4. FUNDAMENTALS OF LIGHT AND IMAGE

4.1. Perceptional, Physical and Psychophysical Features

The quantities normally encountered in communication engineering can be expressed in objective terms such as power, voltage, etc., using units that are independent of the observer. The perception of light and colour are partially subjective phenomena, however, akin to the appreciation of music by the ear and the brain.

Quantities used in photometry and colorimetry can be presented in three different ways as shown in Fig. 4.1. The most upper row presents the obvious description, i.e. how light is actually perceived by the eye and then processed by the brain. Of course, this presentation is purely subjective so that the corresponding quantities cannot be numerically expressed as they are just perceptional equivalents of the terms used in photometry.

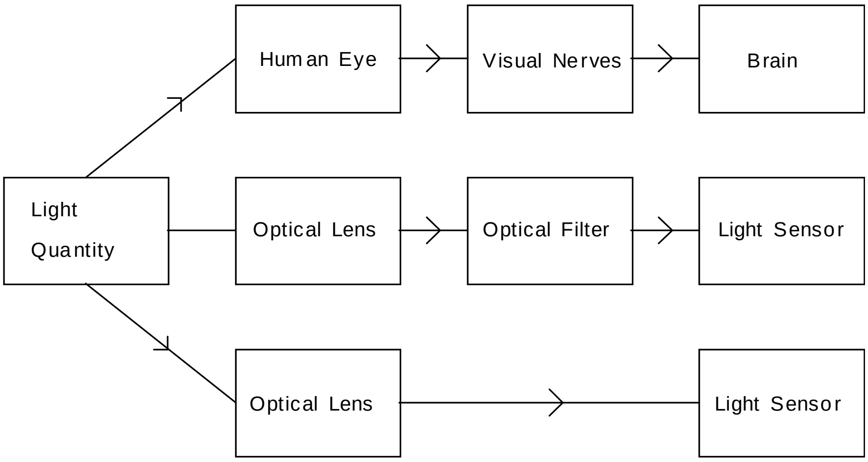

Figure 4.1 Perceptional, Psychophysical and Physical Representations of Light

In the middle row of the Fig. 1. the so called *psychophysical* representation can be seen. Here the light is passed to a sensor through a lens and an optical filter which -together with the characteristic of the sensor- satisfies the internationally accepted standard for the human organ of vision. This standard has been released by the International Lighting Committee, abbreviated as *CIE* (Commission International de l'Ènclairage).The representation is called psychophysical because on one hand it takes into account the properties and limits of the human vision but on the other hand it is an objective measure which can be expressed numerically as well.

Finally, the third of the possible representations is given in the bottom row of the figure. This is a pure physical representation where the lighting quantities are measured just like any other physical quantity without subjective limits. Obviously, this is also an objective representation.

4.2. The Human Eye and Vision

Vision is understood as the perception of visible radiation by the human eye. The organ of vision is a collective term including the eye, the visual nerves and certain areas of the brain. These parts transform the light stimulus to optical excitation resulting in the sense of vision. Picture of the outside world is optically transformed by the *retina,* located on the rear side of the eye. The retina is a light sensitive thin layer containing the terminations of the *visual nerves* (rods and cones), the nerve cells and the supporting tissue. The two different kinds of visual nerve terminations play an important role in vision. It is highly probable that the *rods* are the elements responsible for the perception of strong light and the *cones* enable the sensation under poor light conditions.

Let us see some further terms for describing vision. Lightness, hue and colourfulness are three other sensational parameters playing important roles in vision. *Lightness* is a property characterizing the amount of light that a certain surface is emitting. As it can be seen, this definition fully corresponds to that used in everyday life. *Hue* is another parameter of vision resulting in naming the colours as blue, green, yellow red, purple etc.

The third parameter, the *colourfulness* (or saturation) serves for the estimation where a perceived colour can be located between white and the pure (spectral) colour, provided this later has the same lightness and hue as the colour examined. The saturation grade is usually given by the adjectives attached to the collars, e.g. light green, pastel blue, dark red, faint yellow, etc. All these three sensational parameters have their objective (psychophysical) equivalents which will be discussed in the following chapters.

