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FIRST EDITION

2nd. ISSUE

# COLORIMETRY AND THE BASIC COLOUR TELEVISION SYSTEM

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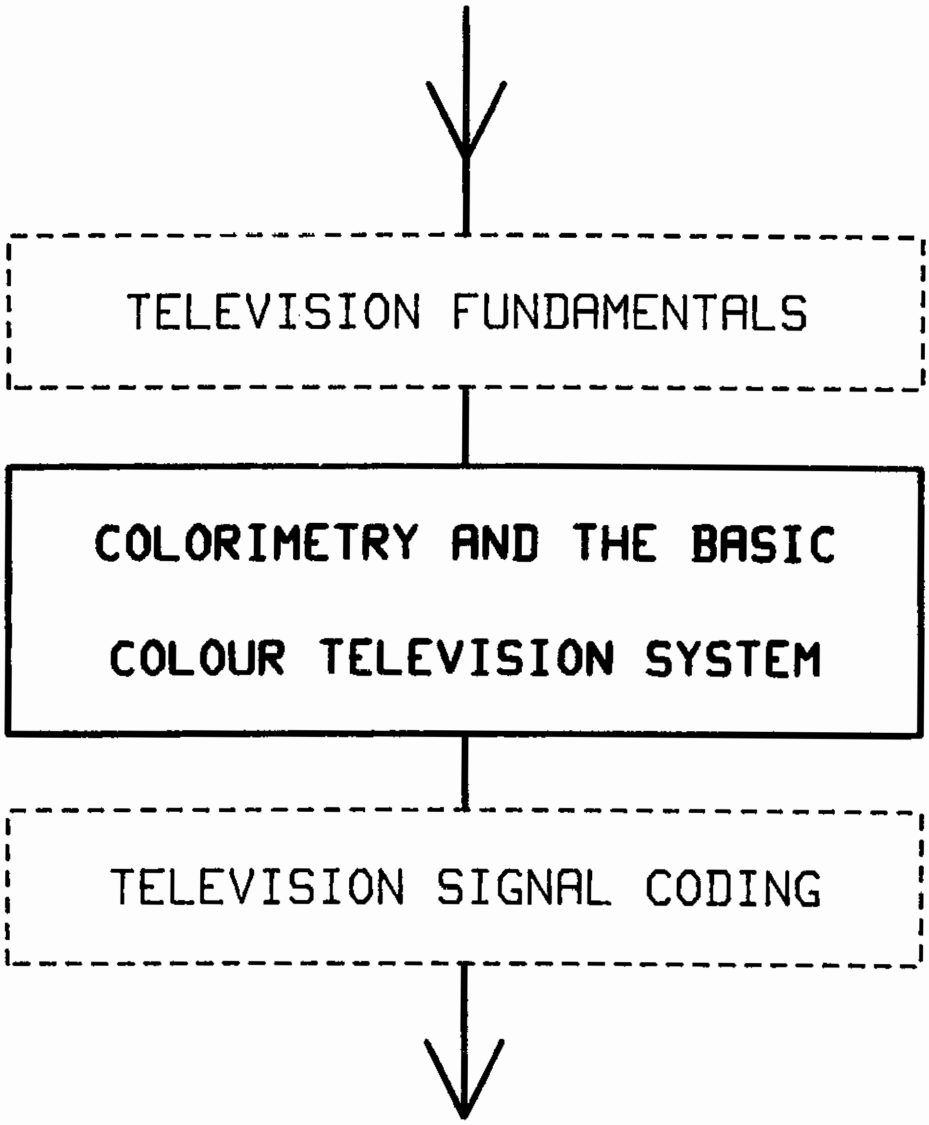
TELEVISION FUNDAMENTALS
COLORIMETRY AND THE BASIC COLOUR TELEVISION SYSTEM
TELEVISION SIGNAL CODING

## SUBJECT STRUCTURE

There are three packages in the Television Principles Module.

The first package dealt with the basic principles of television and developed the requirements of a basic monochrome (black and white) system. The television signal was constructed step-by-step and some particular circuit techniques were considered. Emphasis was placed on describing the U.K. 625 line system.

This is the second package and studies colorimetry. It also describes how the principles can be used together with the monochrome television system to provide a basic colour television system.

The third package develops further the basic colour television system into a final broadcast system. The NTSC system is considered first and then the U.K. PAL system. Reference is also made to the SECAM system.

# AIMS OF THE PACKAGE

Everything in our every day lives is coloured and it would be a far less interesting life if this were not so. The natural development of photography and television from the initial ability to reproduce black and white pictures was to go on towards colour reproduction.

The aim of this package is to introduce you to the study of colour. It will consider the principles of colorimetry applicable to television and combine with television fundamentals to produce a basic colour television system.

## PACKAGE STRUCTURE

The package consists of a written text, two practical demonstrations and two VHS Video Tape presentations.

The written text contains all the necessary theory, and a guide as to when the practical work and viewing of the video tapes are best carried out. The practical work and video tapes support the main text and do not introduce any new theory.

The text is divided into five main sections. An additional section covering a summary, model answers and the practical work are included at the end.

The five main sections are headed as follows.

1. RESPONSE OF THE EYE

   How does the eye respond to light?
   How does the eye respond to coloured light?
   How does the eye respond to the mixing of light?

2. COLOUR MATCHING

   What are the two ways of mixing two colurs together to produce a third?
   Is it possible to describe a colour mathematically?
   Is it possible to show graphically the position of colours with respect to each other

3. COLOUR ANALYSIS

   Is it possible to obtain a direct reading of what a colour is? (As opposed to a colour matching process).
   What are the outputs from a colour television camera?

4. COLOUR TEMPERATURE

   How do you define the quality of illumination from a light source?

5. A BASIC COLOUR TELEVISION SYSTEM

   What are the requirements for colour reproduction?
   How can we minimise the number of information channels?
   Must it be compatible with any existing monochrome system?

## STUDY GUIDE

There are two types of question within the text. The first type poses problems which you should try to answer before continuing. The text then considers the problem and gives reasons for the solution chosen.

The second type is a more formal question which you should answer. A model answer is given at the end of the package.

If at any time you do not understand the material being covered then ask your supervisor for help.

At the end of the text there is a summary of the work that has been covered.

When you have finished you will join with other groups and the supervisor for a tutorial

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# SECTION 1

# RESPONSE OF THE EYE

## SECTION ONE - RESPONSE OF THE EYE

White light, such as daylight, is made up of many different colours and this can be shown by passing a narrow beam of white light through a prism. Each wavelength of light is refracted by a different amount by the prism and the narrow beam of white light is therefore split up into its constituent colours. This array of colours is known as a spectrum.

You have available a colour photograph of the spectrum. This represents the wavelengths of electromagnetic radiation to which the eye is sensitive. The eye is sensitive to wavelengths from 400 to 700 nanometers. (nm)

By looking at the photograph of the spectrum sketch how bright the spectrum looks with respect to the wavelength of light.

You should have a sketch something like this

400 — 700 NM.

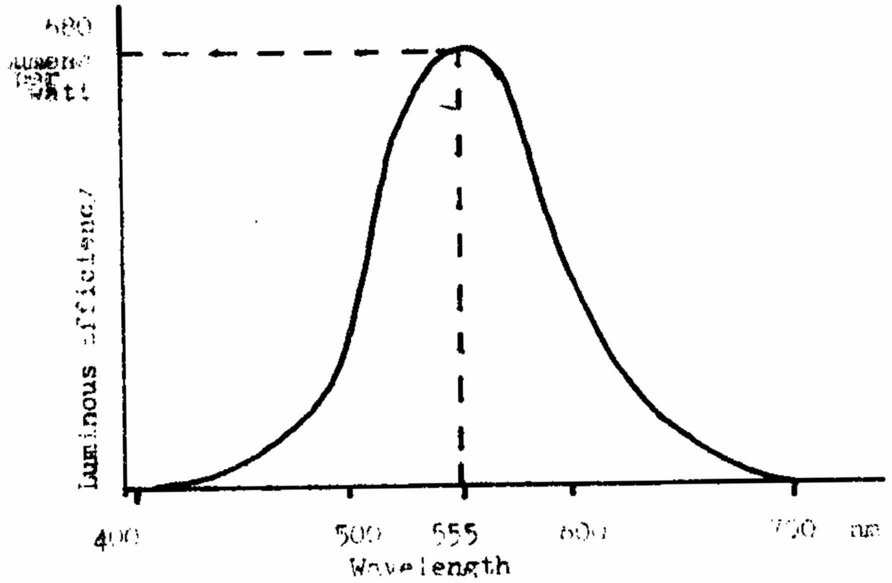


Figure 1.1 Photopic Curve

This response is known as the photopic curve. It is a measure of how bright the colours of the spectrum appear to the eye.

The curve you have drawn up will appear flatter than the sketch shown above, this is because the photograph is the best reproduction possible with a printing process. It is not as vivid as the spectrum produced by passing white light through a prism.

Another, more accurate, way to obtain a photopic curve is to take a large number of monochromatic, or single frequency, light sources, and radiate one watt of power at each of the single frequencies from these light sources. The perceived brightness of each of the light sources would again give the photopic curve.

Perceived brightness is measured in lumens, and one watt of radiated power at 555 nanometers gives 680 lumens of brightness. This is the peak of sensitivity of the photopic curve.

Go to the dark room at the back of L2 and carry out some colour matching on the visual matching colorimeter. See experiments 1 and 2 in Section 7 of this package.

By adjusting the three primary colours, R, G, and B in the colorimeter you should have obtained the following colour matches.

R + G gives yellow  
R + B gives magenta  
B + G gives cyan  
R + G + B gives white

What do these three colour mixes tell us about the response of the eye?

The eye has three different types of receptor. One receptor is sensitive to light mainly at the red end of the spectrum. Another is sensitive to light about the green or middle part of the spectrum. The third receptor is sensitive to light about the blue end of the spectrum. These three receptors are known collectively as cones.

The next experiment looked at the way in which the eye responded in low levels of illumination.

What you should have noticed is that as you gradually increased the light output you could see the shapes on the card before you could see what colour the shapes were. This means that in levels of low illumination, the eye only perceived brightness information and did not know anything about the colour of the object. This means that within the eye there is a second type of receptor. These are only sensitive in low levels of illumination and cannot distinguish between colours. They are known as rods.

No low l  
Colour perc

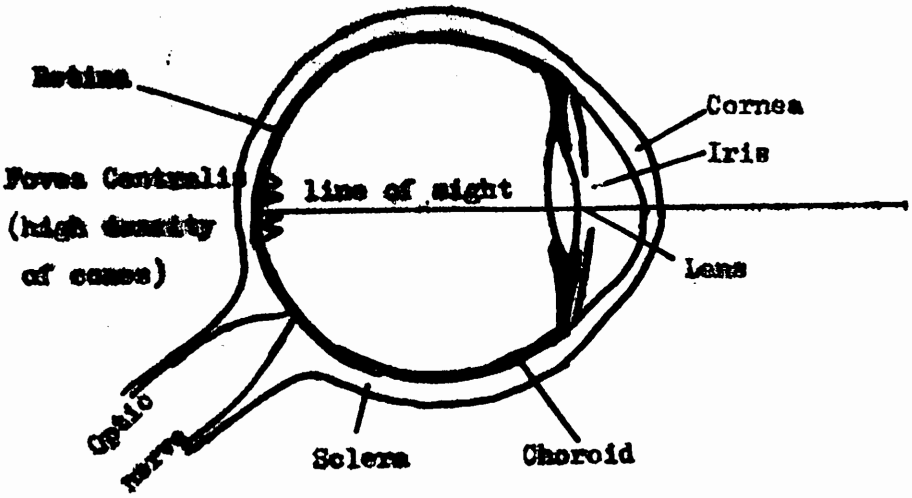


Figure 1.2 Cross Section of the Eye

A cross section of the eye is shown above. The cornea acts as a protective membrane, the iris controls the amount of light entering the eye and the lens is used to focus the scene onto the retina. The retina consists of rods and cones which act as the light sensing terminations to the optic nerve. The choroid contains a black pigment which absorbs light and so prevents unwanted internal reflections, rather like the matt black paint on the inside of a camera body. The cones are mainly grouped about the fovea centralis, which is on the line of sight. Away from the fovea centralis the rods and cones are interspersed until at the periphery only rods are present.

The sensitivity of the rods and cones to light is of a photo-chemical nature. The light falling onto the rods and cones causes a decomposition of the chemicals within the receptors and this in turn causes nerve impulses which are transmitted to the brain via the optic nerve. The nerve ends are constantly being recharged with fresh chemicals to replace those which have decomposed.

Within the cones there are three different photo-sensitive chemicals, one which absorbs mainly red light, one which absorbs mainly green light, and one which absorbs mainly blue light. The probable response curves of the three receptors are as shown below.

