the chromaticity and luminance variations produced when the blue signal is perturbed.

4.1.2 *Colour-film Scanners*

The random noise accompanying the outputs from photomultipliers in a flying-spot colour-film scanner is not of constant r.m.s. magnitude but varies approximately with the square root of the signal current. If, as previously, we assume for the sake of simplicity, although it is not generally true, that the signal-to-r.m.s. noise ratios of the three photomultiplier outputs (red, green, and blue) are equal at the white point the variation in the relative magnitudes of the luminance and chromatic components of the displayed noise over the colour gamut will now differ somewhat from that of the previous case considered (see Fig. 6). In general, the visual magnitude of the chromatic component relative to the luminance component is less than that which obtains for noise of constant magnitude. In fact, as the highly saturated primary colours are ap-

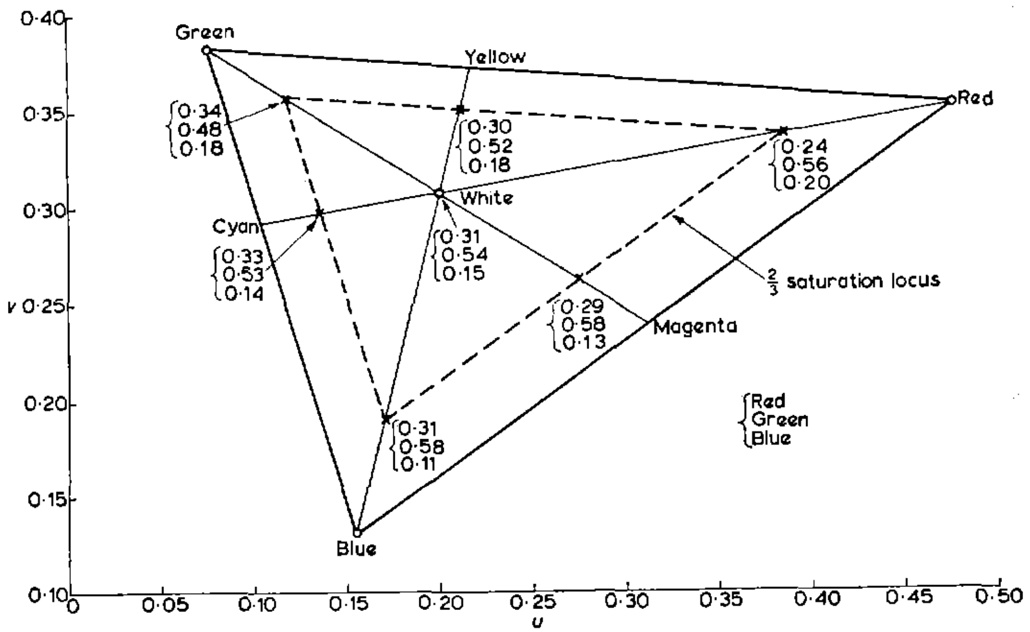

Fig. 8 — Noise-weighting coefficients for colour camera channels.

proached the chromatic component becomes negligible.

The relative contributions of the noise accompanying each of the R, G, and B scanner outputs to the total noise displayed (including chromatic noise) varies widely with the chromaticity of the reproduced colour. Fig. 9 shows the relative noise-weighting coefficients for the red, green, and blue channels respectively at various chromaticities around the two-thirds saturation locus and at the white point. Comparing Fig. 9 with Fig. 8 it will be seen that the noise from the green channel is now no longer the dominant member over the whole colour gamut, as is the case for channel noise of constant power. In the saturated red and magenta regions, for instance, the noise in the red channel is of the greatest import, although the green-channel noise contribution is still large. The blue-channel noise has a relatively low weighting for all colours except those very close to blue primary itself. Hence, in a colour-film scanner, great attention should be paid to obtaining the highest possible signal-to-noise ratios in the red channel as well as in the green channel. Unfortunately, in actual flying-spot colour scanners it is the red-channel output which is usually the noisiest because of the lower available energy in the red portion of the emission spectrum of the scanning tube.

4.2 *Perturbations of the Chrominance Signals*

Apart from the source-noise considered above, three forms of signal interference, different in character, are likely to be present in the chrominance channel of the NTSC receiver, and thus accompany the chrominance signal applied to the synchronous detector. These are:

(*a*) Random noise added in the receiver input stages. This will lead to different distributions of displayed noise over the colour gamut than that due to source noise, since the transmission primaries (Y), (I), and (Q) at this stage are different from the source primaries.

(*b*) Co-channel interference producing a cyclic perturbation of the I and Q signals. The perturbations will be in phase quadrature after synchronous detection if the frequency difference between the colour sub-carrier and the interfering carrier falls within the Q channel bandwidth. The resulting displayed spatial variations in chromaticity will therefore follow chromatic loci which are, in general, ellipses centred on the unperturbed chromaticity.

(*c*) Cross-talk from the wideband luminance channel appears in the single sideband portion of the I channel. This will result in a coherent perturbation of the I signal.

Whatever the form of the signal interference, it will be reproduced, when of sufficient magnitude, as an undesirable fluctuation of both the luminance and the chromaticity of the colour displayed, as mentioned earlier. The relative subjective magnitudes of the luminance components and the chromatic component will depend on

(*a*) the chromaticity of the colour displayed, and

(*b*) the visual sensitivity ratio (luminance/chromaticity) appropriate to the particular form, angular size, and level of the colour disturbance produced.

Some indication was given in Section 3 of how the average-observer visual sensitivity ratio might be expected to vary with these latter factors. For instance, when the spatial disturbance is basically cyclic, say sinusoidal, the visual sensitivity ratio will increase with the angular size of the cycle or coarseness of the pattern.

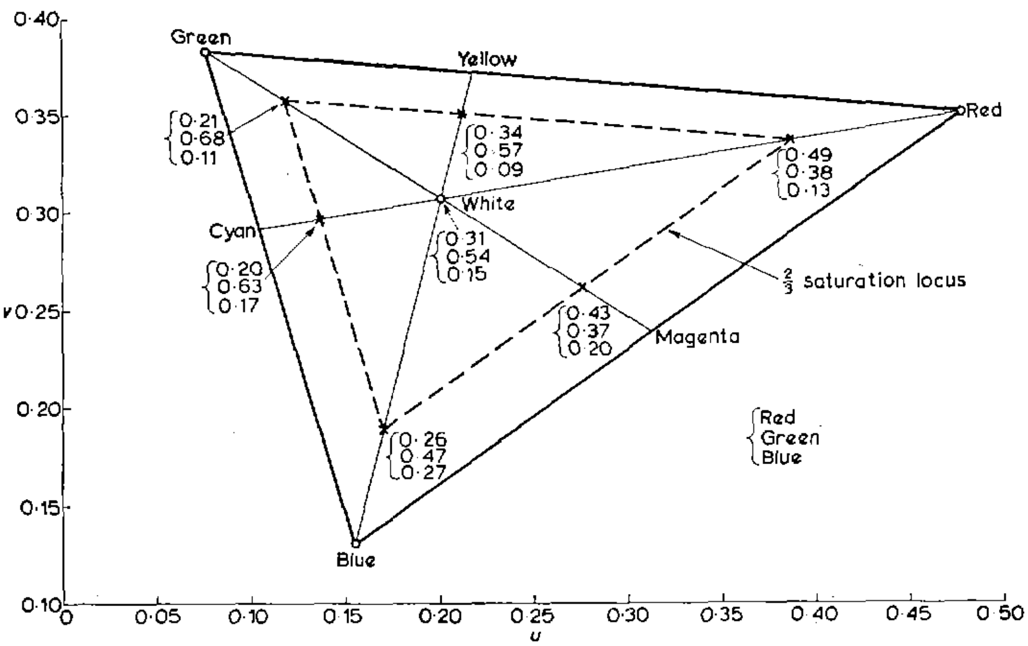

Fig. 9 — Noise-weighting coefficients for flying-spot colour scanner channels.