4.3. Thermal Radiation. Photometry.

The fundamental input to any television system is radiant energy in the form of light. *Photometry*, the measurement of light, is therefore of great importance to television engineers.

As a standard of light a well defined source is needed, parameters of which can be exactly reproduced at any time. As it is known from physics, a perfectly black body (i.e. one that absorbs all radiant energy falling upon it) is suitable for this purpose. When a black body is heated, the power radiated from a given area of its surface has a magnitude and spectral distribution determined solely by its temperature. The energy distribution of such a radiator is expressed by the Planck's law, which gives the spectral concentration of radiant exitance *M* as follows:

$$M_{e\,l} = C_1\, l^{\,-5}(e^{C_2/lT} - 1)^{-1} \tag{4.1}$$

where C_1 and C_2 are radiation constants, λ is the wavelength and T is the temperature.

To have also a well defined photometer, an 'artificial eye' has been constructed which simulates the light sensitivity of the human eye. The relative response of the normal human eye to monochromatic light at the different spectral frequencies has been determined experimentally by the CIE and standardized in 1924. This is known as the *photophic spectral luminous efficiency function* and is illustrated in Fig. 4.2. The symbol of this function is $V(\lambda)$ and it is usually expressed as a function of the wavelength of light (in air).

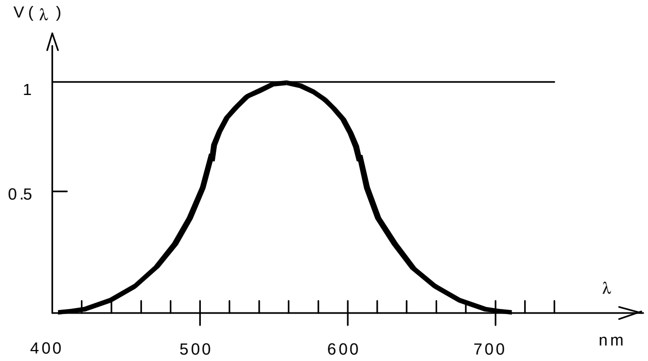

Figure 4.2 The Photophic Spectral Luminous Efficiency Function

To determine the photophic luminous efficiency function, the following procedure was carried out: First, light of constant intensity was emitted and its frequency was varied until the lightness perceived by the observer was found to be maximum. This occurred at a frequency about 5.410^{14} Hz, corresponding to wavelength $\lambda_m = 555$ nm. Then the wavelength was set to another λ and the power was adjusted again until the lightness was judged to be the same as at λ_m. $V(\lambda)$ could be computed then as the ratio of the radiated power at λ_m and λ, respectively. Of course, this experiment has been carried out by many observers and the resulting average was used to define the so called *CIE standard eye* which is an optical sensor with sensitivity corresponding to the function $V(\lambda)$.

The photophic luminous efficiency function serves as a link between the subjective response of the human eye and normal physical measurement techniques. It thus provide the basis for a group a photometric units. As one of the most important of them, *luminance* is defined as the measure of luminous flux (radiated power) per unit solid angle and per unit projected area.

4.4. Colorimetry

Colorimetry is based on the fact that observers can match colours with additive mixtures of three reference stimuli in amounts known as *tristimulus values*. Using reference stimuli at specified wavelengths, CIE has defined a standard set of tristimulus values to match each different wavelength of the spectrum.

Let us see, how these values have been determined. The sketch of the experimental set up is shown in Fig. 4.3. There is a white, non mirroring wedge illuminated by an unknown source of light from the right and by known sources from the left side. In front of the wedge, there is an observer seeing both sides of the wedge. The observer acts as the 'sensor' of this subjective colorimeter. It is up to him to adjust the intensity of the three known sources to achieve matching between the two sides. After that, the unknown colour can be objectively characterized by the readout of the radiation strength of the three known sources.