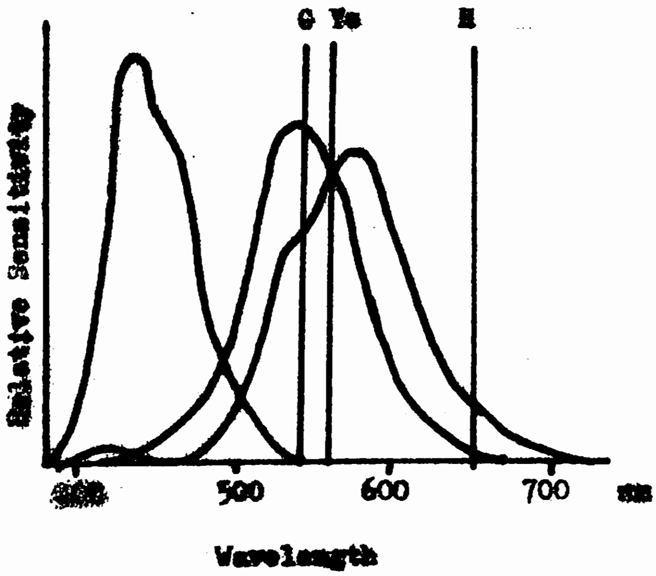


Figure 1.3 Probable Response Curves of the Three Receptors

If a monochromatic yellow light source and a monochromatic red primary and a monochromatic green primary are drawn on the probable response curves you should be able to see the means by which colour matching is obtained. As you can see, the yellow light source stimulates both the red and green receptors. It is therefore required that the two primaries shall stimulate the red and green receptors in the eye by the same amount as the yellow to which you are trying to match.

This completes the section on how the eye responds to both light and coloured light. You are now in a position to go on to the next section which deals in more detail with the matching of colours.

# SECTION 2

# COLOUR MATCHING

## SECTION 2 - COLOUR MATCHING

What are you trying to do when matching colours?

You have already looked at the response curves of the three colour receptors in the eye and colour matching is merely the process of stimulating those receptors, by use of three primary colours,to the same extent as the colour to be matched stimulated them.

The three primary colours may be mixed in two ways.

a) Additive - by mixing coloured lights.

b) Subtractive - by mixing coloured paints or dyes.

### Additive

The three most suitable primary colours for additive mixing are red, green and blue. These primaries may be obtained in several ways. One way would be to take three monochromatic, or single frequency, light sources. Another would be to take three white light sources and place a coloured filter in front of each. An important point here is that the colour produced would not be monochromatic. It would be broad band about the main wavelength. These two methods would probably involve shining the lights on to a reflecting screen and mixing them by superimposing the lights on top of one another.

How does a colour television tube work?

In a colour tube, dots of the three different types of phosphors are placed very close together, so forming groups of three primary light sources. When the three types of phosphor are stimulated by the electron beam, they emit red, green and blue light. The eye does not see three individual colours but integrates them together to see an additive mix of the three colours.

What colour does a mixture of red and green give?

Yellow

What colour does a mixture of red and blue give?

Magenta

What colour does a mixture of blue and green give?

Cyan

What colour does a mix of equal amounts of red green and blue give?

White

The three colours, yellow, magenta and cyan are known as COMPLEMENTARY COLOURS.

## Subtractive

All materials that we look at reflect some wavelengths and absorb others. For example, an object that looks red reflects wavelengths at the red end of the spectrum and absorbs most of the light of wavelengths that are at the green and blue end of the spectrum. An important point here is that the wavelengths that are reflected will be broad band about the colour we are seeing, and not by any means a monochromatic colour. Also there will be some reflection, albeit attenuated, of all the visible wavelengths.

In our example of an object that looks red a plot of the reflected light against frequency could look like this.

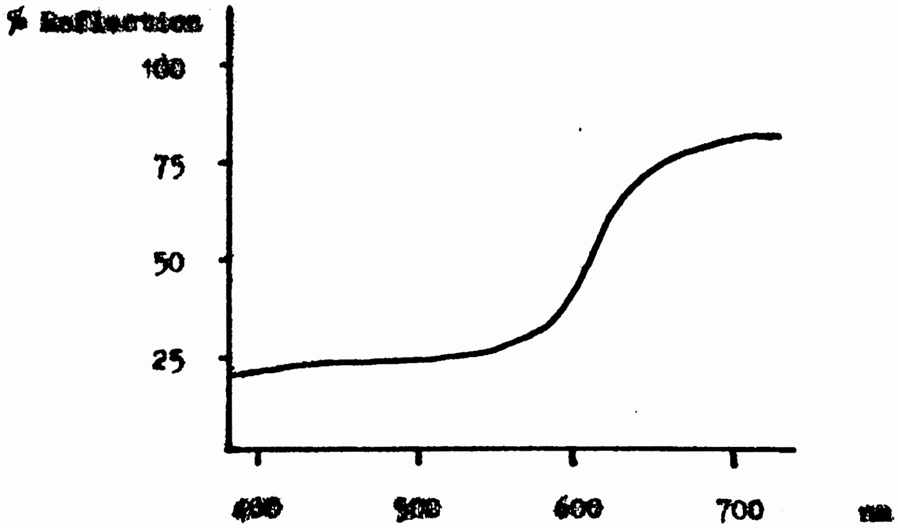


Figure 2.1 Spectral Reflection of a Red Object

What would be the effect of reflecting more green and blue light? The red would look desaturated and the reflected light response would be like this.

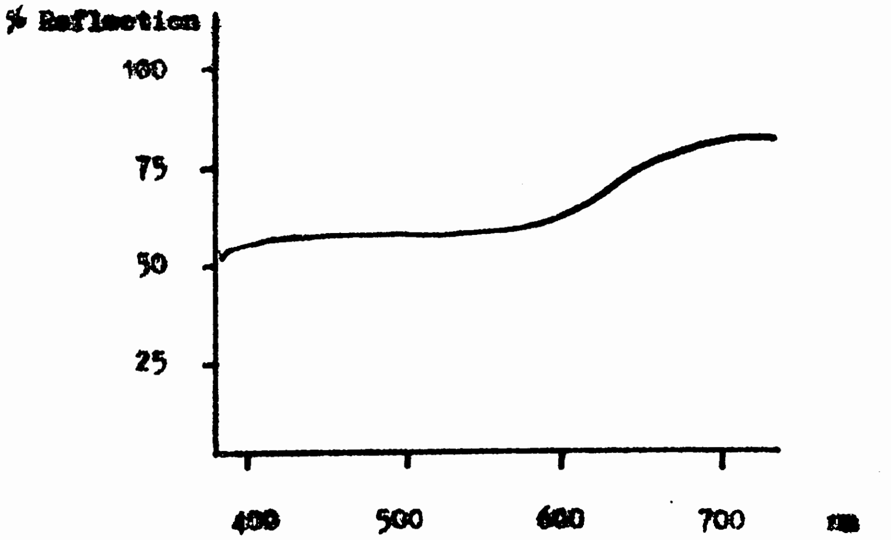
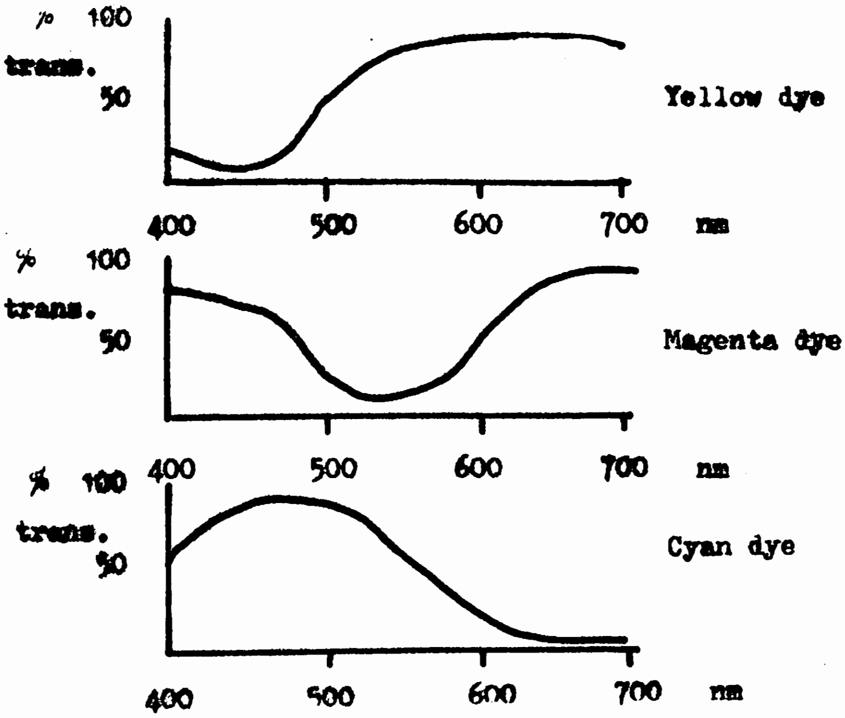


Figure 2.2 Spectral Reflection of a Desaturated Red Object

Now consider the subtractive mixing of colours.

Shown below are the spectral transmission curves for typical yellow, magenta and cyan dyes. These curves show the amount of light, at each wavelength, that will pass through the dye.



R+G (-B)

R+B (-G)

B+G (-R)

Figure 2.3 Transmission Curves of Subtractive Primary Dyes

This means that if the yellow dye was printed on to white paper and then illuminated with a white light, the dye would look yellow. Why? Because the yellow dye absorbs blue light, but transmits red and green light. This stimulates the red and green receptors in the eye and the brain calls that yellow.

Similarly the magenta dye absorb green light, and the cyan dye absorbs red light.

Bearing this in mind, what colour would you obtain by mixing the yellow and magenta dyes together?

The yellow dye absorbs blue and transmits red and green.

The magenta dye absorbs green and transmits blue and red.

If they are mixed together, the yellow absorbs blue and the magenta absorbs green and they jointly transmit red. Therefore the colour produced is red.

$$\mathrm{Ye} \equiv R + G$$
$$\underline{\mathrm{Ma} \equiv R \quad + B}$$
$$\mathrm{Ye} + \mathrm{Ma} \equiv R$$

Similarly, work out the colours obtained by mixing together yellow and cyan, and cyan and magenta.

y+c = G   c+m = B   y+m = R

You should have obtained,

yellow + cyan ≡ green

$\mathrm{Ye} \equiv \mathrm{R} + \mathrm{G}$

$\underline{\mathrm{Cy} \equiv \quad \mathrm{G} + \mathrm{B}}$

$\mathrm{Ye} + \mathrm{Cy} \equiv \quad \mathrm{G}$

Cyan + magenta ≡ blue

$\mathrm{Cy} \equiv \quad \mathrm{G} + \mathrm{B}$

$\underline{\mathrm{Ma} \equiv \mathrm{R} \quad + \mathrm{B}}$

$\mathrm{Cy} + \mathrm{Ma} \equiv \qquad \mathrm{B}$

The three colours yellow, cyan and magenta are known as the subtractive primary colours or sometimes as the artists primary colours.

Another way to consider the action of the subtractive primary colours is as follows:

$\mathrm{White} \equiv \mathrm{R} + \mathrm{G} + \mathrm{B}$

$\mathrm{Yellow} \equiv \mathrm{White} - \mathrm{B}$

$\mathrm{Cyan} \equiv \mathrm{White} - \mathrm{R}$

$\mathrm{Magenta} \equiv \mathrm{White} - \mathrm{G}$

Now view the V.H.S. Video Tape on Colorimetry from counter reading 111.

<u>Properties of Coloured Materials</u>

If you look at a coloured object what properties about the colour of that object are you seeing?

a) HUE is given by the predominant wavelengths that are reflected.

b) BRIGHTNESS OR LIGHTNESS is given by the amount of light that is reflected.

c) <u>SATURATION</u> is given by the amount by which the main reflected wavelengths predominate over the other reflected wavelengths, i.e. the amount of colour over the amount of white light.

## Colour Matching

The diagram below shows a visual matching colorimeter.

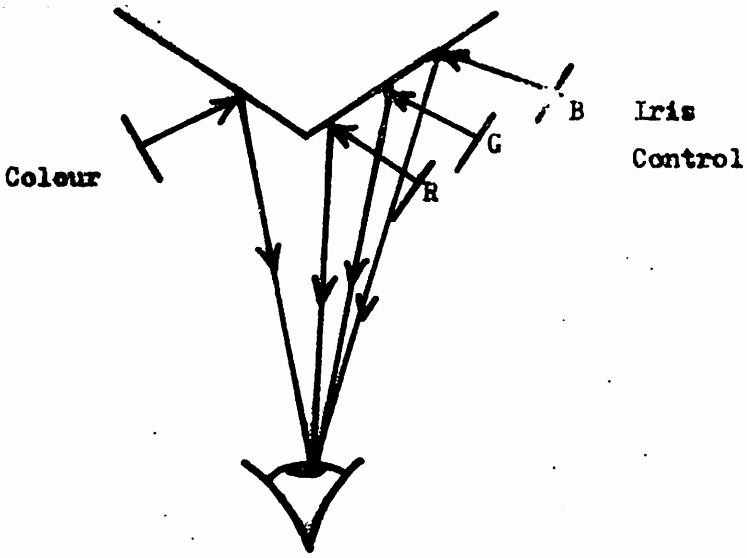


Figure 2.4 Visual Matching Colorimeter

A colour, C, is reflected from the left hand side of a white screen. On the right hand side are three projectors with red, green and blue filters in front of them to give the three primaries. By adjusting the amounts of red, green and blue, it is possible to match the unknown colour. It is also possible to calibrate the three variable primaries. The units used being lumens.