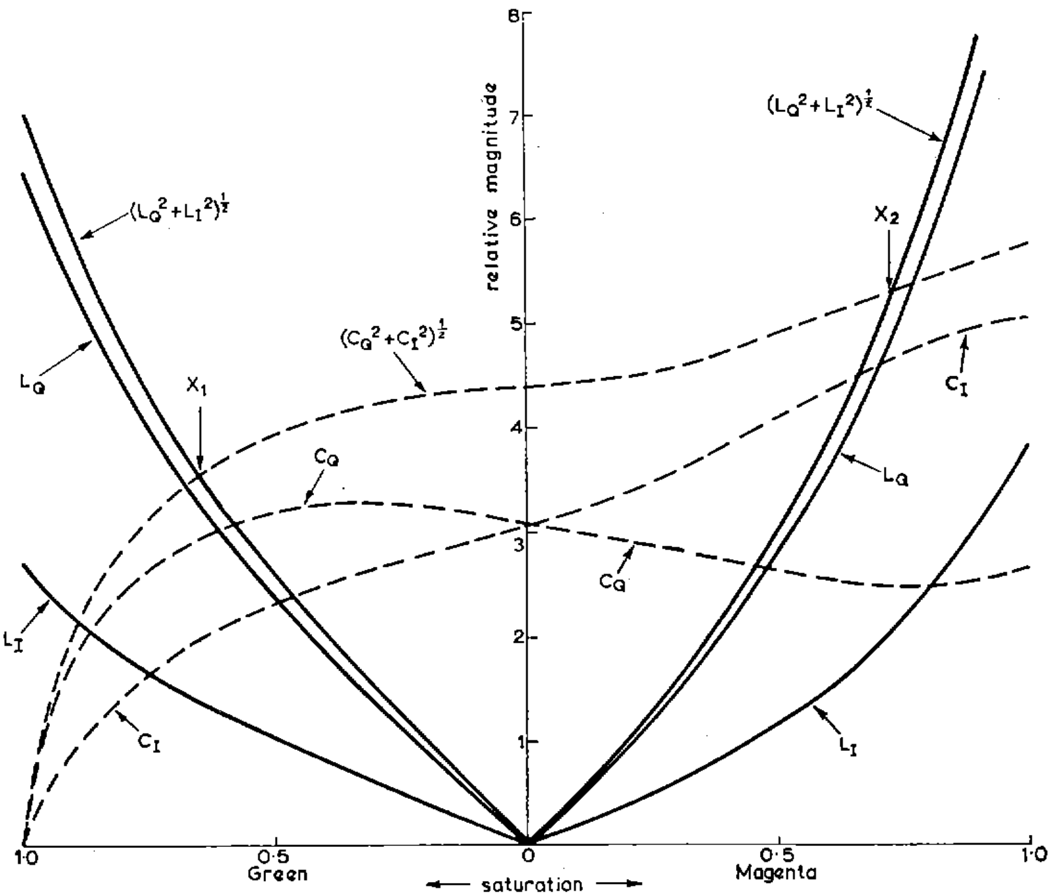

Fig. 10 — *Relative magnitudes of the perturbations produced by interference in the chrominance channel, for colours lying on the green to magenta axis.*

(——) luminance component.
(– – –) chromatic component.

It was deduced in Section 3 that the visual sensitivity ratio (defined as the ratio of $(\delta V/V)_{\text{r.m.s.}}$ to $\delta(u, v)_{\text{r.m.s.}}$ for equal visibility of each component) for coloured random noise, probably lies in the range 2 : 1 to 3 : 1, the actual value within the range depending to some extent on the level of the noise above threshold and the mean chromaticity of the colour. However, for brevity in the analysis which follows, it is assumed that the visual sensitivity ratio has a constant value of 2·5 :1 for all forms of interference.

Using the methods outlined earlier, let us consider the effect of perturbing the NTSC chrominance transmission primaries (I) and (Q) prior to decoding. For reproduced colours lying along the green-white-magenta axis, the result shown in Fig. 10 is obtained for the relative subjective magnitudes of the luminance and chromatic perturbations produced by equal (small) increments of the I and Q signals. In this figure saturation of the reproduced colour with respect to the white point (Illuminant C) is plotted as abscissa: the full lines refer to the luminance components and the dashed lines to the chromatic components. It will be seen that in the region of the white-point (very low saturations) the luminance perturbation becomes negligible, but near the green primary it is the chromatic component that disappears. This is, of course, what one might expect because of the failure of the constant-luminance principle in the NTSC system. Similar kinds of diagram are obtained for the other two primary-complementary chromatic axes.

We can, however, use this type of analysis to obtain a quantitative assessment of the degree of failure of the constant-luminance principle and so provide, perhaps, a more realistic meaning to the more commonly used measure—the constant luminance index. Suppose, for instance, that we consider the constant-luminance principle to have 'failed' when a given amount of interference in the chrominance channel produces chromatic and luminance perturbations that (could they be viewed separately) would be of equal subjective magnitude. Referring to Fig. 10 this would occur at the chromaticities corresponding to the cross-over points marked X_1 on the green side, and X_2 on the magenta side.*

In Fig. 11 the full line shows the effective chromatic limits of the constant-luminance principle, using the

* It has been assumed here that the I and Q components of the displayed perturbations are incoherent so that the total effect is given by the root-sum-of-squares of the component magnitudes.

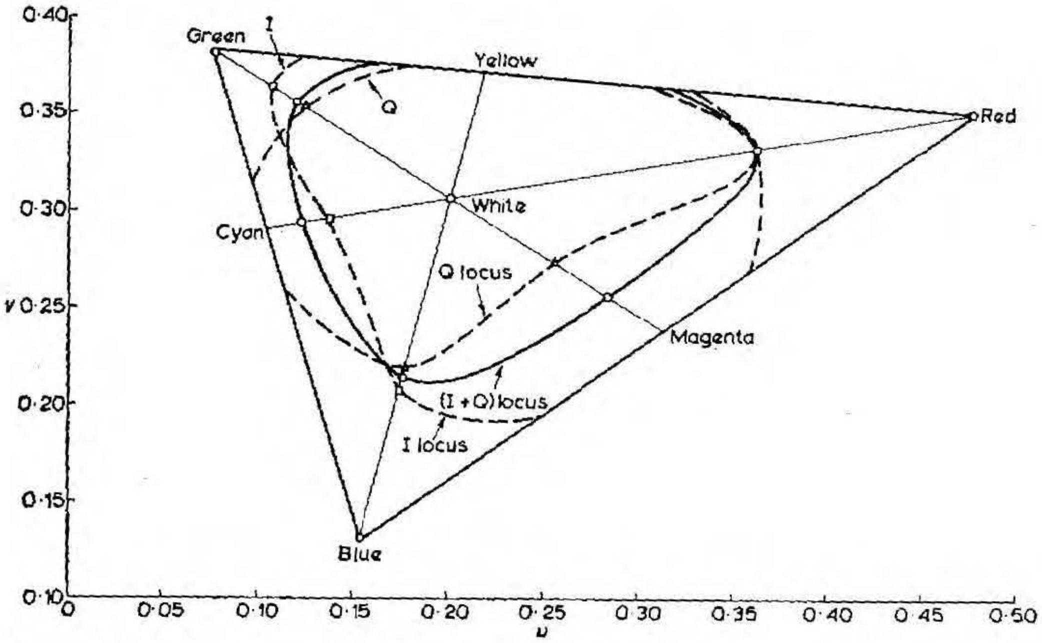

Fig. 11 — *Estimated chromatic limits within which the constant-luminance principle is substantially satisfied by the NTSC system.*

above criterion, while the dashed lines show the limits for the I and Q signals separately. (The limit shown for the I signal would be appropriate for interference giving rise to spectral components of the decoded signal lying within the single sideband portion of the I channel bandwidth.)

Comparison of this data with a map giving the contours of constant luminance index for the NTSC system, shows that the limit locus (full line in Fig. 11) lies in the region where the index is between 0·85 and 0·9 approximately. Thus it would appear that for reproduced colours whose chromaticities lie in a chromatic region where the constant luminance index is less than about 0·85 the advantage of the constant-luminance principle, from the point of view of interference sensitivity, is not very substantial.

In the yellow region the constant-luminance principle does not 'fail' even for full saturation. Also, if the statisics of the chromaticities of colours occuring in natural scenes[4] were taken into account a more favourable assessment of the advantage of the constant-luminance principle would result—because such statistics would be weighted heavily towards desaturated colours expecially in the yellow-orange region.

5. Conclusions

1. For a given reproduced colour, the chromaticities of the effective transmission primaries at any point in the transmission chain permit a rapid estimate of the relative subjective magnitudes of the luminance and chromatic variations of the given colour which would result from any interference or perturbation of these primaries. The chromaticities of the effective transmission primaries are independent of the reproduced colour only if the signals controlling their magnitude are linearly related to the tristimulus values of the colour. If not so related, their chromatic positions vary with the reproduced colour. Further, if the relation is a power law of exponent $\gamma(\neq 1)$, then for any straight-line locus of reproduced chromaticities there is a corresponding straight-line locus for each of the transmission primaries and the direction of these loci is independent of the value of δ.