Experience has shown, however, that the spectral distribution of two compared colours might differ even when they match. What is more, two collars can perfectly match even if their radiation have different spectral distributions. This fact is of essential importance in typography as this is the only way to reproduce colourful pictures by using just three conveniently chosen colours. Different colour stimuli perceived as being the same are called *izochromatic*.

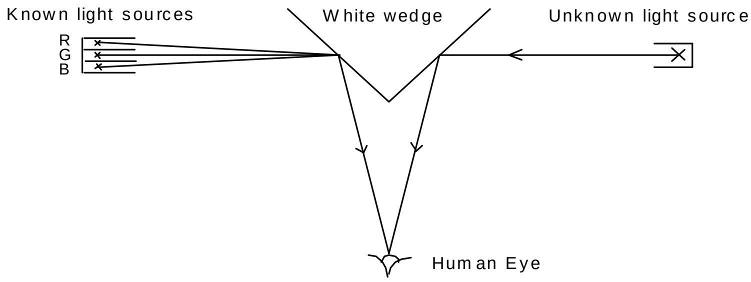

Figure 4.3. The Comparative Colorimeter

To be able to repeat the above procedure, it was necessary to standardize various elements of the system. The CIE has therefore defined a standard set of reference colour stimuli, and a standard set of tristimulus values for them; these data constitute the CIE 1931 standard colorimetric observer. The reference-colour stimuli are radiations of wavelength 700 nm for the red stimulus (R), 546.1 nm for the green stimulus (G) and 435.8 nm for the blue stimulus (B). The tristimulus values were chosen to match the typical white colour. There is a great imbalance in the three amounts (the amount of green being the greatest, and the amount of blue being much smaller). As white is a colour that is not biased towards either red, green or blue, new relative units of R and B were chosen so that the amounts be equal to the amount of green.

Series of measurements have been carried out with the standard colorimetric observer to find the different tristimulus values for different colours. To make use of the resulting huge data file, CIE has worked up a specific 'map' of colours.

As three stimuli are assigned to each colour, a three-dimensional co-ordinate system would have been needed to plot the actual co-ordinates. To simplify this representation (at the expense of loosing the lightness information), co-ordinate transformation and some other calculations have been done resulting in a two-dimensional chart called *chromacity diagram*. In spite of this, the suitability of the diagram for all colorimetric measurements without the need of the related mathematical apparatus, gives chromacity diagram an outstanding importance.

The CIE chromacity diagram is shown in Fig. 4.4. The *x*, *y* co-ordinates are called *chromacity co-ordinates* and are calculated from the original tristimulus values *X*, *Y* and *Z* as

$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}. \tag{4.2}$$

The positions of spectral colours (the spectrum locus) are shown by the curved line and are given by the corresponding wavelengths in nm. The points representing non- spectral (pale) colours are inside the curved line. The straight line at the bottom of the chart connects the red and the blue spectral colours, so that non spectral colours mixed of red and blue (e.g. purple, violet, etc.) are located along this line.

The illuminant (point representing the normal white colour) is located in the middle and is denoted as *E*. Colours radiated by the black body in the temperature range 1000-10000 °K are also presented in the figure.

It follows from the previous explanation that any colour assigned to a point inside the curved line and lying on the straight line going through point *E* can be mixed by the addition of white *E* and the spectral colour given by the intersection of the straight and curved lines, respectively. Of course, if the point of intersection lies on the bottom line ('purple line') then the weighted mixture of red and blue should be taken instead of spectral colours.