Now, if a colour C is matched by five lumens of red, six lumens of green, and seven lumens of blue..

The result may be written as:-

$C \equiv 5(R) + 6(G) + 7(B)$ (where $\equiv$ means "equivalent to" or "matched by" and the () means "units of")

and the quantity of C will be 5 + 6 + 7 = 18 lumens.

Therefore $18(C) \equiv 5(R) + 6(G) + 7(B)$.

i.e. 18 units of a colour are matched by 5 units of Red + 6 units of Green + 7 units of Blue. In this case the units are lumens.

Value The general form of the above is:

$C\ (C) \equiv R\ (R) + G\ (G) + B\ (B)$.

The values of R, G, and B are known as the TRI-STIMULUS values of the unknown colour. This equation is three dimensional and in order to present the colour graphically we reduce it by dividing both sides of the equation by R + G + B.

i.e.

$$\frac{C}{R+G+B}(C) \equiv \frac{R}{R+G+B}(R) + \frac{G}{R+G+B}(G) + \frac{B}{R+G+B}(B)$$

$$\frac{1}{3} \qquad \frac{1}{3} \qquad \frac{1}{3}$$

$$\therefore\ 1(C) \equiv r(R) + g(G) + b(B)$$

where $r = \frac{R}{R+G+B}$, $g = \frac{G}{R+G+B}$ and $b = \frac{B}{R+G+B}$

r, g and b are now only proportions of the primary colours in this match and r + g + b = 1.

Therefore, we need only specify two of the values, usually r and g.

What information have we lost due to the normalising of the equation?

r, g and b do not completely describe the colour, which involves quantity and chromaticity. They only describe CHROMATICITY (i.e. hue and saturation) and not total amount of light. They are referred to as the CHROMATICITY CO-ORDINATES.

If we take our chromaticity co-ordinates and plot them on graph paper, we get a CHROMATICITY CHART.

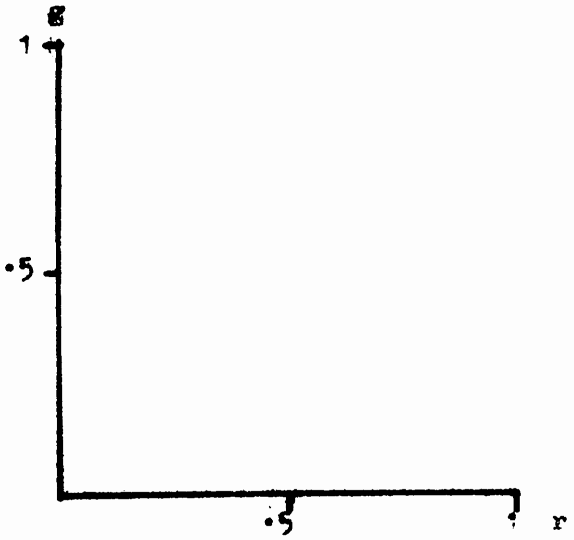


Figure 2.5 Chromaticity Chart

What happens to blue? If we plot chromaticities in terms of r and g, b is implicit (b = 1 - r - g). Therefore, blue plots at the origin of the chromaticity chart, i.e. when g and r = 0, b = 1.

Let's take an example:- a colour is matched by 50 lumens of red, 150 lumens of green and 50 lumens of blue.

Therefore, 250 (C) ≡ 50 (R) + 150 (G) + 50 (B)

Divide through by 250.

Therefore, 1 (C) ≡ .2(R) + .6(G) + .2(B)

This could be plotted as shown below.

$\frac{30}{50}$ = ·29

$\frac{200}{350}$ = ·57

$\frac{50}{350}$ = ·14

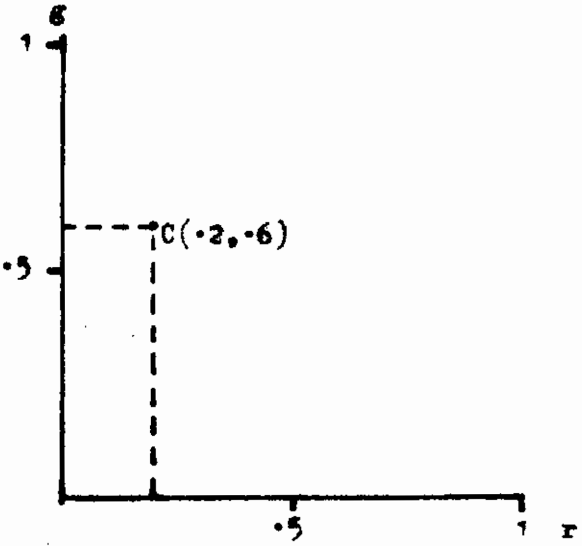


Figure 2.6 Plot of (.2r, .6g)

Questions

Calculate the chromaticity co-ordinates and plot on a chromaticity chart the following colours.

1. Colour, C1, is matched by 100 lumens of red, 200 lumens of green and 50 lumens of blue.
2. Colour, C2, is matched by 25 lumens of red, 100 lumens of green, 25 lumens of blue.

Model Answers are given at the back of this package on page 6.4.

·29(R) + ·57(G) + ·14(B)

C1 = 350(C) ≡ 100(R) + 200(G) + 50(B).

·166(R) + ·66(G) + ·166(R)

C2 150(C) ≡ 25(R) + 100(G) + 25(B)

If the NTSC primaries are chosen, then it is found experimentally that white is matched by:-

1W ≡ .3(R) + .59(G) + .11(B).

This would plot on the chromaticity chart as shown.

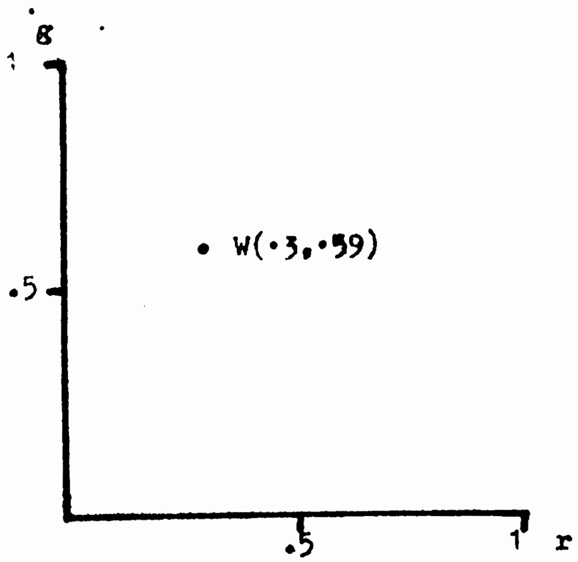


Figure 2.7 Plot of NTSC White

This imbalance of co-ordinates is inconvenient from both a colorimetry and an engineering point of view, because most colours plot near white. Therefore, it was decided to use units such that equal quantities of the three primaries were required to match white.

This new unit is the TRI-CHROMATIC UNIT or T UNIT.

In lumens, 1(W) ≡ .3(R) + .59(G) + .11(B) whereas
In T units, 3(W) ≡ 1(R) + 1(G) + 1(B)

We can now establish a conversion between lumens and T units.

Namely, one lumen white = 3T units of white.
.3 lumens red = 1T units of red.
.59 lumens green = 1T units of green and
.11 lumens blue = 1T units of blue.

Chromaticity charts are still used but are now in terms of T units.

By convention, the colour matching equations are always written on T-units unless stated otherwise.

Draw a chromaticity chart in T units and plot white. What will be the values of r, g and b for white?

$3(W) \equiv 1(R) + 1(G) + 1(B)$

$\therefore$ $1(W) \equiv .33(R) + .33(G) + .33(B)$.

$\therefore$ The chomaticity co-ordinates are r = .33, g = .33

This will plot as shown.

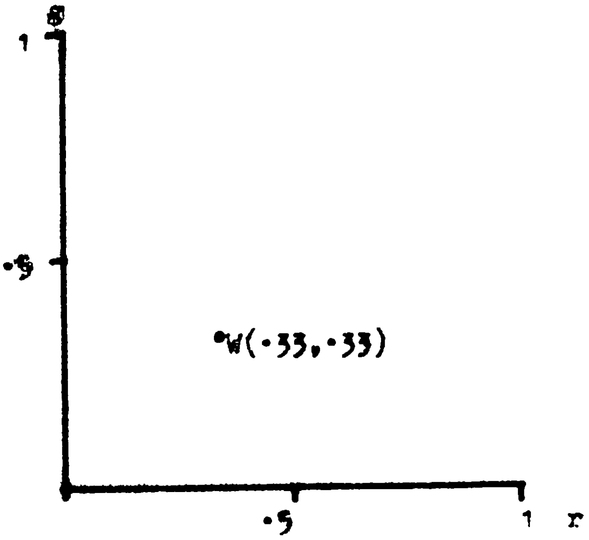


Figure 2.8 Plot of White in T Units

If you want to know how bright a colour appears, then the calculations have to be done in Lumens. Lumens being a measure of perceived brightness.

Example

How bright were the colours C1 and C2 in the previous example?

C1 = 100 + 200 + 50 = 350 lumens.

C2 = 25 + 100 + 25 = 150 lumens.

Example

In the television system, a colour is matched by 100 T units of red plus 150 T units of green plus 50 T units of blue. How bright is that colour?

Brightness is measured in lumens, therefore we have to convert from T units to lumens and then sum the total number of lumens.

$C \equiv 100(R) + 150(G) + 50(B)$

100R = 100 x .3 lumens of Red = 30 lumens

150G = 150 x .59 lumens of Green = 88.5 lumens

50B = 50 x .11 lummens of Blue = 45.5 lumens

$\therefore$ Total brightness = 30 + 88.5 + 5.5 = 124 lumens

Question

3. The following colour matches are in T units

$C1 \equiv 50R + 200G + 250B$

$C2 \equiv 100R + 150G + 100B$

$C3 \equiv 100R + 250G + 25B$

Plot all 3 colours on a chromaticity chart. Which colour is the brightest? A model answer is given at the back of the package.

Finally, on colour matching, let's consider the problem of trying to match the colours of the spectrum. Take as the three primaries, three monochromatic light sources. Take as the colour to be matched, small parts of the spectrum in turn.

If you started by trying to match a monochromatic cyan, you would find that the colour obtained from the primaries would always look too red.

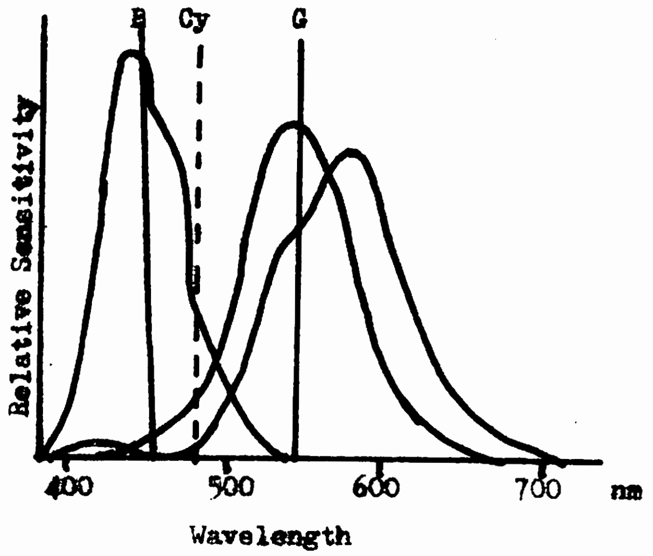


Figure 2.9 Receptor Response Curves

If you look at the three receptor responses, as shown above, we can see why.

Which receptors in the eye does the monochromatic cyan stimulate?

It stimulates mainly the blue and the green receptors, but the red receptor hardly at all. However, when you turn up the blue and green primaries, which receptors in the eye do they stimulate? The blue primary stimulates mainly the blue receptor in the eye. But, the green primary not only stimulates the green receptor, but also the red receptor. This means that on adjusting the blue and green primaries, the colour match obtained would always look too red.

Is it possible to obtain a visually correct colour match? The answer, is to take a visually matching colorimeter and add three more variable primaries to the left hand side of the colorimeter. This gives a visually matching colorimeter as shown below.