2. Theoretical re-examination of the early Bailey experiment reveals that the visual sensitivity ratio $[(\delta V/V)/\delta(u, v)]$ for coloured random noise is in the range 2 : 1 to 2·5 : 1, for the yellow mixture colour used in the original experiment. This result appears to be in remarkable agreement with recent subjective measurements of the visual sensitivity ratio for this colour using spatial, sinusoidal variations (6·7 cycles/degree). (See Appendix.)

3. The displayed noise in a colour receiver, due to noise which originates at the picture source can have a substantial chromatic component in some regions of colour, although the luminance component will usually be the larger. In assessing the relative contributions to the total noise from the signal-to-noise ratios of the three outputs from a conventional camera or film-scanner, the usual noise-weighting coefficients, based on the relative luminosities of the reproducer primaries, need some modification if the chromatic component is above the threshold of visibility. In a camera, for instance, the noise in the blue channel should be accorded more weight than the relative luminosity coefficient of the blue primary would indicate. In a flying-spot scanner the noise from the red channel is perhaps of greater import than the relative luminosity of the red primary would indicate.

4. It is estimated that in the NTSC system the constant-

luminance principle 'fails' for those colours lying in the border region of the total chromaticity gamut where the constant luminance index is less than about 0·85. This estimate is based on the criterion that the principle 'fails' when interference in the chrominance channel produces luminance and chromatic fluctuations of equal subjective magnitude, and on the assumption that the visual sensitivity ratio is 2·5:1.

6. References

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APPENDIX

THE RELATIVE VISIBILITIES OF SPATIAL VARIATIONS IN LUMINANCE AND CHROMATICITY

SUMMARY

An optical method of producing sinusoidal (spatial) variations of the colour of an illuminated screen is described. Either colour variations of chromaticity at constant luminance or colour variations of luminance at constant chromaticity can be selected. An observer viewing the screen can control the magnitude of the colour variation—and hence its visibility. By making visually-equivalent judgments, his relative sensitivity to the two forms of colour variation can be measured.

The results obtained by a group of ten observers for a range of test colours are presented, and their dependence on several factors is briefly investigated.

A1. Introduction

A commonplace generalization is that the eye is more sensitive to spatial and temporal variations in luminance than to variations in chromaticity. Outside the context of a specified system, e.g. a three-colour additive system, the above generalization is clearly meaningless because luminance and chromaticity variations cannot be expressed objectively on the same physical scale. However, in terms of a convenient reference framework, it is of great interest to determine the relative magnitudes of the variations in chromaticity or luminance which would be judged to be visually equivalent. Further data on how these relative magnitudes depend on the chromaticity, absolute luminance and on other factors will be of value.

The existing data obtained by MacAdam[5] on the just-noticeable differences in chromaticity between the two halves of a bipartite visual field provides a valuable guide to the expected variation of just-noticeable chromaticity deviations as a function of chromaticity. One outcome of MacAdam's work has been the recent adoption by the C.I.E. of his proposal for a uniform chromaticity diagram in which just-noticeable differences in chromaticity have approximately the same vector length. Thus an obvious choice of reference diagram on which to express the results of the experiments described below is the C.I.E. uniform-chromaticity-scale diagram.

A2. Optical Experiments

A2.1 *Object of the Experiments*

The purpose of the optical experiments reported here was to obtain some basic information on the visibilities of spatial, sinusoidal variations of colour: a similar type of variation in a colour television receiver could arise, for example, from an unwanted carrier having a frequency near that of the colour subcarrier in a colour television emission.

Suppose that an additive mixture of two primary 'lights' uniformly illuminating a viewing screen produces a particular colour. The colour may be represented as a point (e.g. C in Fig. 12) in a three-dimensional space having co-ordinates V_1, u_1, v_1 with reference to the rectangular set of axes V, u, v, where u and v are the C.I.E. uniform chromaticity co-ordinates and V is the luminance of the colour. A property of this particular reference framework is that planes of constant luminance are parallel to the (u, v) plane, and colours of the same chromaticity lie on lines parallel to the V axis. Suppose that the primary 'lights' are perturbed by a small amount in such a manner that a spatial, cyclic, variation of luminance is seen across the screen (this would appear as a vertical bar pattern similar to that shown in Fig. 13 (*a*), the chromaticity remaining uniform. Hence a plot of the cyclic excursion of the colour C in Fig. 12 would appear as a short line through C parallel to the V axis.

Alternatively, we may suppose that the perturbations are introduced so that a spatial, cyclic, variation of chromaticity is produced on the screen (see Fig. 13 (*b*) the luminance remaining uniform. The corresponding plot of C in Fig. 12 is now a cyclic excursion along a short line through C parallel to the (u, v) plane. If an observer viewing the screen is given a control by which the magnitudes of these luminance-only or chromaticity-only excursions can be varied over a suitable range, he can make settings corresponding to his own judgment of visual equality. From the average of control settings registered by a number of observers the corresponding average lengths of the vectors in the (V, u, v) colour space can be deduced for each condition of the experiment. A range of colours of various absolute luminances and chromaticities can be investigated. Also, using the same observers if possible, the viewing distance can be altered and any influence this may have on the equality judgments determined.

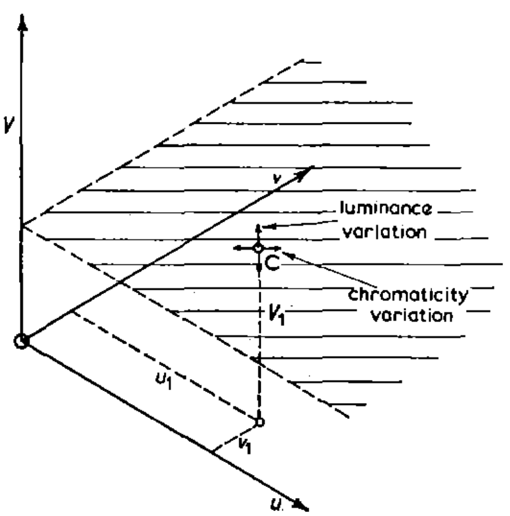

Fig. 12 — (V, u, v) *Colour reference space.*

A2.2 *Optical Arrangement*

An optical arrangement was devised to provide a display suitable for the study of the sinusoidal colour variations outlined above. The principle of the method is that, under certain conditions, the superposition of two incoherent light beams impinging on a screen, each beam being sinusoidally modulated in intensity at the same frequency, can produce colour variations ranging from either pure chromaticity variations to pure luminance variations depending on the relative phases of the respective modulations of intensity. The principle can, in fact, be applied to produce variations in either time or space. However, spatial variations were used in the present experiments and these were obtained by modulating the light beams by means of a sine-wave grating near the viewing screen and common to both beams, as shown in Fig. 14 (*a*).

Two projector lamps, S_1 and S_2 in Fig. 14 (*a*) whose filaments are mutually separated by approximately 2 in. (50 mm), are placed 24 in. (610 mm) from a small viewing screen $2\frac{1}{2}$ in. (60 by 60 mm) square. By interposing two different colour filters, F_1 and F_2, the spectral characteristics of the light falling on the viewing screen from S_1 and S_2 respectively can be modified. Thus the sources are converted into selected colour primaries and, when the amount of each primary has been established, the chromaticity of the additive mixture on the screen can be readily deduced.

Situated at 4 to 5 in. (100 to 125 mm) behind the viewing screen is a large sine-wave grating (photographic transparency) mounted on a 'Vee' slide running on a length of optical bench: the grating-to-screen separation is thus adjustable. It will be seen from Fig. 14 (*a*) that when the grating is in position A the coloured rays from each source arriving at a point Q on the viewing screen intersect the grating at points of indentical transmission. This is the 'in phase' condition and produces mainly luminance variations across the screen, since the angle subtended by the lamp filaments at any point on the screen is substantially invariant. Alternatively, when the grating is in the position B, approximately 1 in. (2·5 cm) farther away from the screen, the rays from the two sources intersect the grating at antiphase points of its sinusoidal transmission characteristic. This grating position produces sinusoidal deviations of chromaticity with respect to the mean chromaticity of the displayed colour if the luminances of the components in the additive mixture are made equal (e.g. by combining neutral density filters with the colour filters, F_1 and F_2).

The spatial frequency of the pattern produced on the screen, by the particular sine-wave grating used throughout the experiments, was approximately 2 cycles per centimetre. There is a small increase (5 per cent) in the spatial frequency when the grating is shifted from position B to position A, which is just-perceptible.

