Intelligent Systems
Project specification
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1

Background

Color is a physiological sensation that our brain uses to recognize the objects around us. The color sensation basically occurs according to the following four steps (see Fig. 1.1):

1. a **light source** emits a light;
2. an **object** reflects this light by modifying it according to its surface characteristics;
3. the **human eye** detects this reflected light and turns it into a stimulus;
4. the **brain** processes this stimulus and generates the chromatic sensation.

1.1 What is light?

Light is an electromagnetic radiation. The portion that the human eye can sense (commonly known as *visible light*) is the radiation with wavelengths ranging from ∼380 nm (violet) to ∼800 nm (red)—see Fig. 1.2.

A light source is something that emits light, such as the neon lamps in office buildings. A light source emits different amount of energy (i.e. power) at each wavelength λ of the visible color spectrum, thus forming its *spectral power distribution*, denoted with SPD or $S(\lambda)$.

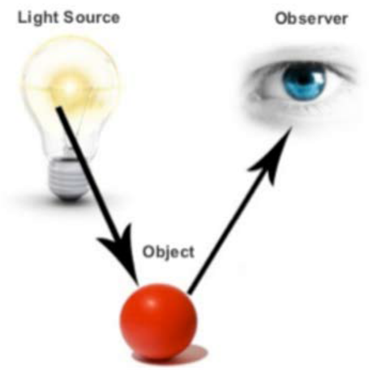

Figure 1.1: Elements of color perception.

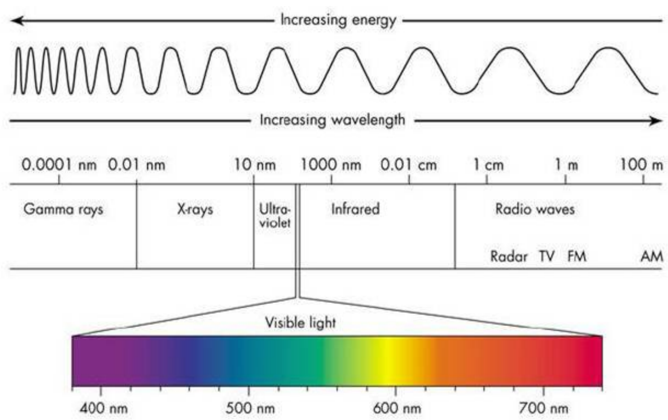

Figure 1.2: Wavelengths of visible light.

1.2 Standard illuminants

As the same light source may vary its characteristics over time (e.g. two equal fluorescent lamps may emit different lights due to usage, small changes of the production process, and so on), the CIE[1] has standardized light sources, thus assigning each of them to a standardized SPD (examples are in Fig. 1.3). These standardized SPDs are called *standard illuminants*. SPDs are generally represented as relative SPDs, thus normalizing the amount of energy emitted into $[0, 100]$.

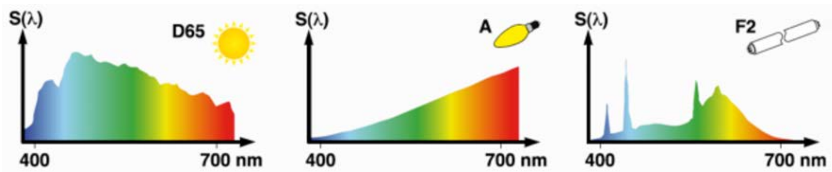

Figure 1.3: SPDs of three standard illuminants: daylight (D65), incandescent bulb (A), cool white fluorescent lamp (F2).

1.3 Object

When a light strikes the surface of objects they absorb and reflect specific amounts of energy at each wavelength of the visible spectrum. In the case of a red object, for instance, the red part of the visible spectrum is reflected almost completely, while the energy emitted at the other wavelengths is mainly absorbed.

The percentage of incident electromagnetic power that is reflected at each wavelength is called *reflectance*. The plot of the reflectance of an object as a function of wavelength is called *spectral reflectance curve* (see Fig. 1.4).