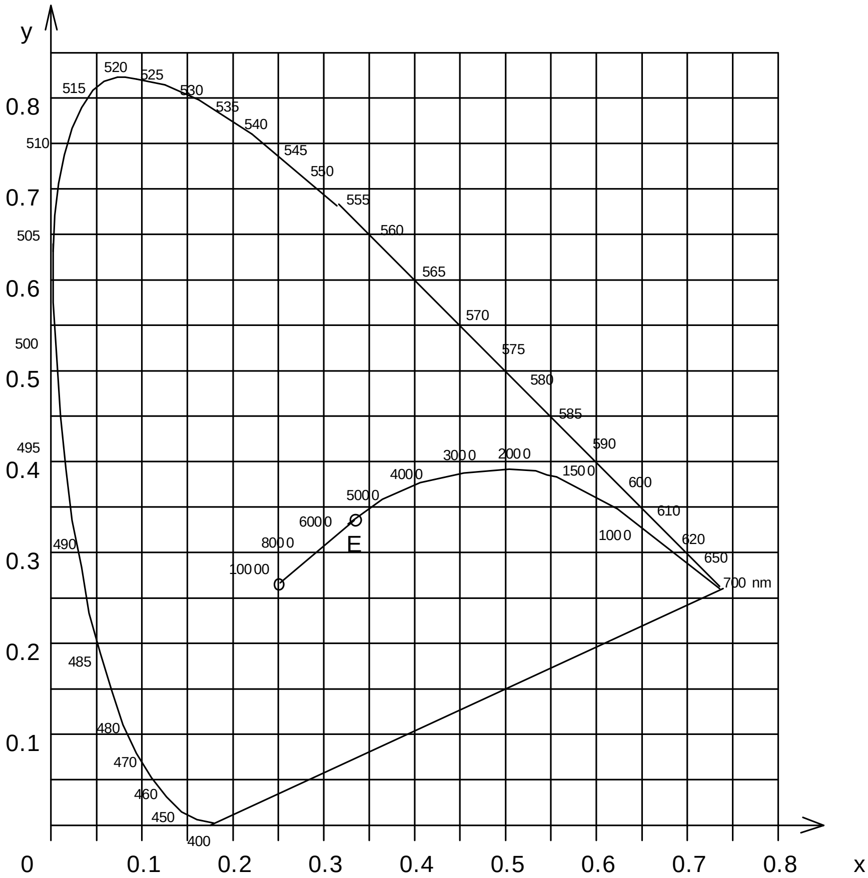

Figure 4.4. CIE Chromacity Diagram

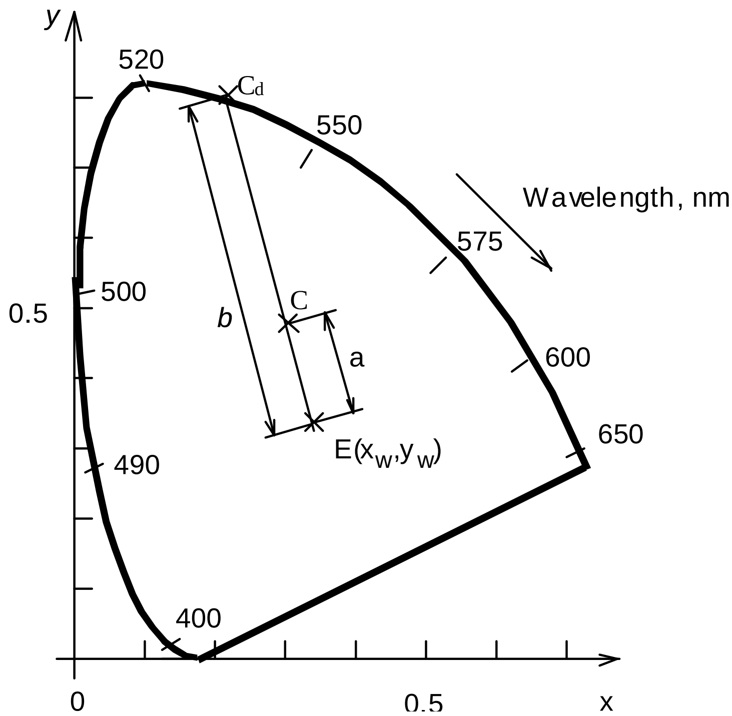

Figure 4.5. Dominant Wavelength and Excitation Purity

The chromacity diagram only shows the proportions of tristimulus values; hence bright and dim colours having the same proportions belong to the same point. For this reason, the illuminant point also represents grey colours; and orange and brown colours, for example, tend to plot at similar positions to each other. That is why luminance has to be given as an additional information for the unambiguous definition of a certain colour.