The arrangement described so far allows either luminance-only or chromaticity-only colour variations to be selected by a simple displacement of the grating but the magnitude of the variations is not continuously variable. The latter facility is achieved by the optical arrangement shown in Fig. 14 (*b*). The illumination from a second pair of lamps, S_3 and S_4 via a second pair of colour filters, F_3 and F_4, is directed on to the viewing screen by means of a semi-transparent beam-splitting mirror, M. This side-arm configuration of lamps and filters is similar to that of the main-arm without the sine-wave grating. Hence, if the light from the main-arm is totally obscured, a uniform patch of colour will be displayed having a chromaticity identical to that produced by the main-arm alone. If a small proportion of the light from the main-arm is allowed to reach the viewing screen the spatial variations or pattern due to the grating will begin to appear. An obvious experimental requirement is that the average total luminance of the displayed colour remains substantially constant. This was achieved by using a 'crossed polarizer' technique. Two Polaroid filters, P_1 and P_2 are placed in each arm of the apparatus respectively, as shown in Fig. 14 (*b*). The Polarizers are oriented so that their polarizing axes are at right angles. Immediately behind the viewing screen is a

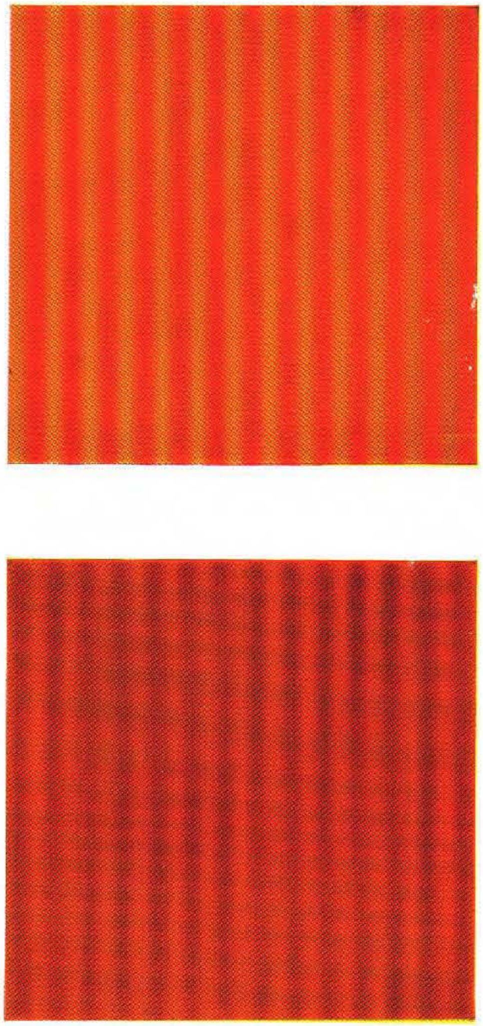

Fig. 13 — Photographs of the test patch showing the two forms of colour variation.
(*a*) Luminance varying—chromaticity uniform
(*b*) Chromaticity varying—luminance uniform

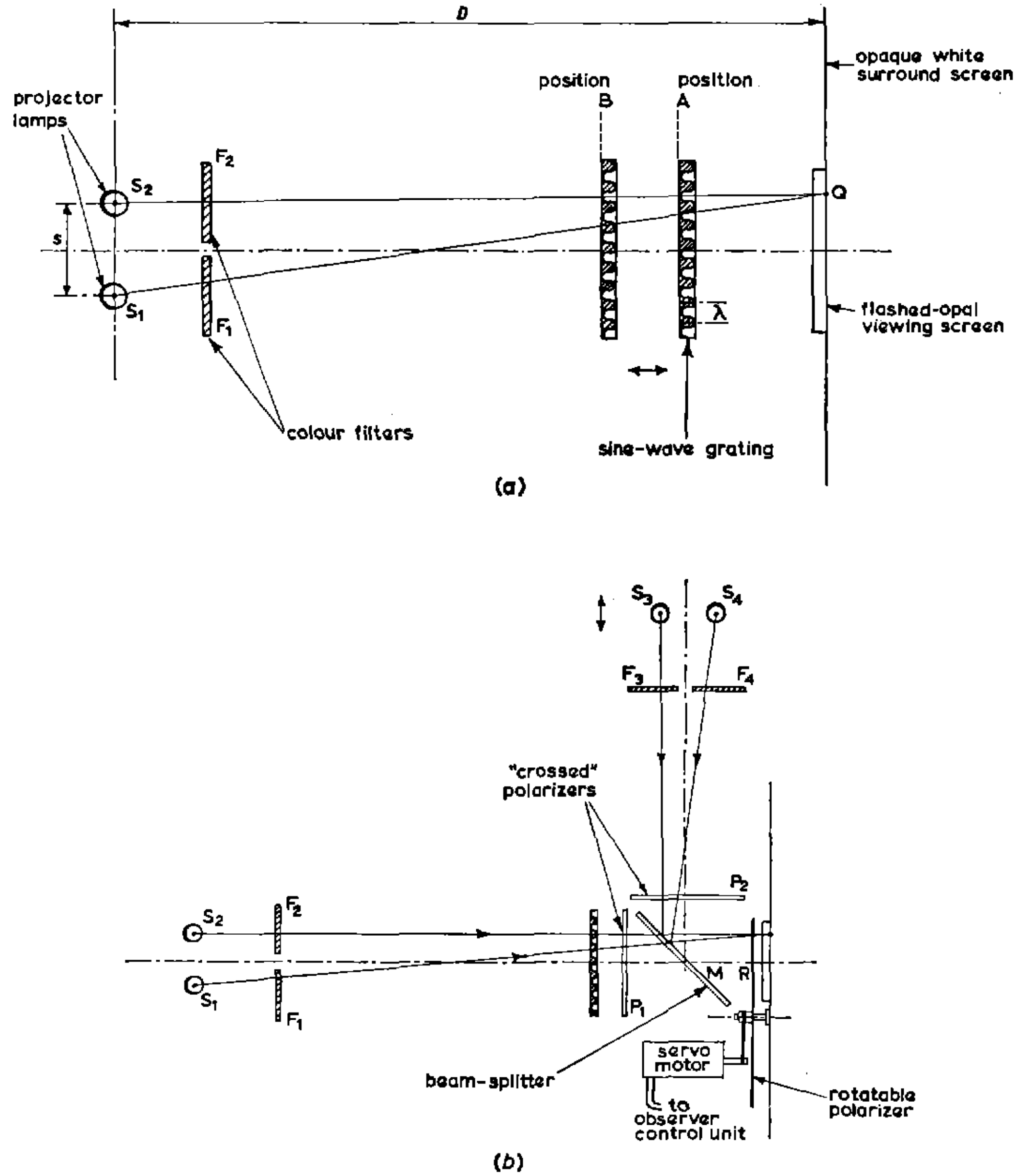

Fig. 14 — *Optical arrangement for producing sinusoidal colour variations.*

large rotatable Polaroid disc, R, rotating about an axis offset from the centre of the viewing screen. Thus, by means of the polarizing system P_1, P_2 and R, the relative proportions of the illumination from the two arms of the apparatus and, therefore, the deviation amplitude of the colour variations can be varied by adjusting the orientation of the disc polarizer, R. A pointer attached to the edge of the disc polarizer, and running over a fixed angular scale, serves to indicate the orientation of the polarizing axis.

It can be shown that if the intensities of the two beams of light, incident on the rotatable polarizing disc, from the two arms respectively are equal then the average luminance of the displayed colour is independent of the orientation of the disc.* (A total variation of mean luminance of approximately 2 per cent was achieved.)

The hub of the rotatable disc is coupled to the shaft of a Selsyn servo-motor by a friction belt (see Fig. 14 (*b*)). The servo-motor is connected by a length of cable to an identical (master) servo-motor within reach of the observer who can then, by rotating the servo-motor shaft, remotely control the magnitude of the colour variations when carrying out the subjective experiments.

The dielectric beam-splitting mirror, M, consists of a single-layer of titanium dioxide on glass, giving a nearly

* A G.E.C. Photo-electric photometer with a Preston liquid filter, to give an overall spectral response close to the C.I.E. photopic response for the standard observer, was used for all adjustments of luminance equality.

uniform spectral reflexion characteristic with a reflexion coefficient of approximately 0·4 for unpolarized light. The rear surface of the glass is anti-reflexion coated.