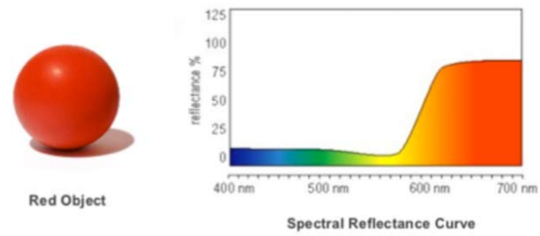

Figure 1.4: Spectral reflectance curve of a red ball.

[1]The *Commission Internationale de l'Eclairage* is the international authority of light, illumination, color, and color spaces.

1.4 Observer

When illuminating an object with a light source, the reflected light coming from the object reaches an observer (e.g. the human eye). This reflected light has an SPD, which is referred to as *reflected SPD* or rSPD.

For each $\lambda \in [380\,nm, 800\,nm]$, the rSPD power is obtained multiplying the energy that comes from the light source by the reflectance of the object, as shown in Fig. 1.5.

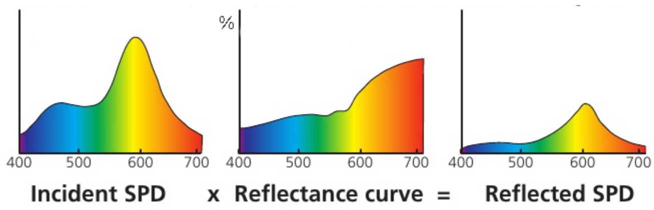

Figure 1.5: Reflected SPD (rSPD) obtained multiplying the relative SPD of the light source (incident SPD) by the reflectance of the object.

1.5 Color perception

A color is almost always a blend of different wavelengths of lights (on the spectrum), rather than just a single wavelength.

Let $S(\lambda)$ be the rSPD, where λ is the wavelength, and consider a set of three *color matching functions*. Color matching functions are functions of the wavelength and make it possible to represent any visible color by a 3-tuple.

There is more than one set of color matching functions. Those used to model the human eye form the so-called *standard observer*. Each function of the standard observer associates each wavelength of the visible spectrum with the response of one of the three types of cones[2] of the human eye. Therefore, given the SPD of a light that reaches the retina—i.e. the rSPD $S(\lambda)$—the three types of cones in the eye generate a 3-tuple (ρ, γ, β) called *tristimulus response*. This 3-tuple is mathematically obtained by integrating the products of wavelength intensity and color matching function, over the visible spectrum, i.e.,

$$\rho = \int_{\lambda_l}^{\lambda_u} S(\lambda)\overline{\rho}(\lambda)d\lambda \tag{1.1}$$

$$\gamma = \int_{\lambda_l}^{\lambda_u} S(\lambda)\overline{\gamma}(\lambda)d\lambda \tag{1.2}$$

$$\beta = \int_{\lambda_l}^{\lambda_u} S(\lambda)\overline{\beta}(\lambda)d\lambda \tag{1.3}$$

[2]There are three types of cones in the eye, which are sensitive to red, green and blue, respectively.

where $\lambda_l = 380$ nm, $\lambda_u = 800$ nm, and $\overline{\rho}(\lambda)$, $\overline{\gamma}(\lambda)$ and $\overline{\beta}(\lambda)$ are the color matching functions of the standard observer. Our color perception is thus determined by this 3-tuple response.

1.5.1 CIE RGB color space

RGB is a convenient color model to represent colors in computer graphics because the human visual system works in a similar way—though not quite identical—to an RGB color space. The most commonly used RGB color spaces are sRGB and Adobe RGB.