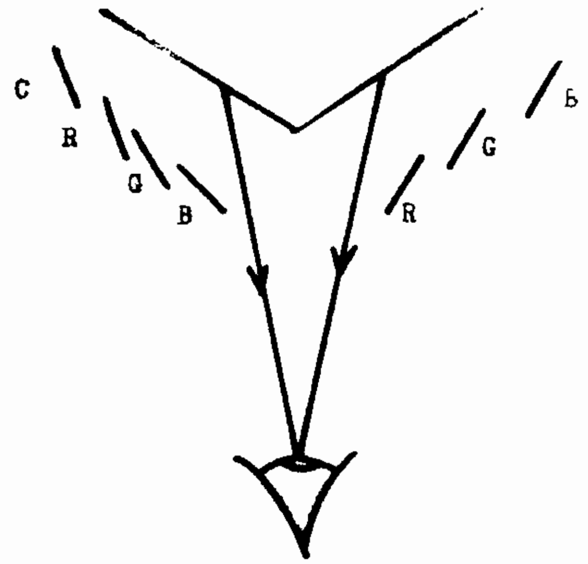


Figure 2.10 Visual Matching Colorimeter

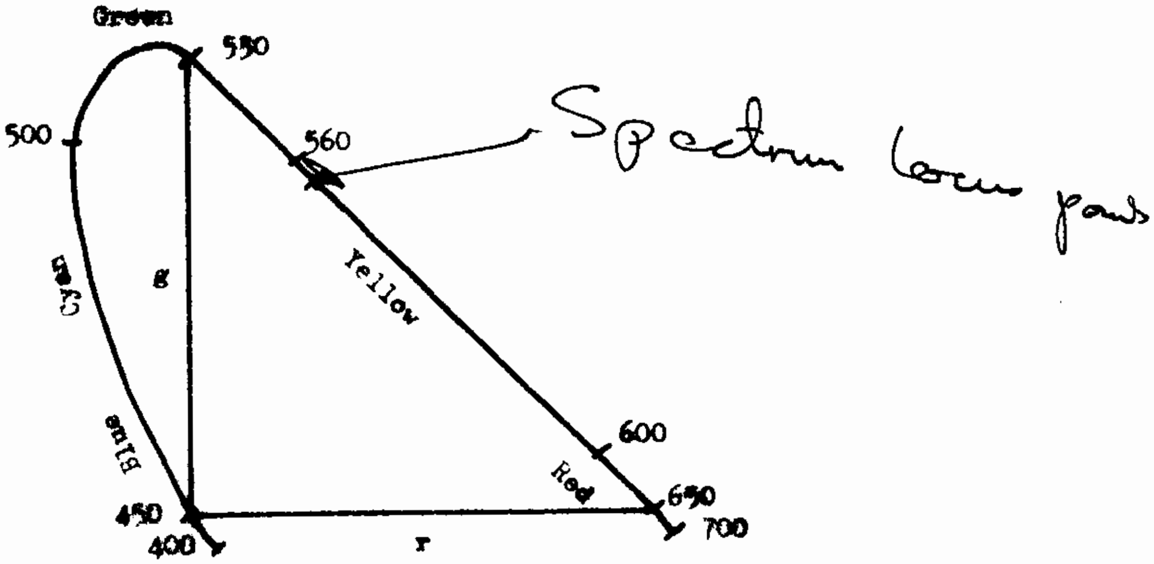
You can now take a mixture of the original cyan, plus a small amount of the red primary on the left hand side of the screen and match it by adjusting the amounts of the blue and green primaries on the right hand side of the screen. This would give a match of:-

Cyan + red ≡ blue + green.

Therefore cyan ≡ - red + blue + green.

Most spectral colours require this idea of negative colour in order to obtain a visual match. It is a function of the broad band and overlapping eye response curves.

A spectrum would plot on a chromaticity chart as shown below.



Spectrum locus points

Figure 2.11 Spectrum Locus

The points so plotted are known as the spectrum locus.

**Example**

$50\ (Cy) + 10\ (R) \equiv 25\ (G) + 5\ (B)$

Therefore $1(Cy) \equiv -.2(R) + .5(G) + .7(B)$.

This will plot on a chromaticity chart as shown below.

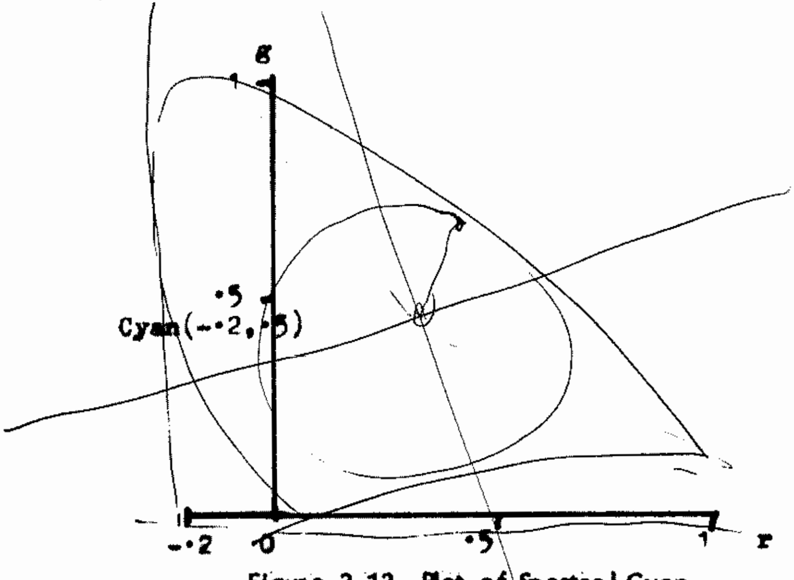


Figure 2.12 Plot of Spectral Cyan

So that is colour matching. You have considered additive and subtractive colour mixing. You have matched colours and reduced the matching equation in order to be able to plot the colour on a chromaticity chart. You have then moved on from a measure in lumens to one in T units. T units are used in television to make the lining up of cameras and monitors much easier, because for grey or white R = G = B.

Read on to the end of this section and then go back to the dark room and colour match a selection of the filters that are available. Plot the colour matches on a chromaticity chart.

From this experiment two points should be noted. Firstly, visual colour matching is a slow and fairly difficult procedure. Secondly, it is unlikely that different members of a group will produce exactly the same colour match for each sample.

These two points led to the need for a direct reading colorimeter. It had the response of a "standard observer", and gave a direct reading of the amount of stimulation that would be required from each of the three primaries.

The next section considers the analysis of colour and the electrical signals required from a camera in order to reproduce a colour on a monitor. It is, in effect, a direct reading colorimeter, whose outputs are the stimulation required by the colour television primaries.

Now go to Section 7, experiment number 3.

# SECTION 3

# COLOUR ANALYSIS

## SECTION 3 - COLOUR ANALYSIS

It would be possible to make a direct reading colorimeter to measure the amount of red, green and blue primaries required for a colour match. This could be done by placing different filters, in turn, in front of a photo-electric cell. The voltage reading being a measure of the amount of red, green and blue stimulation in the colour.

In television, we are trying to recreate a coloured scene on a television tube. This involves a direct measurement of the amount of stimulation required for the three primary phosphors in the tube in order to obtain a colour match.

The direct measurement of each element of the scene is obtained by means of scanning. The parts that we are most interested in at the moment, is the amount of red. green and blue drive required for a colour match. This amount depends upon the tube phosphors.

### Colour Camera

The first requirement is for three camera tubes. One sensitive to red light, one to green light and one to blue light. Camera tubes, as manufactured, are sensitive to light within the visible spectrum. The required sensitivity to red, green and blue is obtained by placing a frequency selective filter in front of each tube.

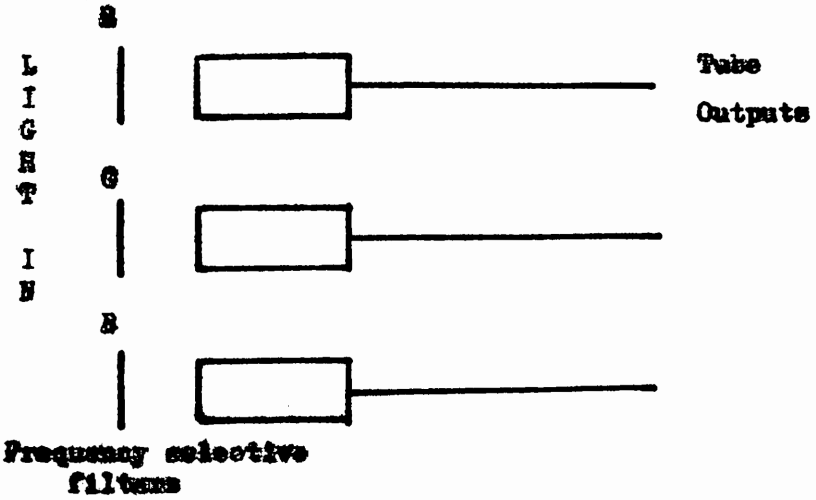


Figure 3.1 Basic Colour Camera

The above diagram looks fine, but in the previous section what was the problem when trying to match cyan? We needed either to add red to the cyan or to obtain negative red on the matching primary side in order to obtain a colour match.

This is also the case when trying to match other spectral colours.

On a chromaticity chart using the NTSC primaries the spectrum locus plots as shown below.

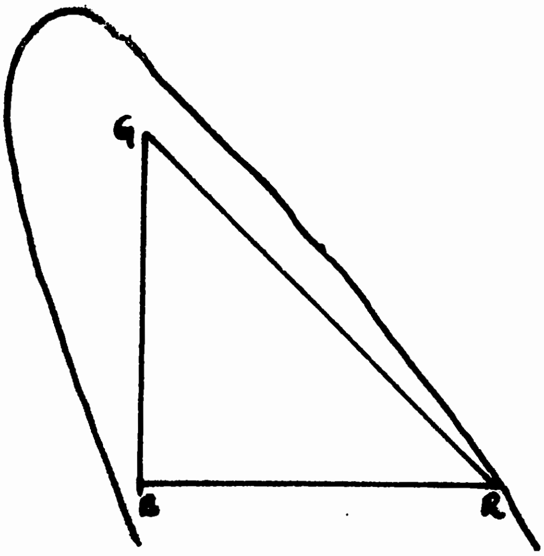


Figure 3.2 Spectrum Locus

Another way of describing the spectrum is by using Colour-matching functions. The colour-matching functions show the amount of red, green and blue light required to match unit power of each wavelength of the spectrum. i.e. Take each wavelength of the spectrum in turn and obtain a colour match in terms of the red, green and blue primaries. Then plot the amount of stimulation required from each primary against wavelength.

For the wavelengths between 500 nm and 600 nm you would obtain the following plots for the ~~NICS~~ phosphors.

NTSC

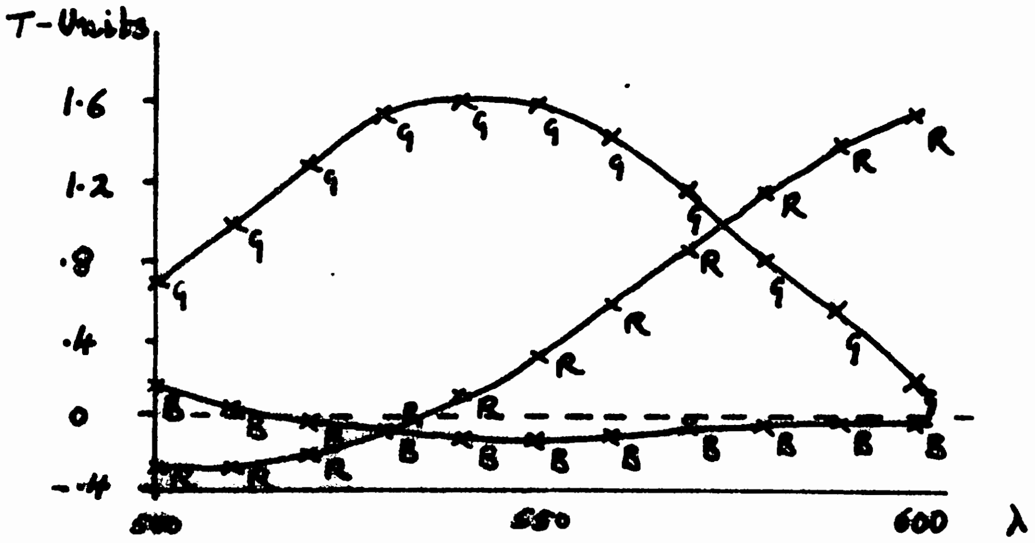


Figure 3.3 Colour Matching Functions

By joining together all the blue stimulations you obtain a curve slowing the amount of NTSC blue primary light in the spectrum. Similarly for the red and green stimulations you obtain curves showing the amount of NTSC red and green primary light in the spectrum.

If this procedure is carried out for all wavelengths in the visible spectrum, then a set of curves is obtained which will be the ideal camera response curves for correct colour analysis. These curves are shown below.