From the position of the observer, the small viewing screen on which the pattern appears (by back projection) is centrally located in the cut-out part of a much larger viewing screen, 12 in. by 16 in. (300 mm by 400 mm). This larger surrounding screen is opaque with a matt-white surface suitable for front projection. In some of the subjective experiments a colour slide was projected on the surround by a small projector by the side of the observer: a small opaque patch on the colour slide prevented direct illumination of the test area, the latter thus appeared to be inlaid in the picture. Fig. 15 is a black-and-white photograph of the display under these conditions as seen by the observer.

A2.3 *Theoretical Basis of the Method*

Let the colour of the viewing screen due to the spectrally-filtered light flux arriving from one of the projector lamps in the main-arm (say, S_1 in Fig. 3) be C_1. The colour C_1 is substantially uniform over the screen in the absence of the sine-wave grating, and may be completely specified in terms of the C.I.E.—uniform chromaticity colour space by the three tristimulus values U, V, W, where the V value is directly proportional to the luminance of the colour. Thus we can write the colour equation:

$$C_1 = U_1 + V_1 + W_1$$

Similarly, for the colour C_2 due to the flux arriving from the second lamp S_2 we have:

$$C_2 = U_2 + V_2 + W_2$$

Introducing the sine-wave grating between the lamps and the screen produces a spatial variation of the luminance of each colour component, their respective chromaticities remaining constant. Hence, with the grating, the respective colour equations become:

$$C_1 = (U_1 + V_1 + W_1)\,\bar{t}\,[1 + m\sin(2\pi f_s x + \beta_1)]$$

$$\text{and } C_2 = (U_2 + V_2 + W_2)\,\bar{t}\,[1 + m\sin(2\pi f_s x + \beta_2)]$$

where f_s is the spatial frequency of the sinusoidal variations in a given direction across the screen, $\bar{t}$ is the mean transmission coefficient of the grating, m is the relative amplitude of the sinusoidal variations in the luminance of each colour component (modulation coefficient), β is the phase angle at an arbitrary point (origin) on the screen, and x is the lateral distance from this origin in the given direction.

Now the difference between the phase angles of the two components at the origin, i.e. $\beta_1 - \beta_2$, depends on the geometrical disposition of the lamp filaments with respect to the grating and the viewing screen. In the apparatus the phase difference between the two components was adjusted by altering the grating-to-screen separation. If the latter is adjusted so that $\beta_1 - \beta_2$ is an even multiple of π the colour C representing the additive mixture of the two components is given by:

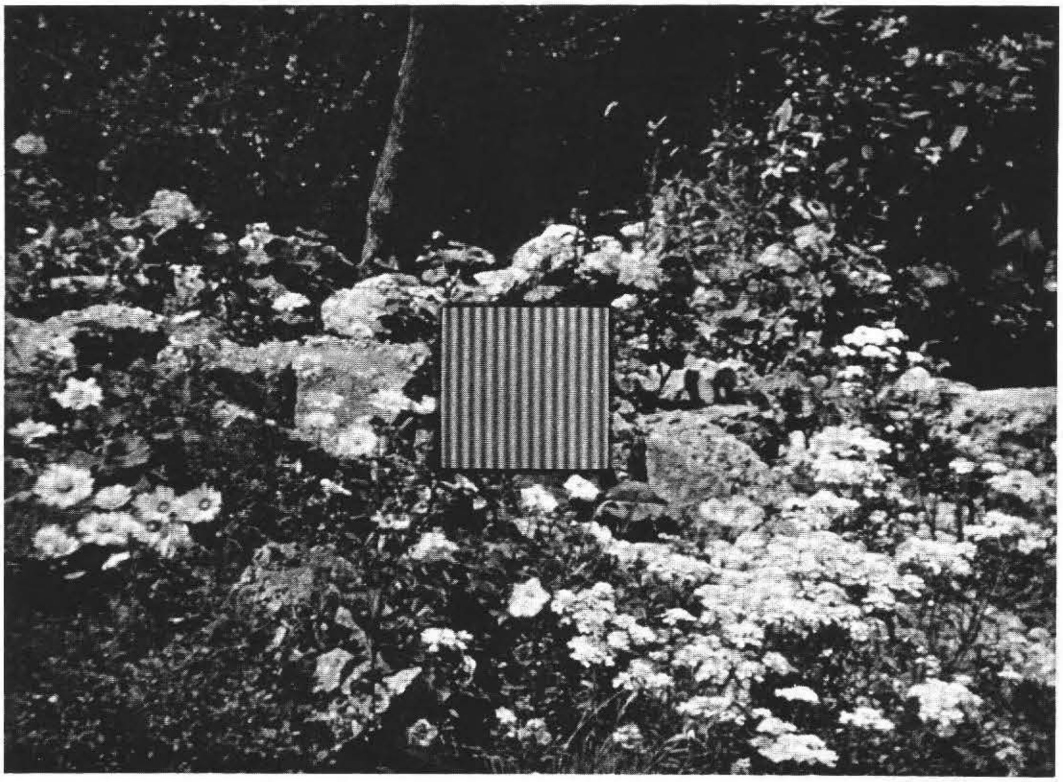

Fig. 15 — Displayed test patch with surround picture.

$$C = C_1 + C_2$$

$$\beta_1 = \mathrm{n}\pi + \beta_2, \text{ (n even)}$$

$$\text{i.e. } C = \bar{t}\,[(U_1 + U_2) + (V_1 + V_2) + (W_1 + W_2)]\,[1 + m \sin(2\pi f_s x + \beta_1)]$$

It will be noted that, for this condition, the colour variation is one of luminance-only, the chromaticity being independent of x.

Alternatively, by moving the grating to another position such that $\beta_1 - \beta_2$ is an odd multiple of π the above colour equation becomes:

$$C = \bar{t}\,\{[(U_1 + U_2) + (U_1 - U_2)\, m \sin(2\pi f_s x + \beta_1)] + [(V_1 + V_2) + (V_1 - V_2)\, m \sin(2\pi f_s x + \beta_1)] + [(W_1 + W_2) + (W_1 - W_2)\, m \sin(2\pi f_s x + \beta_1)]\}$$

If, in addition, the mean luminances of the two components are adjusted to be equal, i.e. if $V_1 = V_2 = V$ in the above equation, then:

$$C = \bar{t}\,\{[(U_1 + U_2) + (U_1 - U_2)\, m \sin(2\pi f_s x + \beta_1)] + [2V] + [(W_1 + W_2) + (W_1 - W_2)\, m \sin(2\pi f_s x + \beta_1)]\}$$

Thus providing that the two components have different chromaticities the colour variation on the screen will now be one of chromaticity-only, the luminance remaining constant.

A2.4 *Subjective Tests*

Two series of subjective tests were conducted, the main difference between these series being the viewing distance. In each series, a test colour was displayed and each of ten observers, in turn, made a number of visual equality judgments as described in Section A2.4.4 below. In the first series the observers sat at a distance of 6 ft (1·8 mm) from the viewing screen. At this distance each cycle of the sinusoidal test pattern subtended an angle of 9 minutes of arc (6·7 cycles/degree) at the observer's eye, and the angular size of the total test area (not including the surround screen) was approximately 2° by 2°. In the second series the viewing distance was reduced to 2 ft (0·6 m), at which distance each cycle of the pattern subtended an angle of 27 minutes of arc (2·2 cycles/degree) and the angular size of the test area was 6° by 6°. For comparison, in television terms, the angular spatial frequency of the observed pattern, in the first series, is approximately equivalent to that produced by a 1·65 Mc/s video signal component on a television monitor working on the United Kingdom 625-line standard viewed at 6 times picture height and, in the second series, to a video signal of 0·55 Mc/s.

A2.4.1 *Observers*

Nine of the ten observers taking part in the experiments in the first series were colour-normal. The one exception appeared to be partially red-green blind, according to the Ishihara colour blindness tests, and was deliberately included.* All the observers were male engineers varying in age from twenty to forty-seven years: four of them had corrected vision. With one or two exceptions the same group of observers took part in the second series of experiments.

A2.4.2 *Test Colours*

Eight test colours were used in the experiments. Table 2 lists the test colours, their chromaticities and their absolute luminances. The test colours 1 to 5 are highly saturated colours and the displayed spatial variations in chromaticity using these colours correspond to variations in hue. The test colours 6 to 8 are desaturated colours. It should be pointed out that, because of the limited number and spectral characteristics of the colour filters available, it is difficult to obtain suitable pairs of 'primary' sources which will, when adjusted for luminance equality, produce test colours having chromaticities and absolute luminan-

* His results, however, were not inconsistent with those given by the colour-normal observers.