The 3-tuple (R, G, B) that describes a color is obtained as

$$(R, G, B) = \left(\int_{\lambda_l}^{\lambda_u} S(\lambda)\overline{r}(\lambda)d\lambda, \int_{\lambda_l}^{\lambda_u} S(\lambda)\overline{g}(\lambda)d\lambda, \int_{\lambda_l}^{\lambda_u} S(\lambda)\overline{b}(\lambda)d\lambda \right) \quad (1.4)$$

where $\overline{r}(\lambda)$, $\overline{g}(\lambda)$ and $\overline{b}(\lambda)$ are the color matching functions shown in Fig. 1.6, which were obtained experimentally. These functions have been introduced to represent colors in terms of an amount of red, green and blue light.

The 3-tuple (R, G, B) uniquely determines a visible color, given a light source.

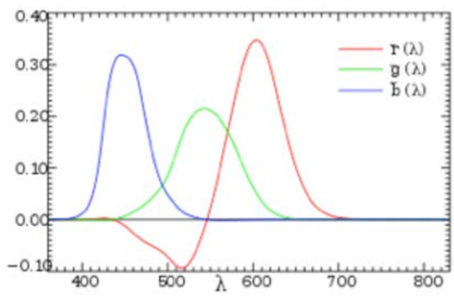

Figure 1.6: Color matching functions of source lights R, G and B. When used as color matching functions, we get the CIE RGB color space.

1.5.2 CIE L*a*b* color space

The CIE L*a*b* is a color space that describes all perceivable colors in three dimensions: L* for lightness; a* and b* for the color opponents green–red and blue–yellow, respectively. The CIE L*a*b* color space was introduced as a perceptually uniform color space where the difference of two colors sampled with given distance in the space is perceived the same way, no matter the region they come from. So the CIE L*a*b* color space is designed to approximate human vision as close as possible.

When printing graphics, it is required to convert them from RGB to a color space that is suitable for printing, which is typically characterized by more than three components (i.e., colors). An example is the CMYK space, which is used by laser printers and is based on Cyan, Magenta, Yellow and Key black. The L*a*b* color space is used to convert graphics because it is machine-independent and its gamut[3] includes the gamuts of the starting and destination color spaces.

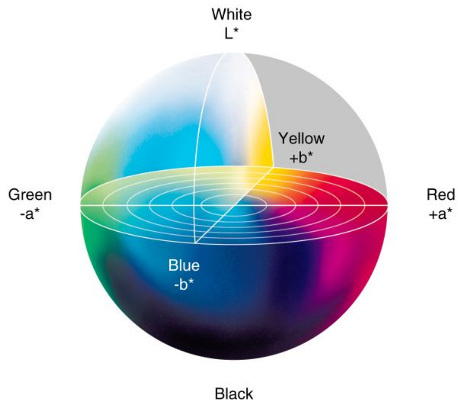

Figure 1.7: The CIE L*a*b* color space.

Given a color, the three coordinates L*, a* and b* represent the color lightness, position between red and green, and position between yellow and blue, respectively. In particular, L* $=0$ is the darkest black and L* $=100$ indicates diffuse white; negative values of a* indicate green, while positive values indicate red; negative values of b* indicate blue and positive values indicate yellow.

1.5.3 Measuring the difference of colors

As CIE L*a*b* is a perceptually uniform color space, the difference between two colors can be measured as the Euclidean distance in the color space. This way of measuring the difference of colors (ΔE^*_{ab}) was introduced by the CIE in 1976. Let (L^*_1, a^*_1, b^*_1) and (L^*_2, a^*_2, b^*_2) be two colors in the CIE L*a*b* color space, then their difference is:

$$\Delta E^\star_{ab} = \sqrt{(L^*_2 - L^*_1)^2 + (a^*_2 - a^*_1)^2 + (b^*_2 - b^*_1)^2}. \tag{1.5}$$

From a perceptual point of view, it holds that:

- when $0 < \Delta E^\star_{ab} < 1$, an observer does not notice the difference;
- when $1 \leq \Delta E^\star_{ab} < 2$, only experienced observers can notice the difference;
- when $2 \leq \Delta E^\star_{ab} < 3.5$, unexperienced observers also notice the difference;
- when $3.5 \leq \Delta E^\star_{ab} < 5$, clear difference in color is noticed;
- when $\Delta E^\star_{ab} \geq 5$, an observer notices two different colors.