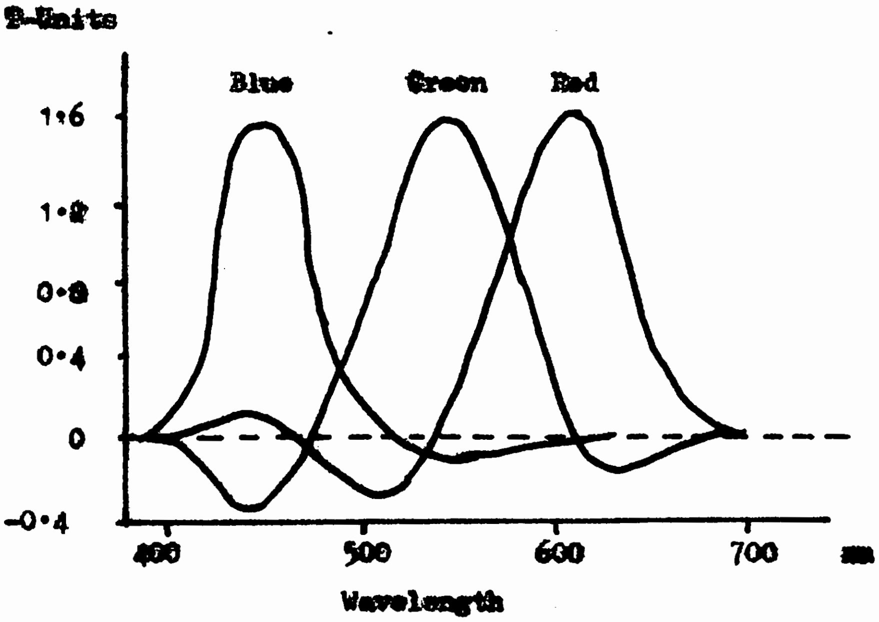


Figure 3.4 Ideal Camera Channel Response Curves for NTSC Phosphors

The problem now is how to obtain these curves in practise. The basic colour camera shown on page 1-3 will only give positive outputs around the blue, green abd red parts of the spectrum. It is not possible to make a camera tube that gives a positive output at some wavelengths and a negative output at others.

One way would be to provide a camera tube with its output suitably shaped and inverted, if necessary, for each portion of the response curves. You would need a tube for

1. the positive blue output
2. the positive green output
3. the positive red output
4. the negative blue output
5. the negative cyan output
6. the negative green output
7. the negative red output
8. the low level of red stimulation required at the blue end of the spectrum.

The outputs from these tubes could then be combined to give the final Red, Green and Blue response curves.

This would result in a large and expensive colour camera.

The answer was to use a resistor matrix and sum and difference inputs to an amplifier to combined the outputs from three tubes in order to provide the camera response curves. See diagram below.

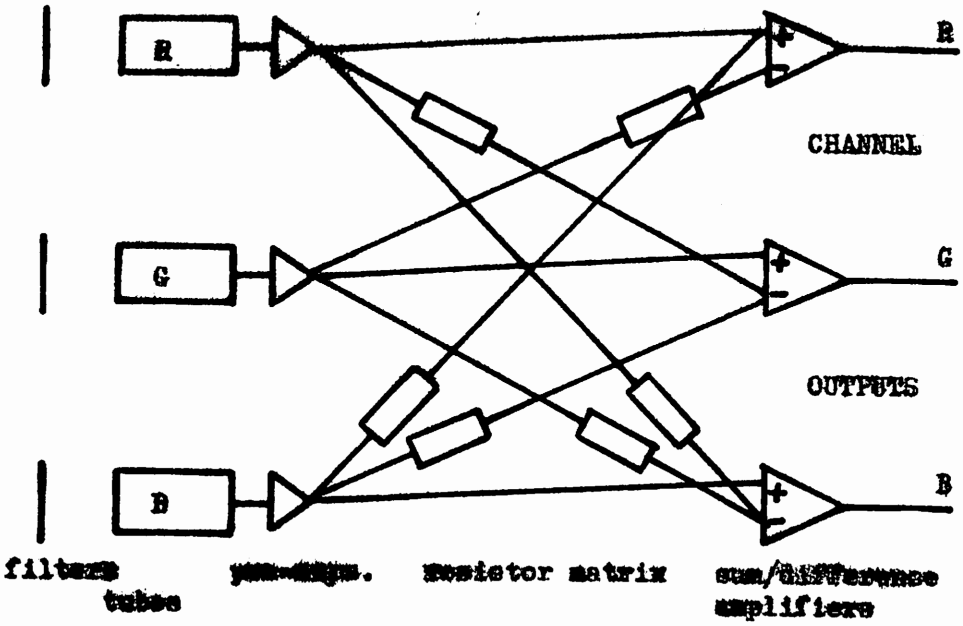


Figure 3.5 Colour Camera with a Matrix

How are the resistor values and cross commections chosen?

These values depend upon the required camera channel outputs. As we have already seen, these outputs depend upon the phosphors in the television tube.

After matrixing the practical response curve will look like this.

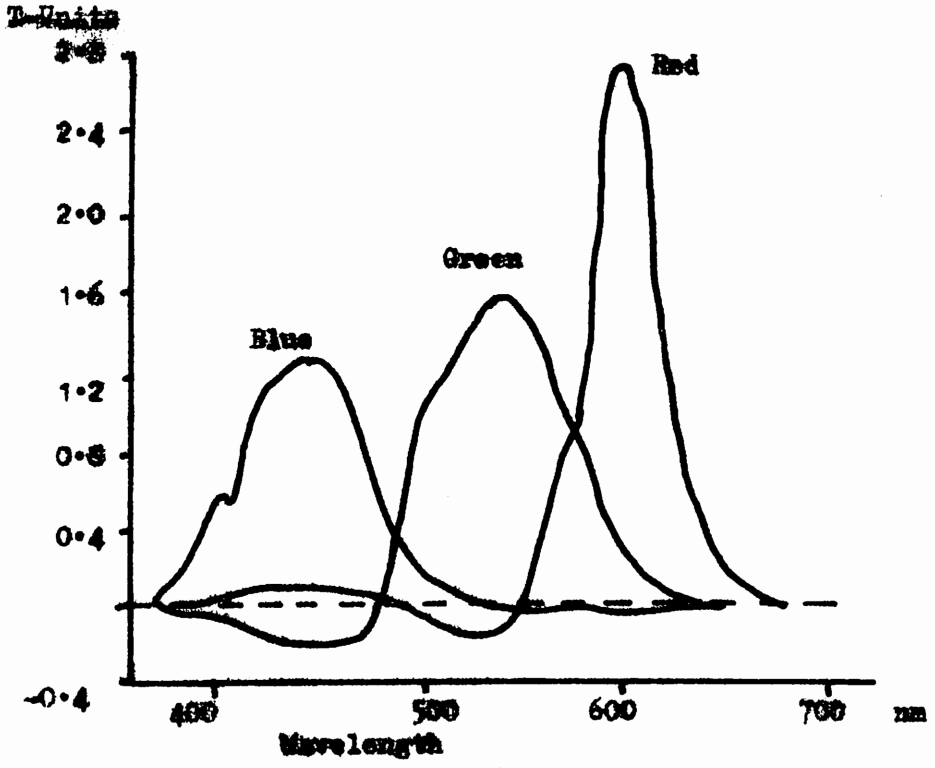


Figure 3.6 Practical Camera Channel Response Curves after Matrixing

By matrixing we have managed to produce negative lobes to the response curves. Unfortunately, the colour television display tube is unable to glow negatively and therefore we are still unable to produce colours lying outside the NTSC chromaticity triangle. However, in the diagram shown below the shaded area represents the gamut of chromaticities occurying in pigments illuminated by daylight. As you can see only a few lie outside the triangle.

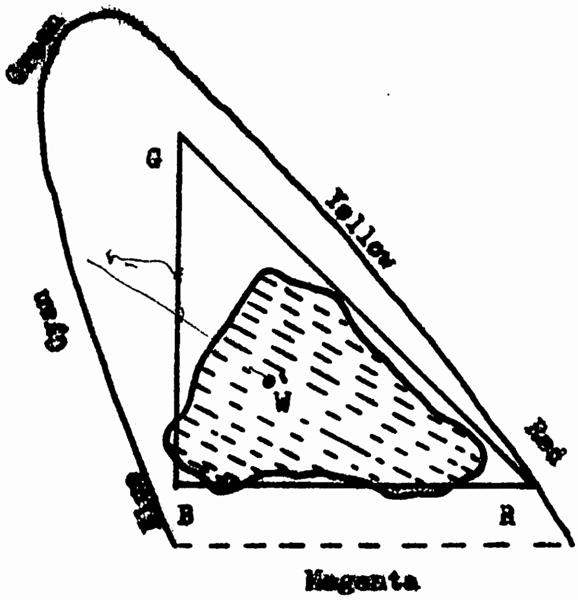


Figure 3.7 NTSC Chromaticity Triangle

The inability to reproduce the spectral colours on a colour monitor, and the fact that most known pigments lie within the chromaticity triangle does not mean that we do not require matrixing. For ordinary pigments, in order to reproduce them accurately, we still need negative lobes and the idea of negative colour.

The following example of colour matching shows the need for negative colours, even for those pigments that lie within the chromaticity triangle.

Example

Take the previous example of cyan on page 2.12 where (in T units)

$50Cy + 10R \equiv 25G + 35B.$

Therefore $50Cy \equiv -10R + 25G + 35B$

Therefore $1Cy \equiv -.2R + .5G + .7B$ equation 1.

Plot this point on a chromaticity chart (point 1).

Now take the same hue of cyan but one that has been desaturated by 30 T units of white.

Therefore $80Cy + 10R \equiv 25G + 35B + (10R + 10G + 10B).$

(Remember, $30\ W = 10R + 10G + 10B$).

Therefore $80Cy \equiv 35G + 45B.$

Therefore $1Cy \equiv .44G + .56B.$ equation 2.

Plot this point on a chromaticity chart (point 2).

Points one and two have been found by using a visual matching colorimeter. If we now look at these two same colours with a camera, the camera outputs should be the same as the right hand side of the equation. If not, then the camera is distorting the reproduction of the colours, i.e. it does not have correct colorimetry.

Take the first example of cyan, and look at it with a camera. The camera tube outputs would be 25T units of green and 35T units of blue. If there was not a matrix, then the channel output would also be 25T units of green and 35T units of blue.

Therefore $cyan \not\equiv 25G + 35B$

The camera would therefore be giving a total reading of 60 T units.

Therefore $60\ Cy \equiv 25G + 35B.$

Therefore $1Cy \equiv .42G + .58B.$ equation 3.

Plot this point on the chromaticity chart (point 3).

Now, take the desaturated cyan. What will the camera outputs be without the matrix?

$Cyan \equiv 25G + 35B + 10R + 10G + 10B$

$Cyan \equiv 10R + 35G + 45B$

Therefore $90Cy \equiv 10R + 35B + 45B$

Therefore $1Cy \equiv .11R + .39G + .5B$ equation 4.

Plot this point on the chromaticity chart (point 4).

If a matrix were included in the camera channels, then the minus 10T units of red would be produced and correct channel outputs would follow.

The conclusions to be drawn from this exercise are as follows:-

a. If the camera channel has a matrix, then it produces negative lobes.

b. If negative lobes are produced, then the camera will correctly analyse the colour and the colour will be correctly plotted on the chromaticity chart.

c. Point 1 will not be displayed correctly on a monitor, because even with negative gun drives, the phosphors cannot glow negatively.

d. However, point 2 will not only plot correctly, but will also be displayed correctly, because the positive and negative inputs to the red channel cancel out.

e. If a camera does not have a matrix to produce negative lobes, then point 2 which lies within the boundary of the chromaticity triangle will not only plot incorrectly, but will also be displayed incorrectly.

It will appear desaturated and slightly the wrong hue.

Now view the VHS Video Tape on Colorimetry from the beginning.

## Light Splitting

The camera tubes are basically sensitive to all wavelengths within the visible spectrum. It is therefore necessary to split the incoming light into its red green and blue components. This is done by using frequency selective dichroic mirrors.

A single untreated glass surface will reflect approximately 4% of the incident light. If the glass is coated with a material having a higher refractive index than the glass then the reflection can be increased to 40 - 50% of the incident light. Maximum reflection occurs when the coating thickness is λ/4 of the incident light.

If multiple layers of alternate high and low refractive index are used then the reflection at some parts of the spectrum can be as high as 90% and as low as 10% at others.

In practice the layers are deposited onto the back of prisms which are then cemented together. This results in a compact block which is hermetically sealed.

A typical light splitting system is shown below.

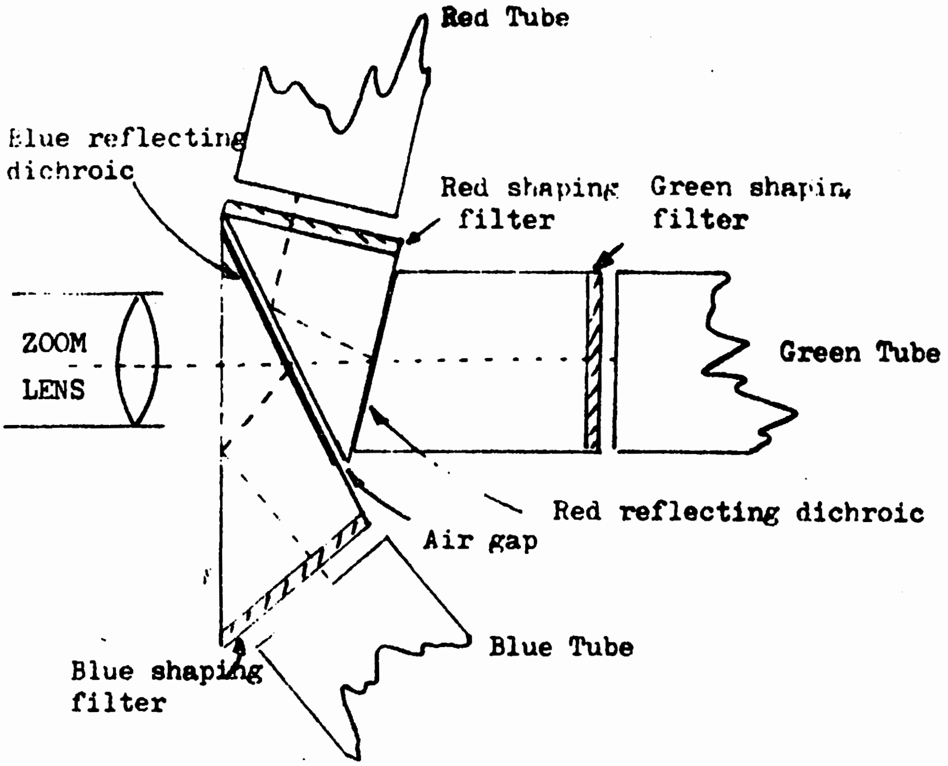


Figure 3.8 Light Splitting Within the Camera

Light passes through the zoom lens to the blue reflecting dichroic. At this point light at the blue end of the spectrum is reflected and the rest passes on to the red reflecting dichroic.