There are some other important terms related to the previous notation which will be discussed on the basis of Fig. 4.5. Let us choose an arbitrary point denoted as C representing a colour which can be composed of the white colour E and the spectral colour C_{d}. Since the latter plays the dominant role in the hue, the wavelength of the spectral colour C_{d} is called the ***dominant wavelength*** and is denoted as l_{d}.

Since there is no difference in the hue wherever the point C is located on the line connecting the points E and C_{d}, the dominant wavelength can be considered the psychophysical equivalent of the hue. Similarly, the *excitation purity* p_{e} can be derived as the psychophysical equivalent of saturation:

$$p_e = a / b \tag{4.3.}$$

where a and b are the distances between C and E and between C and C_d , respectively.

4.5. The Picture

To transmit a picture or a series of pictures through a communication channel, it has first to be converted to a time function. Suppose we have a monochromatic picture composed of a great number of light and dark elements. Although this picture is continuous in fact, it can be divided into small picture elements called *pixels* and characterized by their luminance, provided the elements are so small that their luminance can be taken as constant.

The procedure of converting the picture into a time function is as follows: First, the picture is divided into numbered pixels and the luminance of the individual pixels is determined and converted into the corresponding analog values. These values are then put in the same order as the pixels are numbered. This process is performed by the camera which scans the picture pixel by pixel and generates electrical output voltage proportional to the luminance of the pixels. A similar process comes on at the receiver side where the cathode ray tube converts the changes of the signal to visible changes of the luminance.

It is also important to know how great the information content of a stationary and of moving pictures is or should be. To determine these values, first we have to decide into how many pixels a picture has to be divided. Since the 'final receiver' of all pictures is the human eye, we have to decide about its resolution. For monochromatic pictures the resolution is about 2', i.e. if the visual angle between two pixels is less then 2' the eye is not able to differentiate between them. As it was also determined experimentally, the optimum visual angle for the whole picture is about 20□. The third important factor is the aspect ratio which was set to 4:3 which is the value commonly used in photography. From all these data summarized in Fig. 4.6., the number of pixels in the vertical and horizontal directions can be computed:

$$n_V = \frac{20^\circ}{2} = \frac{20 \cdot 60}{2} = 600, \qquad n_H = \frac{4}{3} n_V = 800$$

which makes $n = n_1 \times n_2 = 4.8\ 10^5$ pixels for the whole picture. The last step is to decide how many tones a pixel shall have. Here we refer again to experimental results indicating that a picture seems to be natural if the number of tones chosen is about 100.

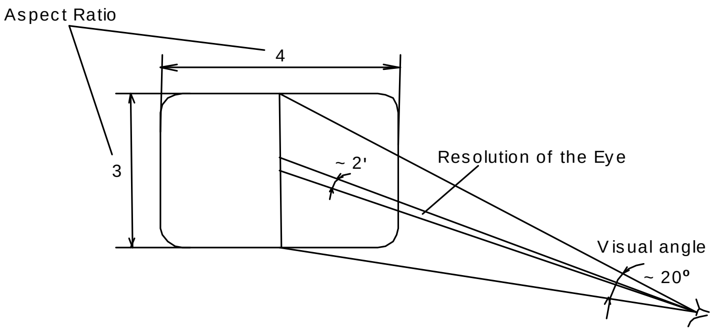

Figure 4.6 Parameters Determining the Number of Pixels

From the above data the information content of a monochromatic picture can be computed. Suppose the gradation number is s = 100. The information content of one pixel is then

$$I_{\text{pixel}} = \log_2 s = \log_2 100 = 6.65 \text{ bit}$$

so that for the entire monochromatic picture

$$I_{\text{pic}}^{\text{mc}} = nI_{\text{pixel}} = 4.8 \cdot 10^5 \cdot 6.65 = 3.19 \cdot 10^6 \text{ bit} \quad (4.4)$$

This means that to send one stationary picture which satisfies the above conditions, more than 3 million bits have to be transmitted through the channel.