TABLE 2

Test Colour					*Mixture Primaries*
No.	*Name*	*Chromaticity* *u*	*v*	*Absolute Luminance* (ft-L)	
1	Orange	0·402	0·358	3·0	Red/Yellow
2	Lime green	0·179	0·376	5·0	Green/Yellow
3	Bluish green	0·089	0·333	4·5	Green/Cyan
4	Dark blue	0·129	0·210	0·5	Blue/Cyan
5	Purple	0·242	0·193	0·5	Blue/Magenta
6	Pink	0·344	0·338	5·0	Red/Cyan
7	Pale green	0·190	0·338	5·5	Cyan/Yellow
8	Pale pink	0·282	0·329	2·0	Green/Magenta

ces exactly as desired. For example, it was not possible to obtain with the filters available a desaturated blue colour having an absolute luminance greater than about 0·5 foot-Lambert.

The chromaticities of the test colours were deduced from spectrophotometric measurements on the colour filters used in the apparatus, and from a measurement of the effective colour temperature of the 'white' display when the colour filters were removed: the effective colour temperature was approximately that of Standard Illuminant A, i.e. 2850°K.

A2.4.3 *Surround Picture*

In the first series each equality matching by an observer was repeated with the test area surrounded by a colour-picture of a garden scene (see Fig. 15) obtained by optical projection of a 2 in. by 2 in. colour slide. The projector was situated slightly behind and to the side of the observer. A small opaque square patch on the slide prevented direct illumination of the test area of the viewing screen as mentioned in Section A2.2. The peak-white areas of the surrounding picture had a luminance of 10 ft-L. With the projector on, the luminance of the test area due to lens flare and ambient illumination was 0·04 ft-L: the luminance due to the ambient alone was 0·02 ft-L. The ambient illumination was mainly due to a small bench lamp behind the observer: the room was otherwise dark. In the second series of experiments the surround picture was not used.

A2.4.4 *Test Procedure*

(*a*) *First Series*

A test colour was displayed and the grating position set to produce luminance-only variations. An observer,* seated with access to the manual control of the pattern visibility, was asked to rotate the control until the luminance-only variations were just-perceptible. This setting was recorded and the grating, starting with the control in a zero-visibility position, was then moved to the position which produced chromaticity-only variations, and the observer again rotated the control until these variations were just-perceptible: the new setting was recorded. The grating was then returned to the luminance-only position and the observer asked to set the control so that the pattern appeared to him quite-definitely-perceptible. No restriction was placed on his interpretation of this criterion. Then, with the grating moved back to the chrominance-only position, he was asked to adjust the control to produce a pattern which he judged to be equally visible. If the observer wished, he was allowed to return to the luminance-only condition and start again, perhaps selecting a slightly different reference level from that chosen previously. His final pair of settings were recorded.

The above procedure was repeated but with the surround illuminated with the colour picture.

After the ten observers had carried out, in turn, the required tests, another test-colour was set up.

* The observer was previously given two or three minutes to adapt himself to the test conditions.

(*b*) *Second Series*

In this series, the observers were seated at a much closer viewing distance but the basic procedure was identical with that outlined above. No surround picture was present in this series. The visual matchings for the two criteria, i.e. just-perceptible and quite-definitely-perceptible, were recorded for each of the following conditions of the experiments:

(i) with the test-colour at approximately the absolute luminance level used for that colour in the first series.

(ii) with the absolute luminance level reduced to two-fifths of the above values respectively.

The sequence in which these two tests were carried out was varied from observer to observer.

Four test-colours (nos. 1, 3, 5, 7 of the eight used in the first series) were used in the second series.

A3. Results

A3.1 *Sensitivity Ratio*

The results are presented here in terms of the (V, u, v) colour space outlined in the introduction. The visual sensitivity ratio (luminance/chromaticity) is here measured by the ratio (denoted by ϕ)

$$\phi = \frac{\delta V/V}{\delta(u, v)}$$

where δV is the peak-to-peak magnitude of the sinusoidal variation of the luminance and V is the mean value. $\delta(u, v)$ is the (peak-to-peak) excursion of the sinusoidal chromaticity variation judged to be visually equivalent. This particular ratio was chosen because in addition to being non-dimensional both the numerator $\delta V/V$ and the denominator $\delta(u, v)$ were not expected to vary in value to any great extent over the limited region of the (V, u, v) colour space investigated. Hence, their ratio ϕ is likely to be almost invariant over this region of colour space.

Where the results are averaged for the ten observers taking part in the experiment the sensitivity ratio will be denoted by:

$$\phi_{av} = \frac{(\delta V/V)_{av}}{\delta(u, v)_{av}}$$

The sensitivity ratio can be deduced from the recorded pair of modulation coefficients, corresponding to the pair of control settings selected by an observer in a single equality judgment.

A3.2 *Variation of Sensitivity Ratio with Test Colour*

The observer-averaged sensitivity ratios, ϕ_{av}, as a function of the relative luminance variation are shown in Figs. 16 (*a*) and 16 (*b*) with test colour as parameter.† The plot points in these figures now represent average values for the ten observers. The numbers on the lines joining the

† It was found that the average sensitivity ratio ϕ_{av} was a function of the magnitude of the luminance-only variation $(\delta V/V)_{av}$ selected as the reference level against which the chromaticity-only variation was matched. Thus the results are presented in graphical form with $\delta V/V$ as abscissa. Corresponding pairs of plot points are linked by a straight line.

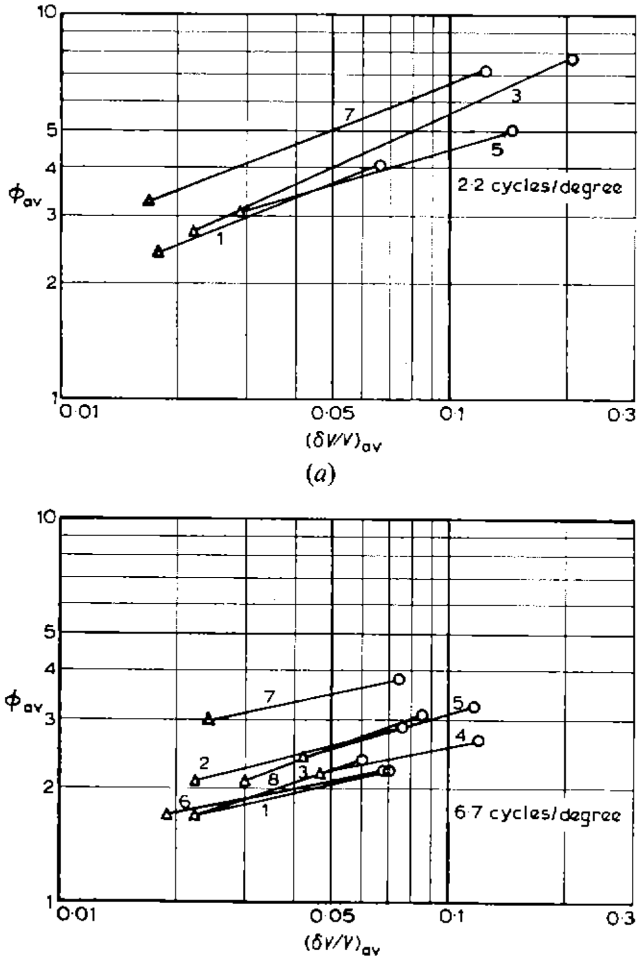

Fig. 16 — Observer-averaged sensitivity ratios for the eight test colours.

(*a*) 2·2 cycles/degree
(*b*) 6·7 cycles/degree
Δ just-perceptible criterion
O definitely-perceptible criterion

pairs of plot points denote the test colour to which the values refer (see Table 2). Fig. 16 (*a*) relates to the 2-ft viewing distance and Fig. 16 (*b*) to the 6-ft viewing distance.

The average sensitivity ratio at a given level of perceptibility does not appear to vary greatly with the chromaticity of the colour or the direction of the chromaticity variations. This is, of course, the general result one might expect if the properties of the C.I.E. uniform chromaticity scale hold for cyclic, spatial, fluctuations of colour as well as for chromatic differences between two juxtaposed (large) coloured fields. Test colour no. 7 seems to be a significant exception: this colour was a desaturated lime-green with chromaticity variations in the yellow to cyan direction. Inspection of the results for this particular colour shows that the increase in sensitivity ratio is due to the somewhat lower value of $\delta(u, v)_{av}$ obtained for this colour rather than to an increase in the $(\delta V/V)_{av}$ value (see Section A4). For instance, the average $\delta(u, v)$ value for this colour corresponding to the just-perceptible criterion is approximately two-thirds that of the averge of all the colours tested.