At the red reflecting dichroic, the red end of the spectrum is reflected and the remaining green light passes on.

After splitting into its red, green and blue components, the light passes through a shaping filter before being focussed on to the target of the tube. The shaping filter is used to ensure that the spectral sensitivity of the camera tube is that required for correct stimulation of the television tube phosphors.
In other words, it affects the shape of the camera response curves.

Although camera tubes are basically sensitive to all wavelengths of light within the visible spectrum, they are marked for use in the red, blue or green channels by the manufacturer. There are two reasons for this.

Firstly, it is quite difficult to manufacture a tube that is sensitive to the limits of the eye response at the red end of the spectrum. The manufacturer therefore makes special efforts on the tubes to be used in the red channel. They are called EXTENDED RED tubes.

Secondly, the sensitivity of the tube to different wavelengths of light depends to some extent on the thickness of the target layer and after manufacture, the tubes are tested on their sensitivity to light at the blue and green parts of the spectrum, and are labelled accordingly.

That completes the section on colour analysis. You now know the shape of the signals required from a camera to produce a correct colour match on monitor, and how this is produced in practice.

# SECTION 4

# COLOUR TEMPERATURE

## SECTION 4

## COLOUR TEMPERATURE

What factors affect the perceived colour of an object?

Firstly, it will depend upon the reflectivity against wavelength characteristic of the object. The peak reflectance giving hue and the balance between the main wavelengths and the rest giving saturation.

Secondly, it will depend upon the spectral power distribution of the light source. (i.e. the power at each wavelength in the visible spectrum.) This is because the object can only reflect wavelengths that are present in the illuminating source.

A means of calibrating light sources was therefore required.

What is the effect of heating a piece of iron in a gas flame?

As the iron heats up, it starts to glow a dull red. As the temperature of the iron continues to go up, its colour changes from dull red to red to orange to yellow and finally if enough heat is available to a yellow white. The spectral energy from the light source, in this case a piece of iron, depends upon its temperature.

This, therefore, is the basis of specifying the nature of the light source. Take on one hand a light source to be calibrated and on the other a perfect black body radiator with some means of measuring its temperature in degrees Kelvin. The black body radiator is then heated until its emission visually matches the emission from the light source to be calibrated. When a match is obtained, the temperature of the black body radiator is the "colour temperature" of the light source. If the light source itself approximates to a black body radiator (Tungsten Lamp and the Sun as viewed above the earths atmosphere, are two examples of this) then the spectral energy of the source and the perfect black body radiator would not only match visually but would also be similar in distribution. Other light sources, i.e. fluorescent lamps, might well match visually, but their spectral energy distributions could be different.

The spectral energy distribution of several light sources are shown below.

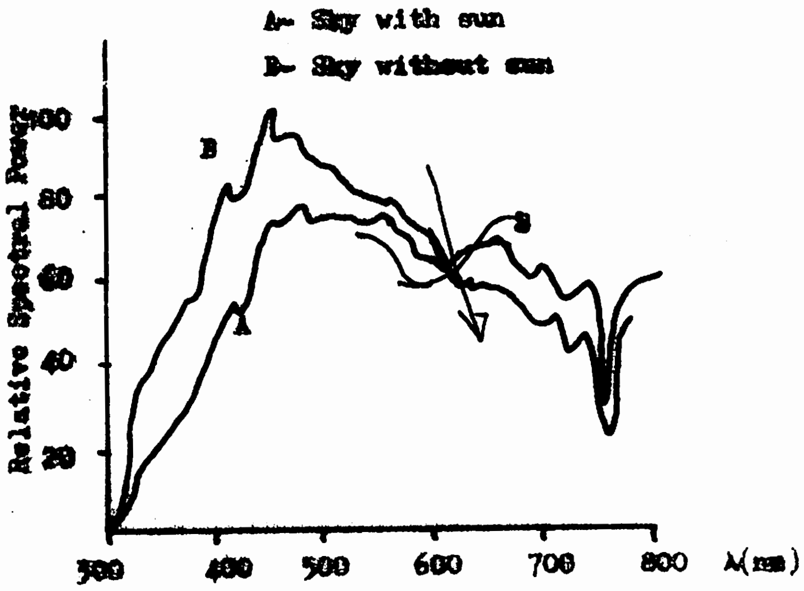


Figure 4.1 Spectral Power Curves for Daylight

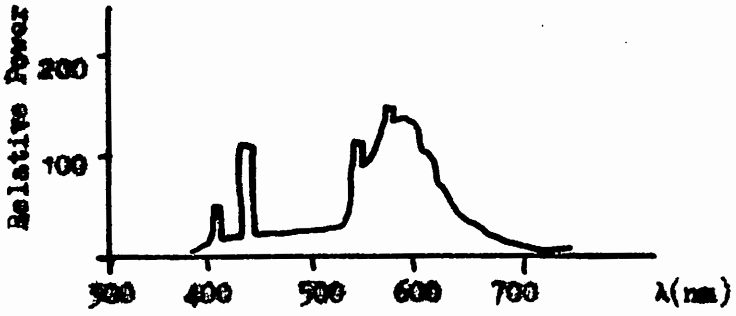


Figure 4.2 Spectral Power Curve for Fluorescent Lamp

| Light Source | Colour Temperature K |
|---|---|
| North-sky light | 7,500 or higher |
| Sun light | 5,500 |
| Photographic blue flash bulb | 5,500 |
| Photographic clear flash bulb | 3,800 |
| Warm white fluorescent lamp | 3,000 |
| Tungsten lamp | 2,900 |
| Candle | 1,900 |
| Studio lighting (television) | 2,950 |
| PAL Television, illuminant D65 | 6,500 |

(This is the intended colour temperature of white as displayed on a colour tube).

# SECTION 5

# A BASIC COLOUR TELEVISION SYSTEM

## SECTION 5 - A BASIC COLOUR TELEVISION SYSTEM

You have covered the television fundamentals package and the four sections dealing with colorimetery and should now be in a position to develop a basic colour television system.

In the mid-1960's, four networks were allocated within the UHF band to give high definition (625 line) monochrome television broadcasting. This meant that the signal which was subsequently introduced for colour viewers had to contain information suitable for the monochrome viewer. It was not feasible, nor in fact desirable from a cost point of view, to produce and transmit a separate signal.

The paragraph above introduces three constraints to the basic colour television system.

The three constraints are;-

1. Compatability - The new colour television system must contain a signal that will produce a good quality picture on existing monochrome television receivers.
2. Reverse Compatability - If a monochrome signal is transmitted, then a good quality monochrome picture must be produced on a colour receiver.
3. Colorimetry - The signal must contain accurate colour information, but in such a form as to produce little or no interference for the monochrome viewer.

Consider a scene consisting of half white light and half red light as shown below.

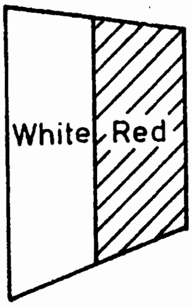


Figure 5.1 Red and White Scene

Draw a simple diagram to show the connections required from a colour camera to a colour monitor in order to display this scene on a colour monitor. Include any variables that may be necessary.

A basic system could look like this:-

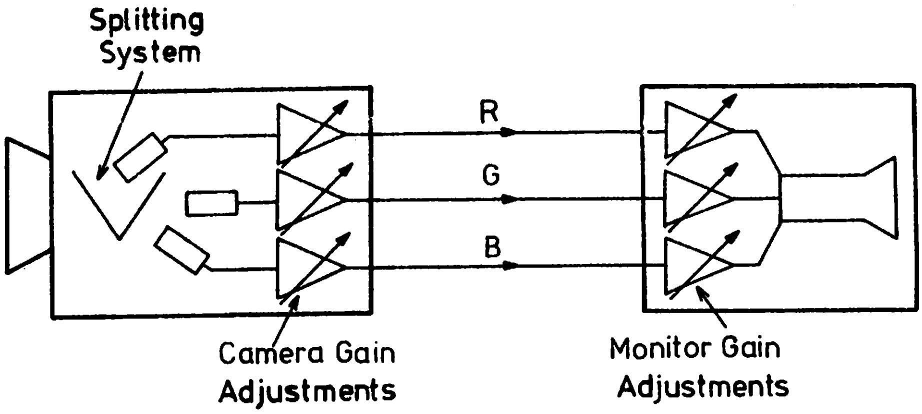


Figure 5.2 Basic Colour Television System

As you have already seen, the incoming light is split by the dichroic block and shaped by the filters before landing on the target of the camera tube. The camera would have gain controls in each of the red, green and blue channels. These outputs are connected to the colour tube via three gain controls in the monitor.

What adjustment would you make to match the scene with the monitor display?

You could vary the gains of either the camera or the monitor to obtain a match.

If you have two colour cameras and two monitors and you wanted to be able to display either cameras output with either monitor, would you have to be more careful in your line-up adjustments?

You would, of course, want both camera outputs to be the same when viewing the same scene. Similarly, if the same input is applied to both monitors, you would want the displays to match.

In our television system, let's work in T units. How would you line up the cameras?

For the white display, make $R = G = B$.

i.e. White $= 1R + 1G + 1B$.

If you point the camera at a grey scale chart going from black to white in several stages, not only can you make $R = G = B$ for white, but also for all levels of grey. This will check the linearity of each channel.

You could also make the inputs to the monitor equal over several steps. What would the display look like?

If the gains are correctly adjusted, it will be a grey scale. Therefore, in our colour television system, for neutral scenes, R = G = B.

What is the standard video system level for peak white in a monochrome system?

0.7volts. (i.e. from black level to white).

The standard voltage from a colour camera for peak white is also 0.7 volts.

i.e. R = 0.7 volts
G = 0.7 volts
B = 0.7 volts

To make calculations in this section and in the coding package easier, we shall consider 0.7 volts as being to equal one signal unit.

Therefore, for white R = G = B = 1.

What will the camera outputs be for the red half of the scene?

R = 1, G = 0, B = 0.

The red would be said to be 100% amplitude. 100% saturated. i.e. the red output is a maximum and there is no desaturation from the green and blue outputs.

If R = 1, G = .1 and B= .1

that would be 100% amplitude, 90% saturated red. (90% saturated because the red is desaturated by 10% white.)

In general, $\text{Saturation} = \dfrac{\text{largest signal - smallest signal}}{\text{largest signal}}$

Question.

1. What would the camera outputs be for R.5 B1 G1
   a. 100% amplitude, 50% saturated cyan. R[illegible] B.[illegible] G.[illegible]
   b. 75% amplitude, 33 1/3% saturated magenta. R.75 B75 G.25
2. If the camera outputs are
   a. R = 1, G = 1, B = .5, 100% yellow 50% Sat
   b. R = .25, G = .25, B = .75. 75% blue [illegible]%Sat

   what is the amplitude and saturation of each of the colours?

75% A 50% Sat

R.75 B.75 G.25

.75 .75 .5.

A S.

ANSWERS.

1. a. $R = .5$, $G = 1$, $B = 1$.
   b. $R = .75$, $G = .5$, $B = .75$.
2 a. 100% amplitude, 50% saturated yellow.
   b. 75% amplitude, 66 2/3% saturated blue.

We have now looked at the outputs from a colour camera for coloured scenes. These outputs may be fed to a colour monitor and, if the system is correctly lined up, the display will match the original scene.

What about the monochrome viewer?

His display has only different levels of brightness. Therefore, from a colour camera outputs we need to produce a brightness or luminance signal.

What is the relative brightness of the three phosphors in a colour monitor? (Clue. What were the conversion factors from T units to lumens in the colorimetry section.)

For the NTSC phosphors, in lumens

white $\equiv .3R + .59G + .11B$.

This means that the red phosphor contributes 30% of the brightness, the green phosphor contributes 59% of the brightness and the blue phosphor contributes 11% of the brightness.

We therefore produce a brightness (or LUMINANCE, Y) signal from the colour camera outputs, such that,

$Y \equiv .3R + .59G + .11B$.

That should give a compatable colour system.