4.5.1. Transmission of Moving Pictures

Similarly to the projection of films, we can make use of the inertia of the eye and transmit about 25-30 pictures in one second instead of a continuous transmission of 'all', phases (which is impossible, anyway). The series of pictures transmitted with such a frequency will give the impression of a continuously varying picture. Of course, the individual pictures are divided into pixels in the same way as it is done when stationary picture is transmitted.

Suppose that we want to transmit 25 monochrome pictures every second. The information rate of such a number of pictures is

$$v_{\text{mpic}} = N \cdot I_{\text{pic}}^{\text{mc}} = 25 \cdot 3.19 \cdot 10^6 = 80 \text{ Mbit / s} \quad (4.5)$$

so that to transmit monochrome TV pictures, a channel with the information rate of at least 80 Mbit/s is needed theoretically.

4.5.2. Transmission of Colour Pictures

Let us examine the information rate needed for the transmission of colour pictures. First, we have to make clear what the information surplus of a colour picture is in comparison to the monochrome one. We shall follow the procedure used for monochrome pictures, i.e. we compute first the information of one pixel and then multiply it by the pixel number to obtain the information capacity of the entire picture.

As we already know, one colour pixel is defined by three independent data. One of them is the luminance, and the other two contain the colour information. These data can be the chromacity co-ordinates used in colorimetry, or others, e.g. R-Y and B-Y (so-called colour-difference signals) are used (detailed discussion of these terms is given in Chapter 20).

As for the gradation of monochrome pictures, it was also experienced that instead of the transmission of infinite number of colour tones it is sufficient to distinguish just 20 different colour gradations to reproduce a satisfying picture. That is, 20 different colour attributes can be assigned to each pixel.

Furthermore, we have to consider that the resolution of the human eye is poorer for colour pictures. According to experiments, the resolution partly depends on the pairing of the colours of adjacent pixels but it can be said that on the average the resolution is about one fifth of that for the monochrome picture, i.e. the minimum visual angle is about 10' compared to the 2' of the monochrome picture.

It can be concluded from the previous discussion that the size of a colour pixels may be five times greater than the size of the monochrome pixel, or in other words just one colour pixel is needed to cover the square grid of 5 x 5 = 25 monochrome pixels. So that human vision is pleased with a colour picture having the pixel structure 25 times more rough than a finely detailed monochrome picture.

At this point we can already compute the information surplus of the colour picture:

$$I_{\text{pic}}^{\text{c}} = 2n_1 n_2 \frac{1}{25} \log_2 20 = 166\,\text{kbit} \tag{4.6.}$$

Let us compute now the resulting information of the colour picture:

$$I_{\text{cpic}} = I_{\text{pic}}^{\text{mc}} + I_{\text{pic}}^{\text{c}} = 3.19 \cdot 10^6 + 0.166 \cdot 10^6 \text{ bit} = 3.36\,\text{Mbit}$$

Note that the colour information contributes very little to the information content of the picture.

Finally, the transfer rate for the colour picture is

$$v_{\text{cpic}} = NI_{\text{cpic}} = 25 \cdot 3.36 \cdot 10^6 \approx 84\,\text{Mbit/s}$$

which is the minimum channel capacity for the TV colour picture transmission. Practically, much greater capacity is needed, since neither the channel nor the time can be used up one hundred percent.

Control Questions:

1. How can the lighting quantities be classified? Name the features of these classes!
2. How has the photopic luminous efficiency function $V(\lambda)$ been determined?
3. What are the definitions of the CIE psychophysical quantities? Interpret the meaning of these quantities!
4. What is the definition of a monochrome and a colour pixel?
5. How can be computed the information of a colour and a monochrome picture?

References

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