Unfortunately, the previous rules do not hold everywhere in the CIE L*a*b* color space. For example, there are regions where an observer perceives a difference between two colors only when they have a value of $\Delta E^\star_{ab}$ that is much

[3]The gamut of a color space includes all colors that the color space can represent.

higher than 3.5. It is the case, e.g., of the dark region of the CIE L*a*b* color space. Further imprecisions of $\Delta E^{\star}_{ab}$ occur in the blue-violet region.

Due to these drawbacks, the CIE has revised Eq. (1.5) over the last decades. Nevertheless, the version released in 1976 is still the most used.

2

Project specification – Part I

The aim of this part is to design and develop a neural network-based system that compares a master color to a copy, in order to measure how similar they are.

2.1 Basic concepts

Let us consider a *master* color and an industrial process that prints *copies* of the master. The more accurate the process, the more similar each copy is to the master. The similarity is mainly evaluated by means of visual checks, where copies are compared to the master. These checks are affected by imprecision and subjectivity.

2.2 Dataset

The dataset is made up of 1269 reflectance spectra. Each spectrum is related to a master color and is measured with 1 nm step, ranging from 380 nm to 800 nm. This results into 421 samples for each spectrum.

The file provided (`dataset.m`) is a MATLAB file that contains two matrices named `spectra` and `coordinates`, whose structure is as follows:

- `spectra`: 421×1269 matrix where each column corresponds to a color patch, and each row to one of the 421 samples of the reflectance curve of that color patch;
- `coordinates`: 6×1269 matrix where each column corresponds to a color patch, rows from 1 to 3 contain the RGB coordinates in the order, and rows from 4 to 6 contain the L*a*b* coordinates in the order. The color coordinates are calculated using D65 light source.

2.3 Reproducing masters

One way to generate "synthetic" copies of a master color is to add noise to its spectral reflectance curve. This can effectively simulate the slight color changes that inevitably occur when printing huge quantities of copies of a master color in an industrial process.

A copy of a master can thus be generated, e.g., by first dividing the spectrum into wavelength ranges and then adding a noise to one or more wavelength ranges. The amounts of noise to add have to be found experimentally, depending on the wavelength range.

In order to see how the perturbation modifies a master color, compute the corresponding 3-tuple (R, G, B) and use a graphics editor (e.g., Microsoft Paint, Adobe Photoshop,...) to visually compare the 3-tuple (R, G, B) of the copy to that of the master. The RGB coordinates of the master are in `coordinates`, those of the copy have to be calculated. The *optprop* MATLAB toolbox—which is available at `https://www.mathworks.com/matlabcentral/fileexchange/13788-optprop-a-color-properties-toolbox`—contains a useful set of functions that can help you make these calculations.

When making comparisons, set the color profile of your monitor to sRGB.

2.4 How to represent colors

Represent a color in terms of specific features that can be found by means of feature extraction and/or feature selection techniques applied to the corresponding reflectance curve in `spectra`.

For example, feature extraction may be performed by first dividing the visible spectrum into k wavelength ranges, and then associating each wavelength range to one or more features, whose values are calculated, e.g., based on statistics. The value of k, the length of each range and the number/type of features have to be determined to obtain good features to represent a color.

2.5 Comparing colors

When dealing with printing processes, the color of each copy must be as close as possible to that of the master. This means that there should be no difference between a master and a copy. If a bit of difference exists, it must be hard to detect by the human eye. As said in Section 2.1, master and copy must be compared to each other in order to decide whether they are perceived the same way by a human observer. Visual checks are typically carried out by experienced workers, but these checks are affected by imprecision and subjectivity.