The second requirement was for reverse compatability. This means that a black and white signal should produce a neutral scene of the correct brightness on a colour monitor.

Can you prove that this is so?

Proof.

If you put Y on to all three inputs of the colour monitor, how bright will the display be?

$$\begin{aligned} \text{Brightness} &= .3R + .59G + .11B \\ &= .3Y + .59Y + .11Y \\ &= Y. \end{aligned}$$

Also, $Y = R = G = B$.

Therefore, a neutral scene is displayed.

What was the third requirement of our system?

We have to find a means of transmitting the colour information with a minimum of interference for the black and white viewer.

How can we transmit the colour information?

Remember that we must transmit the luminance (Y) signal.

What does $Y + (R - Y)$ equal?

$$Y + (R - Y) = R$$

Similarly, what does $Y + (G - Y)$ and $Y + (B - Y)$ equal?

$$Y + (G - Y) = G$$

$$Y + (B - Y) = B$$

$(R - Y)$, $(G - Y)$ and $(B - Y)$ are called colour difference signals.

They are a measure of how much colour there is in a scene.

What is the value of the colour difference signals for a neutral scene?

For a neutral scene, $Y = R = G = B$.

Therefore, $(R - Y)$, $(G - Y)$ and $(B - Y)$ equal zero.

This is quite useful, because most scenes are low in saturation and hence the colour difference signals are small. This helps to minimise any interference caused to the monochrome viewer.

How many colour difference signals do we need to transmit?

Two out of the three, because the third can be reproduced in the receiver.

Can you show that one colour difference signal may be obtained in terms of the other two?

Proof. From the definition of the luminance signal

$Y = .3R + .59G + .11B$ - equation 1

We could also write

$Y = .3Y + .59Y + .11Y$ - equation 2

Equation 1 minus equation 2 gives

$0 = .3(R - Y) + .59(G - Y) + .11(B - Y).$

Therefore any of the colour difference signals can be obtained in terms of the other two.

Find the values of (G - Y), (B - Y), and (R - Y) in terms of the other two colour difference signals.

Which two would you transmit and why?

$$-(G - Y) = \frac{.3}{.59}(R - Y) + \frac{.11}{.59}(B - Y)$$

This involves fractions of (R - Y) and (B - Y) followed by an inversion.

i.e. resistor matrix followed by single transistor stage.

(R - Y) and (B - Y) in terms of the remaining two colour difference signal would always involve multiplication of the (G - Y) value. This would mean that any noise introduced onto the (G - Y) signal during transmission would be amplified when the (R - Y) and (B - Y) signals were produced. We therefore transmit the (R - Y) and (B - Y) colour difference signals.

The block diagram for a compatible system would look like this.

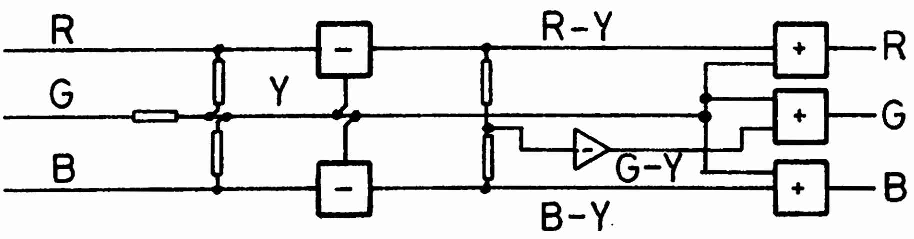


Figure 5.3 Compatible Colour System

We have now covered a basic compatable colour system.

But is it compatable for all scenes?

What will the camera outputs be for the red scene?

R = 1, G = 0, B = 0.

What will be the value of the Y signal.

$Y = .3R + .59G + .11B = .3.$

Assume that the display tube is linear. How will the brightness of the colour display tube compare with the brightness of the monochrome display tube?

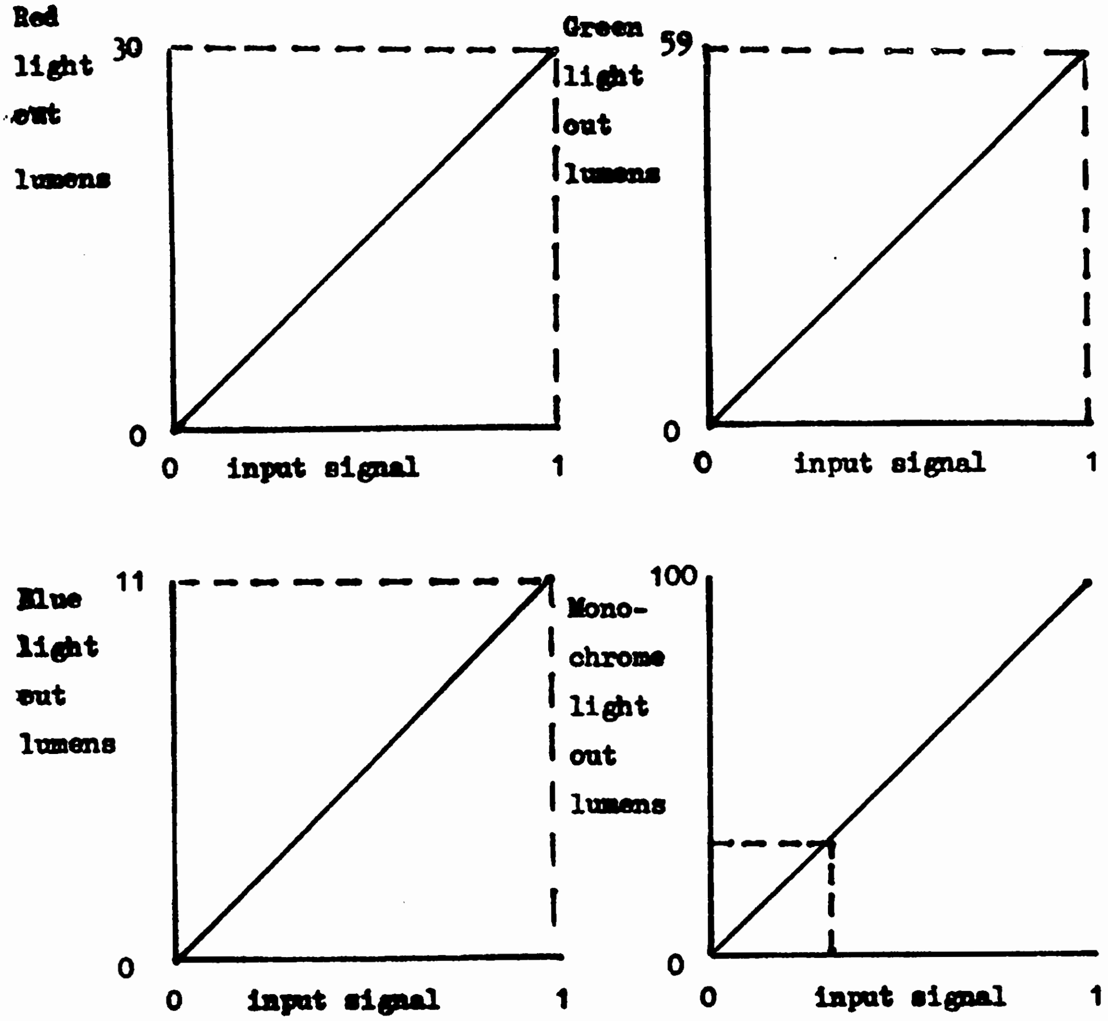


Figure 5.6 Light Output for a Gamma of 1

The colour display tube will have an output of 30 lumens of Red. The monochrome display tube will have a brightness output of 30 lumens.

Unfortunately, display tubes are not linear devices. A colour tube has a gamma of between 2.6 and 2.8.

Now consider the light outputs when the gamma of the tube is taken into account.

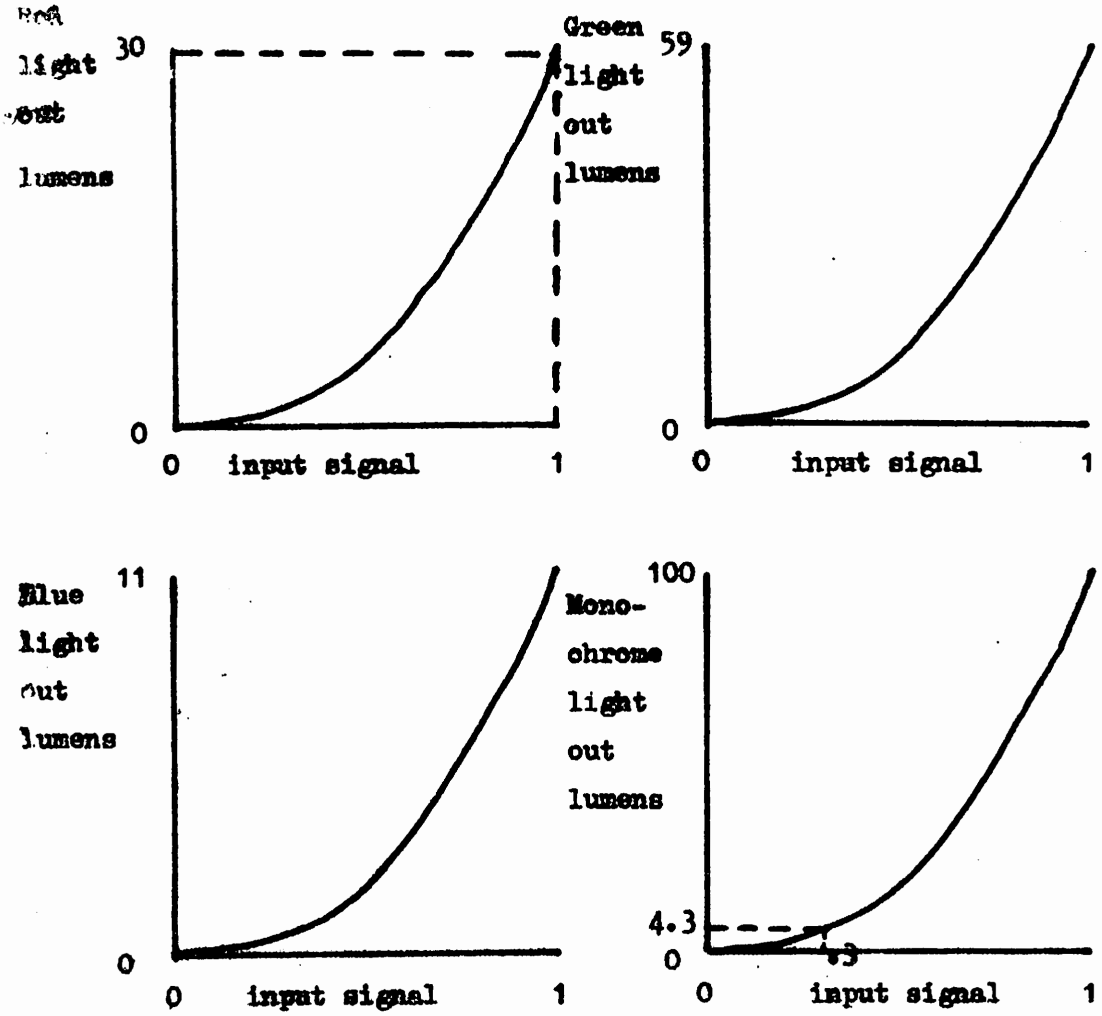


Figure 5.7 Light Output for a Gamma of 2.6

The colour tube still has a display brightness of 30 lumens of Red. The monochrome tube, however, has only a brightness of 4.3 lumens. The monochrome viewer therefore does not see a correct brightness sceme for highly saturated colours. Also, if you were to send only a Y signal to a colour display tube, it too would not display the correct scene brightness. The colour tube only displays the correct brightness when the Y signal has been combined with the colour difference signals in order to obtain the R, G and B signals.

There are two conclusions to be drawn from the above.

1. The display brightness for the Y only signal is not correct and therefore the monochrome viewer does not see the correct brightness for highly saturated scenes.
2. Because of the gamma of the system, the colour difference signals not only carry colour information they also carry brightness information to the colour viewer. The colour difference signals are bandwidth limited. This means that in practice highly saturated scenes, such as captions, lack definition.

# SECTION 6

# SUMMARY

## SUMMARY

PHOTOPIC CURVE (It is a measure of apparent brightness of the colours of the spectrum).