It is shown later that a significant dependence of the sensitivity ratio on the absolute luminance of the test colour was found, hence some modification of the results shown in Fig. 16 might be expected if the experiment had been carried out with the test colours at the same absolute luminance. Nevertheless, the test colours used had approximately the relative luminances that might be encountered in natural scenes, e.g. highly saturated blue or purple colours do not usually occur at such high luminances as saturated orange or yellow-orange colours in the same scene.

A3.3 *Variation of Sensitivity Ratio with Viewing Distance*

The general increase in the average sensitivity ratio when the viewing distance is reduced, seen by comparing Fig. 16 (*a*) with Fig. 16 (*b*), was expected because it is well known that the perceptibility of chromatic differences diminishes with increasing viewing distance at a faster rate than does the perceptibility of luminance differences.

The increase in average sensitivity ratio is approximately 50 per cent when changing the viewing distance from 6 ft to 2 ft, which corresponds to decreasing the angular spatial frequency of the pattern display from 6·7 cycles/degree to 2·2 cycles/degree.

A3.4 *Effect of Surround Picture*

There appears to be no systematic difference between the results obtained with or without the surround picture.

A3.5 *Variation with Luminance*

In the second series, results were obtained for each of the four test colours at two levels of absolute luminance, the lower level in each case being two-fifths of the higher. The effect of this luminance change on the average sensitivity ratios is shown in Fig. 17, where the dashed lines refer to the lower luminance level and the full lines to the higher.

These results show that the sensitivity ratio is dependent on the absolute luminance of the colour: reducing the luminance produces a relatively greater reduction in sensitivity to chrominance-only variations than to luminance-only variations, hence ϕ is reduced at a given level of $(\delta V/V)$. A more detailed experiment is required to establish a working empirical relationship between absolute luminance and sensitivity ratio.

A4. Further Analysis of the Results

Although the emphasis in the experiments was on the measurement of the sensitivity ratio ϕ, it is interesting to examine the measured variation of the just-perceptible difference in chromaticity $\delta(u, v)_{av}$ with respect to test colour. Table 3 shows the threshold values (averaged for the ten observers) of $\delta(u, v)$ corresponding to the only-just-perceptible criterion.

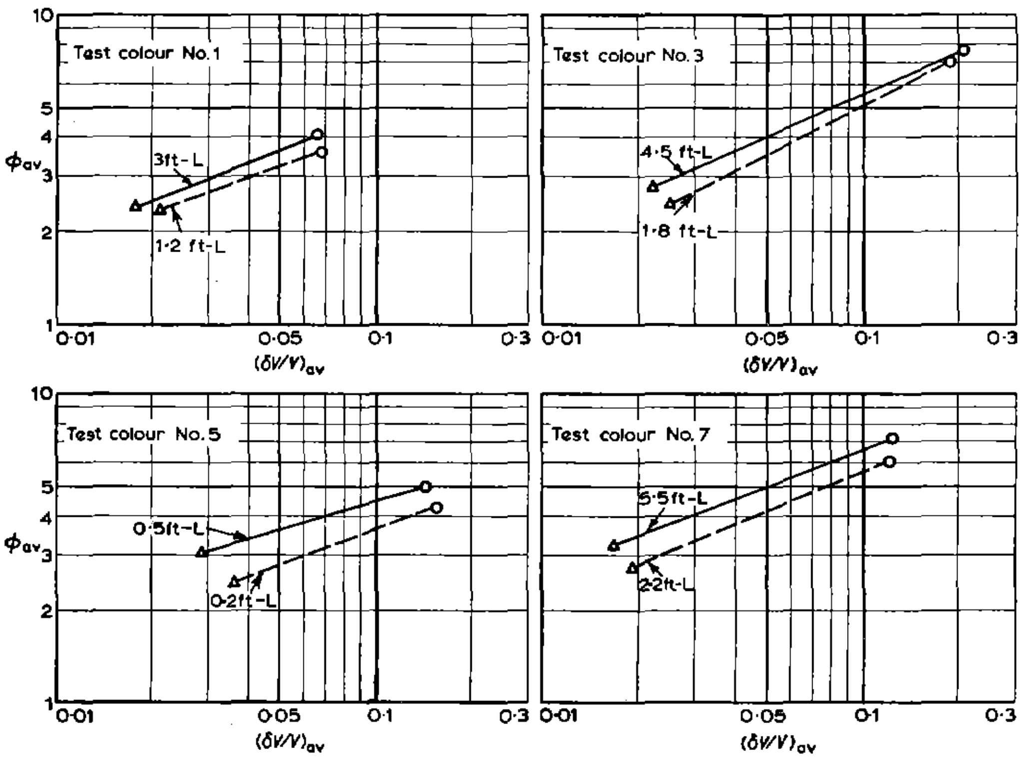

Fig. 17 — *Effect of absolute luminance on the average sensitivity ratios.*
Δ just-perceptible criterion O definitely perceptible criterion

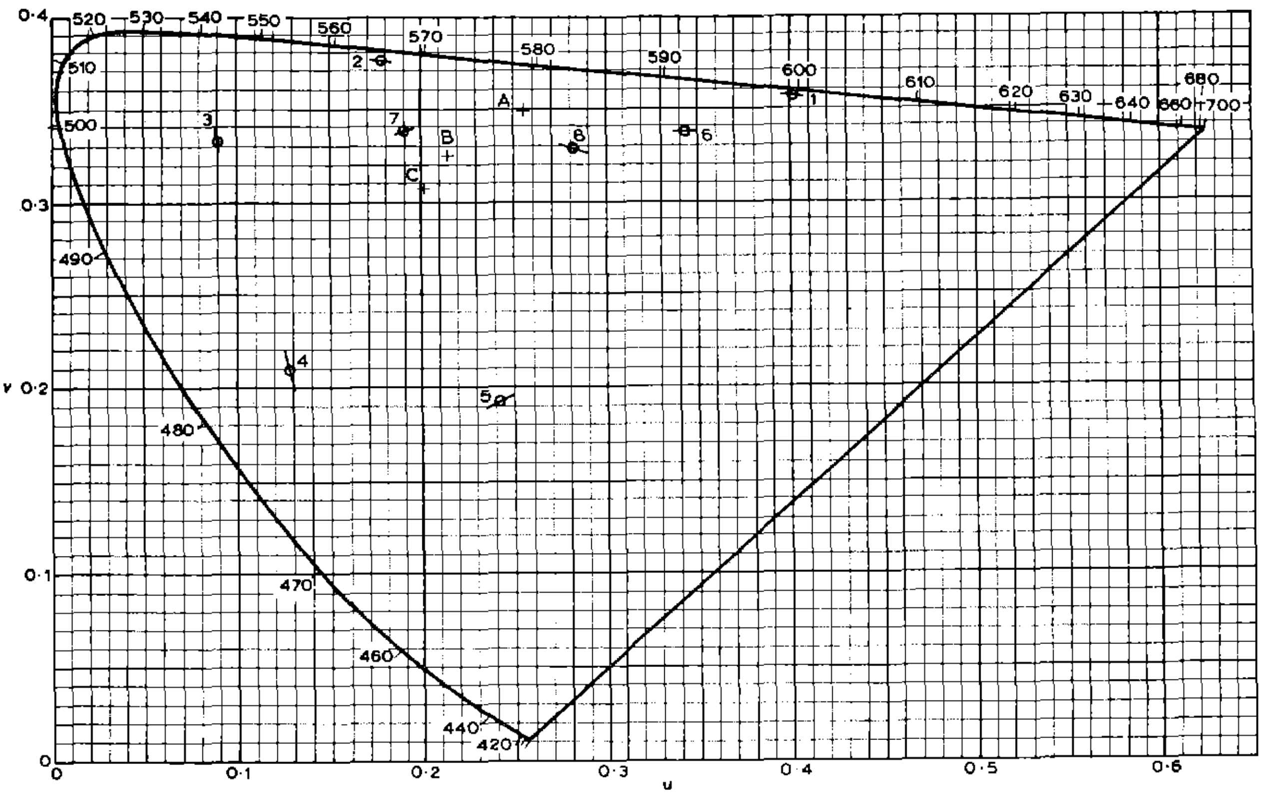

Fig. 18 — *Just-perceptible 'peak-to-peak' excursion of a sinusoidal variation in chromaticity. (Spatial frequency* 6·7 *cycles/ degree.) Circles show mean chromaticity, lines through circles indicate direction and magnitude.*

TABLE 3

These results refer to the larger viewing distance without surround picture

No.	*Test Colour*			*JP threshold value of* $\delta(u, v)_{av}$* *(C.I.E.-U.C. units)*
	Description	*Direction of chromatic variation*	*Luminance ft-L.*	
1	Orange	Red—Yellow	3·0	0·013
2	Lime green	Green—Yellow	5·0	0·010
3	Bluish green	Green—Cyan	4·5	0·013
4	Dark blue	Blue—Cyan	0·5	0·021
5	Purple	Blue—Magenta	0·5	0·018
6	Pink	Red—Cyan	5·0	0·011
7	Pale green	Cyan—Yellow	5·5	0·008
8	Pale pink	Green—Magenta	2·0	0·014
				Mean value 0·0135

* Peak-to-peak excursion.