In order to objectively compare a copy to a master, it is required to design and develop the neural network shown in Fig. 2.1, which must be designed and trained to measure the difference between two similar colors. From an operational point of view, the network takes as input the representations of a master color and of a copy, and returns their *color difference*. This quantity measures how different the copy appears when compared to the master.

For simplicity, in order to find the best representation of colors, it is possible to start considering $\Delta E^{\star}_{ab}$ as output from the network. This output will then be replaced with another quantity that will be explained in Part II.

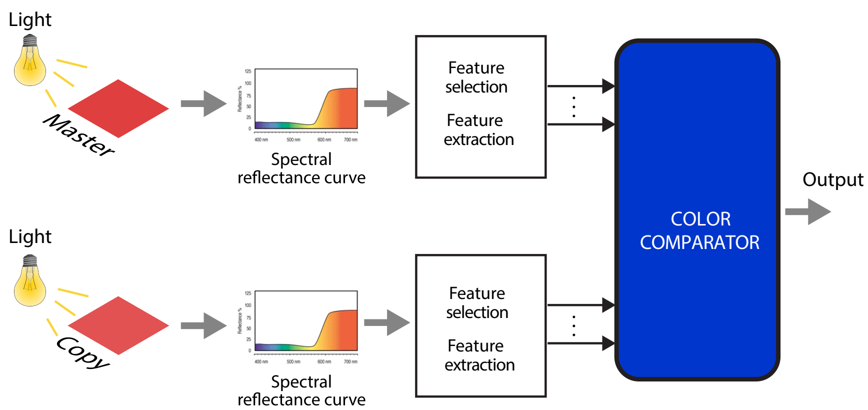

Figure 2.1: The neural color comparator.

3

Project specification – Part II

The aim of this second part is to design and develop a fuzzy inference system to fix the deficiencies of Eq. (1.5), explained in Section 1.5.3.

3.1 CIE L*C*h color space

The CIE L*C*h color space is a perceptually uniform color space that represents colors by means of *lightness* (L^*), *chroma* or *saturation* (C^*), and *hue angle* or simply *hue* (h or h_{ab}). The L*C*h color space has the same diagram as the L*a*b* space, but uses cylindrical coordinates, as shown in Fig. 3.1. Given a

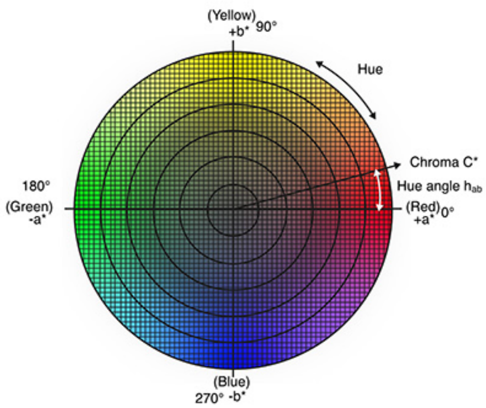

Figure 3.1: A slice of the L*a*b* color space at L*=50.

color (L^*, a^*, b^*), the C^* and h coordinates can be obtained according to the following equations:

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \tag{3.1}$$

$$h = \begin{cases} \arctan\left(\frac{b^*}{a^*}\right) & \text{if } \arctan(b^*/a^*) \geq 0 \\ \arctan\left(\frac{b^*}{a^*}\right) + 360° & \text{otherwise.} \end{cases} \tag{3.2}$$

The value C^* of chroma is the distance from the lightness axis. The higher C^*, the higher the color saturation and purity. Chroma is 0 along the L* axis, and its maximum value C^*_{max} depends on the value of L*. For example, if $L^* = 50$ then C^*_{max} is approximately equal[1] to 127.

Values of L^* that are lower/higher than 50 lead to lower values of C^*_{max}. Chroma is also expressed as a percentage. Looking at Fig. 3.1, the color at the center of the circle has $C^* = 0$, whereas the colors on the outermost circumference (i.e., the surface of the L*a*b* sphere) are those with 100% saturation/chroma.