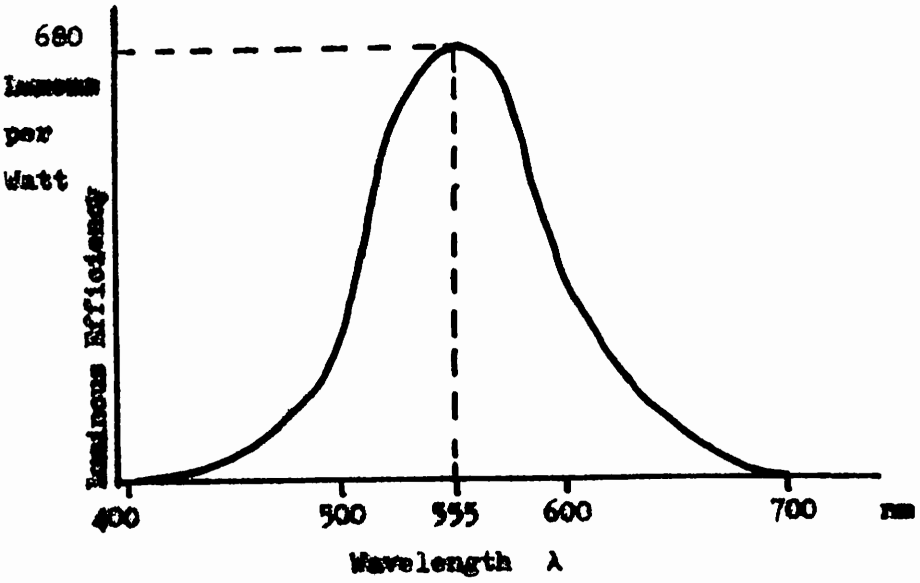


Figure 6.1 Photopic Curve

The eye has a receptor for low levels of illumination. These receptors are called rods and can only contain brightness information.
The eye has three types of colour receptor, known as cones. Their response to different wavelengths of light is as shown below.

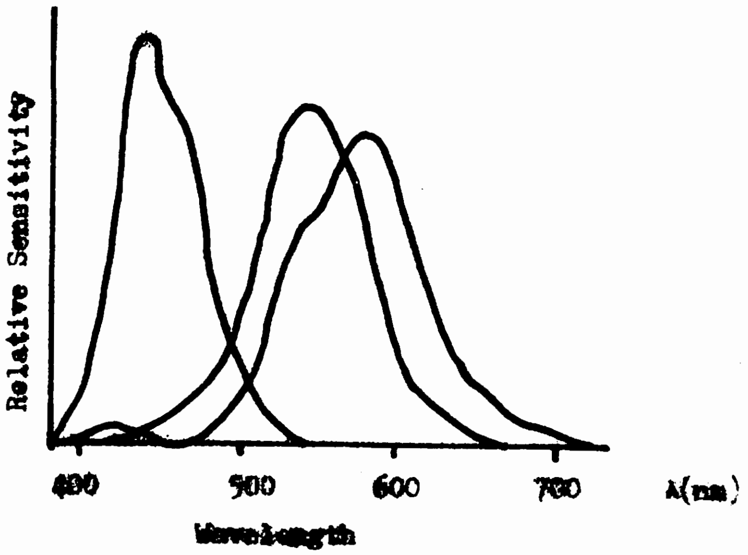


Figure 6.2 Receptor Response Curves

Because of the three colour receptors, tri-chromatic colour matching is possible.

Colour matching is possible in two ways, additive and subtractive.

Additive

The primary colours are red, green and blue. The complementary colours are yellow, magenta and cyan.

Yellow = Red + Green

Magenta = Red + Blue

Cyan = Green + Blue

Subtractive

The primary colours are yellow, magenta and cyan.

The complementary colours are red, green and blue.

Yellow + Magenta = Red

Yellow + Cyan = Green

Magenta + Cyan = Blue

Colour television is produced by a additive mix of the light from the three primary phosphors.

There are three properties of coloured materials,

Hue

Brightness or Lightness

Saturation.

Colour matching may be done by means of a visual matching colorimeter. The three matching primaries may be calibrated in either lumens or T Units. In both cases, colours so matched may be plotted on a chromaticity chart once the chromaticity co-ordinates have been calculated.

The chromaticity of a colour refers to its hue and saturation. It does not contain any information about the brightness of the colour.

The T Unit is defined as equal amounts of the three primaries to match white.

Hence, in T Units,

$$3W \equiv 1R + 1G + 1B$$

and for NTSC primaries, a match in lumens is,

$$1W \equiv .3R + .59G + .11B.$$

This then gives conversion factor from T Units to lumens for NTSC phosphors.

Brightness of colours must always be calculated in lumens, and this will sometimes mean using the above conversion factors.

The matching of spectral colours requires negative primaries.

The line joining the chromaticity co-orindates of the spectral colours is known as the spectrum locus.

A colour camera requires a dichroic splitting block, frequency selective filters, camera tubes and a matrix. The matrix is required in order to produce the negative lobes on the camera response curves. These negative lobes are necessary for correct colorimetry.

However, colours that lie outside the chromaticity triangle formed by the three NTSC primaries cannot be reproduced on a monitor.

The colour temperature of a light source is the temperature of a perfect black body radiator in degrees Kelvin, at which the two radiations visually match.

## MODEL ANSWERS

1. C1 is matched by 100R + 200G + 50B

   Therefore 350C $\equiv$ 100R + 200G +50B

   divide both sides by R + G + B (which = 350)

   Therefore $C1 \equiv \frac{100R}{350} + \frac{200G}{350} + \frac{50B}{350}$

   Therefore C1 $\equiv$ .29R + .57G + .14B

   Therefore r = .29, g = .57 and b = .14

   Therefore the chromaticity co-ordinates are r = .29, g = .57.

2. C2 is matched by 25 + 100G + 25B

   Therefore 160 C2 $\equiv$ 25R + 100G +25B

   Therefore $C2 \equiv \frac{25R}{150} + \frac{100G}{150} + \frac{25B}{150}$

   Therefore C2 $\equiv$ .17R + .67G + .17B

   Therefore r = .17, g = .67 and b = .17

   Therefore the chromaticity co-ordinates are r = .17, g = .67.

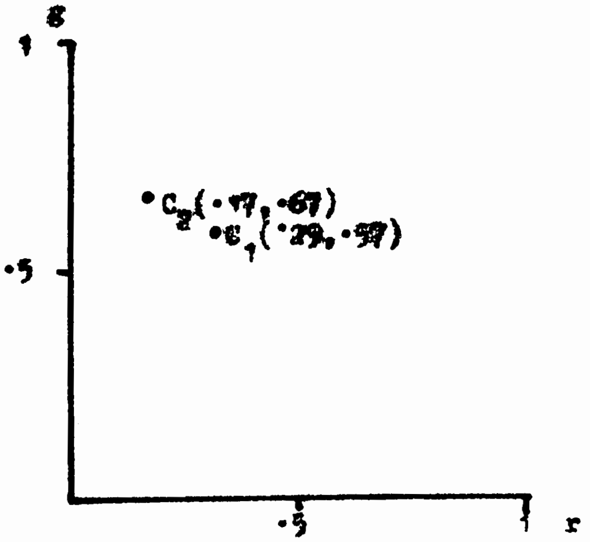


Figure 6.3 Chromaticity Chart for Question 2

3. C1 is matched by 50(R) + 200(G) + 250(B)

   Therefore 500(C1) $\equiv$ 50(R) + 200(G) + 250(B)

   Therefore $C1 \equiv \frac{50(R)}{500} + \frac{200(G)}{500} + \frac{250(B)}{500}$

   Therefore C1 $\equiv$ .1(R) + .4(G) + .5(B)

   C2 is matched by 100R + 150G + 100B

   Therefore 350 C2 $\equiv$ 100R + 150G + 100B

   Therefore $C2 \equiv \frac{100R}{350} + \frac{150G}{350} + \frac{100B}{350}$

   Therefore C2 $\equiv$ .29R + .43G + .29B

C3 is matched by 100R + 250G + 25B

Therefore 375 C3 ≡ 100R + 250G + 25B

Therefore $C3 \equiv \frac{100R}{375} + \frac{250C}{375} + \frac{25B}{375}$

Therefore $C3 \equiv .27R + .67G + .07B$

The three colours may then be plotted on a chromaticity chart.

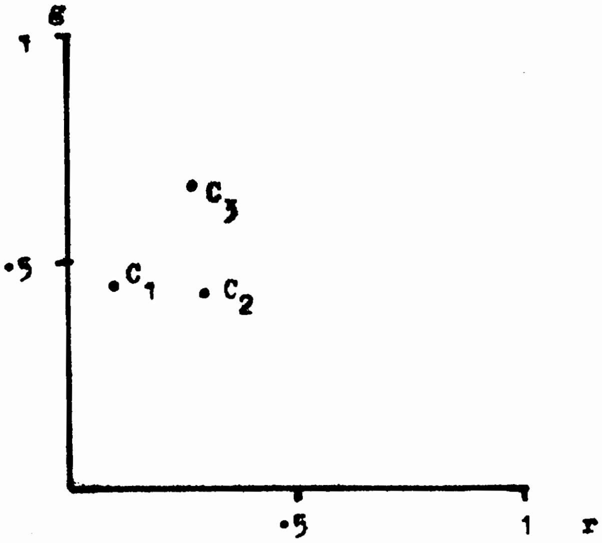


Figure 6.4 Chromaticity Chart for Question 3

The brightness of each colour is given by converting the T units into lumens.

i.e.

$$\begin{aligned}
C1 &= 50 \times .3 + 200 \times .59 + 250 \times .11 \\
&= 15 + 118 + 27.5 \\
&= 160.5 \text{ lumens} \\
C2 &= 100 \times .3 + 15 \times .59 + 100 \times .11 \\
&= 30 + 88.5 + 11 \\
&= 129.5 \text{ lumens} \\
C3 &= 100 \times .3 + 250 \times .59 + 25 \times .11 \\
&= 30 + 147.5 + 2.75 \\
&= 180.25 \text{ lumens}
\end{aligned}$$

Therefore C3 is the brightest colour.

## TUTORIAL

1. Why is it possible to obtain colour matches by using three primary colours?
2. Give an example of when you might expect the rods to be contributing most of the perception of light?
3. Why are chromaticity co-ordinates so called?
4. Where does blue plot on a chromaticity chart?
5. What factors affect the position of the spectrum locus on a chromaticity chart?
6. Why do the camera response curves have negative lobes? How are these obtained in practice?
7. Even with negative lobes on the camera response curves, a colour monitor is still unable to reproduce colours that lie outside the chromaticity triangle. Why is this? Does it matter in practice?
8. What do you understand by the term colour temperature?
9. What is the colour temparature of,

   i) average daylight;

   (ii) studio lighting?
10. Three colours are matched in T units as follows:-

    C1 matched by 60R + 20G + 30B

    C2 matched by 80R + 10G + 45B

    C3 matched by 55R + 35G + 20B.

    Which colour is the brightest?
11. A colour is matched by 50 red + 50 green + 100 blue. Plot the colour on a chromaticity chart.
12. A colour is matched by 100 red + 100 green + 75 blue. Plot the colour on a chromaticity chart.

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# PRACTICALS

## SECTION 7 PRACTICAL WORK

1. The Frakus colorimeter has three slide controls on the right hand side to vary the amount of Red, Green and Blue light appearing on the screen. Vary the amount of light from the primaries in pairs (Red and Green, Green and Blue, Red and Blue) and note the colour mixes obtained.

   Try to obtain White by use of all three primaries.

2. The next experiment looks at the way in which the eye responds to low levels of illumination. For this experiment you will need a card with different coloured shapes on it and the variable level light source. Variation in light level is obtained by means of an iris.

   Turn the lights out in the dark room and allow your eyes to become accustomed to the dark for about half a minute. Gradually increase the light from the variable light source, shining it towards the card with the coloured shapes on it, and note the effect. You should increase the light source from zero light up to its maximum light output. Then, gradually decrease the level of the light source back down to zero.

   Can you make any observations from this experiment?

Now continue with the main text from page 1.2.

3. Before starting on the colour matching, look at the colorimeter to see how the colour matching is obtained. The top may be raised after releasing the catches at the sides.
The R.H.S. contains the measurement primaries with the sliders calibrated to T units for the 'average observer', i.e. equal R, G, B matches white. The screwdriver adjustable potentiometers on the front panel are for calibration purposes and should not be touched.
The L.H.S. contains the position for the colour sample and sliders for the addition of negative primaries, these should normally be closed and only used if the colour sample is too saturated to match with the measurement primaries.
Select the clear slide from the box of colour samples and match the white in the L.H. window by mixture of R, G and B in R.H. window. All members of the group should make independent matches. Record your readings, and compare with your partners. You are unlikely to produce identical results but if all of you have normal colour vision you will not differ by much more than 10T units. Select several sets of samples of the same hue, one maximum brightness, one half brightness (1/2 Y) and one desaturated (with hole in middle). Match each saple and record results in a table. Select Deep Amber, Orange, Canary Yellow or Double Blue sample. Obtain match using negative primary sliders on L.H.S. if necessary. To measure amount of negative primary used remove colour sample, and record amount of primary on R.H.S. required to obtain a brightness match with primary on L.H.S.
Calculate the chromaticity co-ordinates and plot on a chromaticity chart.
It is interesting to make several white matches at regular intervals during the session and noting the variations of individual matching characteristics as well as those between members of the group.
After completing this experiment return to Section 3 in the main text.

4. Switch on the V.H.S. video tape recorder, monitor and loudspeaker amplifier. Insert the tape and reset the counter. Fast spool to counter reading 111.

   This part of the video tape demonstrates the principle of subtractive colour mixing using practical filters.

5. The second video tape presentation starts at counter reading 000. It recaps that a camera requires a matrix in order to have correct colorimetry. It also covers the plotting of spectral cyan by a camera, both with and without a matrix.