Fig. 18 shows the data in Table 3 plotted on a C.I.E.-U.C. diagram: the solid lines through the plot points show the extent of the sinusoidal chromaticity deviations (peak-to-peak) corresponding to the just-perceptible criterion.

It will be seen from the figure and from Table 3, that the measured maximum variation of the just-perceptible chromatic differences for the test colours investigated is slightly greater than 2·5 : 1. However, if allowance were made for the differences in the absolute luminances of the test colours, it is expected that the variation would be reduced considerably. Hence, the present results relating to sinusoidal chromaticity variations provide further evidence of the approximate uniformity of the C.I.E. uniform chromaticity scale. It is possible that the low value of 0·008 C.I.E. units obtained for test colour no. 7 indicates that a substantial change may occur in the properties of the C.I.E. uniform chromaticity scale when the colour variations are between areas subtending very small angles at the eye. Test colour no. 7 had chromatic variations in the yellow to cyan direction and the result obtained for this colour would support the conclusions of earlier researches that, for medium detail in pictures, chromatic discrimination tends to be better along the orange to cyan axis of chromaticity (a fact which led to the adoption of the wide-band I signal in the NTSC colour television system).

TYPE OF CHROMATIC VARIATION		SIZE OF TEST FIELD	AVERAGE LUMINANCE OF TEST COLOURS (ft-L)	$\delta(u, v)$ (C.I.E.-U.C. UNITS)
SINUSOIDAL (6·7 cycles/ degree)	$\delta(u, v)$	2°	3·25	0·0135 *
SINUSOIDAL (2·2 cycles/ degree)	$\delta(u, v)$	6°	3·40	0·0075
BIPARTITE	$\delta(u, v)$	2°	16·00	0·0033

Fig. 19 — Average just-perceptible chromatic differences for various types of chromatic variation.

Fig. 19 gives the values of the just-perceptible chromatic differences averaged for the test colours investigated: for comparision the result obtained by MacAdam using a bipartite field is included.

The average sensitivity ratio, ϕ_{av}, was found to be somewhat dependent on the magnitude of the colour variations and all the results have been presented as a function of $(\delta V/V)$. However, the general relation between $(\delta V/V)$ and a six-point subjective scale of perceptibility and annoyance is known, from previous work on co-channel interference, and noise in monochrome television.[6, 7] Assuming this relation to hold for sinusoidal luminance variations of a coloured field the sensitivity ratios can be expressed in terms of a subjective scale of perceptibility, as shown in Fig. 20. Here the abscissae scale $\delta V/V$ used in the previous figures has been replaced by the reference numbers of the six-point grading scale given in the text below. Thus an increase of one grade represents an increase of 5 dB in $\delta V/V$. Since one criterion in the experiment was that of 'just-perceptible' the average result for this criterion is assumed to be aligned with Grade 2 of the following six-point scale:

1. Imperceptible.
2. Just perceptible.
3. Definitely perceptible but not disturbing.
4. Somewhat objectionable.
5. Definitely objectionable.
6. Unusable.

The full line in Fig. 20 refers to the larger viewing dis-

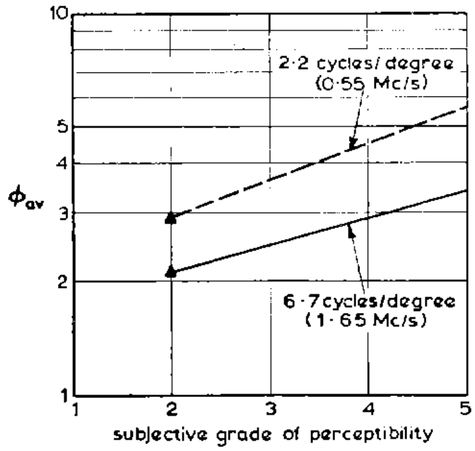

Fig. 20 — *Average sensitivity ratios for all test colours as a function of subjective grade of perceptibility.*
—— 6·7 cycles/degree (1·65 Mc/s)
- - - 2·2 cycles/degree (0·55 Mc/s)

tance (angular spatial frequency = 6·7 cycles/degree) and the dashed line refers to the shorter viewing distance (2·2 cycles/degree): also, the lines represent the average sensitivity ratios for all observers and all test colours.

The video frequency of a television signal component which, applied to a 625-line television monitor viewed at 6 times picture height, would give rise to a pattern of equivalent angular spatial frequency is also indicated on the Figure.

It is clear that since ϕ_{av} increases with increasing degree of perceptibility the denominator of ϕ_{av}, i.e. ($\delta(u, v)$, must increase at a somewhat lower rate than that of the numerator $\delta V/V$. Thus, from the slopes of the lines in Fig. 20, it may be shown that the relation between the magnitude of chromaticity-only variations and perceptibility is approximately 3·3 dB per grade, compared with the assumed value of 5 dB per grade for luminance-only variations.

A5. Conclusions

1. A general conclusion which may be drawn from the results is that the rate of change of perceptibility with change in absolute luminance, or with viewing distance or with perturbation magnitude is greater for chromaticity-only variations than for luminance-only variations. Consequently the visual sensitivity ratio is somewhat dependent on these factors. The average value of the ratio at the just-perceptible level was found to be in the range 2 to 3.

2. If, as in this report, the chromatic variations are measured on the C.I.E.-U.C. scale, i.e. $\delta(u, v)$, then the visual sensitivity ratio appears to be substantially independent of the chromaticity of the colour and the direction of the variation for a given magnitude of perturbation. (Chromatic variations along the cyan to yellow axis may be a significant exception to the latter statement.)

3. For a given colour and perturbation magnitude, the visual sensitivity ratio appears to be substantially unaltered by the presence of other colours in the surrounding visual field of the same order of luminance.

A Recent BBC Technical Suggestion

CONTROL OF SOUND VOLUME IN BROADCAST RECEIVERS ACCORDING TO THE NATURE OF THE PROGRAMME

A common source of complaint by listeners to broadcast sound concerns the relative levels at which different types of programme are transmitted, and in particular, the relative levels of speech and music. Those listeners who use broadcast music as a low-level background to other activities tend to complain that news announcements or commentaries are too quiet, while those who reproduce music at a high level often find the accompanying speech uncomfortably loud. The following suggestion aims at satisfying listeners of both groups.

Broadcast receivers designed to take advantage of the proposal would be provided with alternative volume controls for speech and music; these controls, which could be connected in cascade with the normal volume control, would be pre-set by the listener in accordance with his personal tastes. Switching signals, transmitted by the broadcasting authority in such a manner as to be inaudible to the listener, would be detected by appropriate circuits in the receiver and would bring into operation one or other of the pre-set volume controls according to the nature of the programme. These switching signals would be varied as necessary by the broadcasting authority at each change of item and would be continuous, so that a receiver tuned in at any time in the course of an item would be automatically set to the appropriate volume. Indicator lights could be provided on the receiver to show which one of the two pre-set controls is operating at the moment. The receiver circuits would be so arranged that in the absence of the switching signals the system 'fails safe' by reverting to a single volume control for all items. In the programme as broadcast, the relative levels of the various items would be arranged as far as practicable to suit the needs of the majority of listeners using receivers of the existing type; it would then be open to any listener to satisfy his individual requirements at the cost of the more elaborate receiver described above.

The necessary switching signals would be transmitted in a form which would produce no audible interference with the programme, and in V.H.F. broadcasting could conveniently be accommodated in the modulation range 16 kc/s to 18 kc/s.

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