The hue angle is expressed in degrees, and starts from the +a* axis, where $h = 0$. Given a slice of the L*a*b* space, the hue angle varies in $[0°, 360°)$ counterclockwise. The hues at 0°, 90°, 180° and 270° lie on the four axes that correspond to the L*a*b* primaries red, yellow, green, and blue, respectively.

A CIE L*a*b* color can easily be converted into the corresponding CIE L*C*h coordinates by using either the `lab2lch()` conversion function of the *optprop* toolbox, or by means of Eqs. (3.1) and (3.2). The reverse transformation can be done with function `lch2lab()`[2].

3.2 Structure of the fuzzy system

The system to develop is a Mamdani-type fuzzy inference system, shown in Fig. 3.2. The system takes four inputs and has one output.

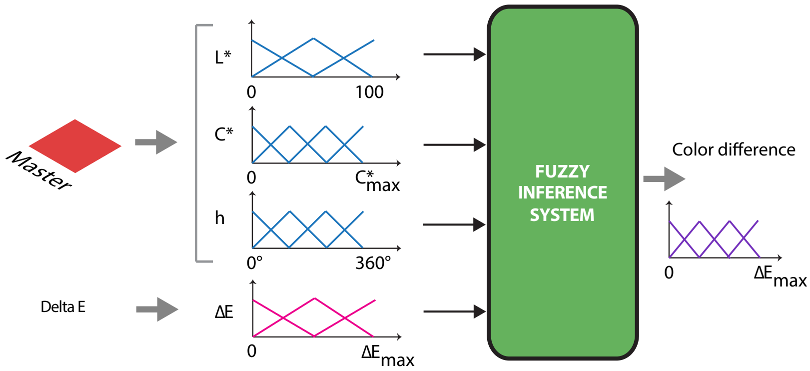

Figure 3.2: The fuzzy inference system.

The first three inputs stem from an appropriate linguistic modeling of the (L^*, C^*, h) coordinates, which indicate a specific region of the color space. The fourth input stems from the linguistic modeling of $\Delta E^\star_{ab}$, from now on simply referred to as ΔE. When designing the system, consider the values of ΔE that

[1] More precisely, when varying the hue at $L^* = 50$, you have that $C^*_{max} \in [127, 128]$ because $a^*, b^* \in [-128, 127]$. There is thus a little bit of asymmetry at any L^*, and then C^*_{max} slightly depends on h. However, you can consider 127 as the maximum value of C^* for all the hues at $L^* = 50$, and can suppose that the maximum value of C^* is the same for all hues at a given L^*.

[2] Before using these conversion functions, as well as all the other functions of the toolbox, read the help documentation carefully.

range from 0 to a maximum value ΔE_{max}. A reasonable maximum value may be $\Delta E_{max} = 10$.

The linguistic modeling of the inputs has to be performed by using appropriate sets of membership functions. Pay particular attention when designing the linguistic modeling of C^*, because the maximum value of this color coordinate changes depending on the value of L^*, as explained in the previous section.

The output of the system is a linguistic variable that expresses the perceptual difference, based on the input value of ΔE, between two colors that come from the region identified by L^*, C^* and h. The linguistic modeling of the output has to be performed by means of appropriate membership functions.

3.3 How to use the fuzzy inference system to improve ΔE

The output of the fuzzy inference system can be used to train the neural network described in Part I. This makes it possible to obtain an improved version of ΔE, whose behavior is the same whatever the region of the L*a*b* space where the difference between two colors is measured. As a result, using this improved measure, a given amount of change applied to two different colors is perceived the same way by a human observer, no matter the regions of the L*a*b* space the two colors come from.

In order to achieve this result, the output of the fuzzy inference system described in this section has to be first defuzzified and then used to replace the value of ΔE calculated using Eq. (1.5), where needed.