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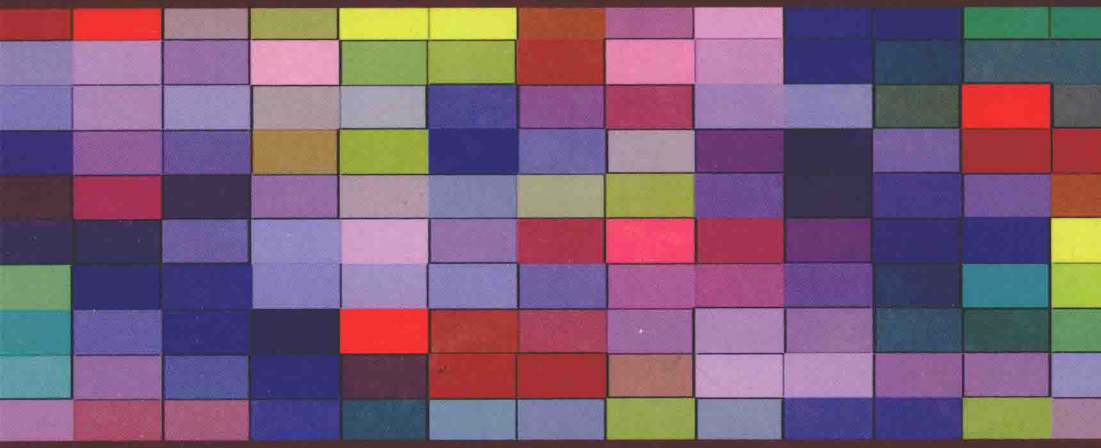

Digital Color

Acquisition, Perception, Coding and Rendering

Edited by
Christine Fernandez-Maloigne
Frédérique Robert-Inacio and Ludovic Macaire

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Foreword

The evolution of human vision occurred naturally with time. Some anthropologists suggest that the cells that are sensitive to color, cones, were developed when we were *gatherers*, in order to distinguish fruits from foliage. In fact, each of the three kinds of cones is sensitive to a wide spectrum of electromagnetic waves. The sum of these three spectra is what we call *light*. Color does not exist in nature but it is reconstituted, or learned, by our brain based on the quantities of light received on each of the three elements. Of course there are defects inherent to this chain, related to the imperfections of the eye (aging, color-blindness, etc.), or to the learning or the diversity of our cultures. In any case, naming a color is highly subjective. Moreover we denote by the same word a color that would be obtained either by adding the three cones excited by a continuous or discontinuous spectrum of a portion of light or by a pure ray. This is what specialists call *metameric* colors. They thus have different spectral compositions and we *see* them or denote them by the same color, the same word. Colors, in human vision, are also influenced by their environment which may cause optical illusions. But we are also able to name a color by the same word even if the lighting conditions change: this is *color constancy*. All this is already very difficult to understand.

It is along this path that the authors of this book on digital imaging color, like others before them, take us. It is a difficult path fraught with questions starting from image capture up to making a decision. It is a path where the authors have added the acquired knowledge and their own research, and where each element of the chain affects the other and

vice versa. Of course, they rely on human vision that, as we have seen, has its defects, while scanning an image adds even more. The selection or the variability of the illuminant, the light/matter interaction from a macroscopic point of view (reflection, diffusion, diffraction, polarization, etc.), the particle size of the object, etc., make the spectrum received by the sensor already complex and influenced by all these physical phenomena. The different technologies of the digital sensor are also added to the complexity of obtaining an objective digital image.

Reader, all this is largely explained in this book which will guide you through this science of colorimetry associated with physiology – that is to say to our body functions, which is in this case our human visual system (HVS). Other explanations will guide you in choosing different models, often standardized by the CIE (International Commission on Illumination) through to the *color appearance model* used to approach the HVS. Every word of this model clearly demonstrates the difficulty of understanding the concept of colorimetry. It is a genuine aid that is proposed to base the choices of the sensor and the model on what we want, i.e. based on our application. Algorithms and hints are included to assist you and resolve issues, while the explanations at every turn of a page increase your understanding.

So if the image is digital why not create a resemblance to reality. A whole chapter is reserved for rendering and image synthesis. You will therefore find how to perform computationally some of the issues of the first section of this preface. Representation models of light sources up to spectrum rendering passing through the simulation of light propagation (ray tracing, etc.) make us travel in this world of virtual reality. Encryption, watermarking to protect authors will have almost no secret for you. If you want to know how to set the quality of an image and contrast it with the fidelity of an image, then approaches in this thriving field will bring you, if not solutions, at least the tools for you to build a good workshop. In contrast to the sensor, there is the visualization. So, how can we measure – for the sensor as well – how to calibrate it? Nothing is simple in this field since subjectivity is ultimately the teacher. At the end of the bench there is the user, the observer, and it is here that everything escapes us. We open the time to the reader and his

memory. A second book[1] by the same authors is also to be published that is complementary to this one, but with a more algorithmic and applicative vision.

I would like to extend thanks to Christine Fernandez-Maloigne (University of Poitiers), Frédérique Robert-Inacio (ISEN-Toulon) and Ludovic Macaire (University of Lille) for having successfully led this team of authors, each an expert in their field. In addition thank you to all of the authors for devoting your time and dispensing your knowledge to share with us this major work, which is obviously useful for our community and also beyond. This book is intended for all those who wish to develop a chain of acquisition, processing and analysis of color digital images. To you, reader, I wish you good reading and am sure you will find the answers to your problems in this field.

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March 2012

1 C. FERNANDEZ-MALOIGNE, F. ROBERT-INACIO, L. MACAIRE, Digital Color Imaging, ISTE, London, John Wiley & sons, New York, 2012.

Table of Contents

Chapter 1

Colorimetry and Physiology – The LMS Specification

To test and improve the quality of color images, we need to know how the human visual system operates. Colorimetry is a method that quantitatively assesses the changes that the engineer makes to an image. Recent advances in this field are due to a better understanding of visual mechanisms.

This chapter first describes the physiological mechanisms that are transferred from the retina in the eye to the human brain, which produce the physiological perception of color. Then it presents two approaches to colorimetry: first, as recommended by the International Commission on Illumination (CIE), and second, deriving directly from the physiology of the visual system that results in the ability to specify stimuli and color differences. Finally, the chapter outlines the difficulties in defining the appearance of color and the advantages in modeling the human visual system.

Chapter written by Françoise VIÉNOT and Jean LE ROHELLEC.

1.1. Physiological basis

Light detected by the eye excites the photoreceptors that are photosensitive cells. It produces biochemical changes and yields a signal, which is relayed by different classes of post-synaptic retinal neurons. The post-synaptic retinal neurons are organized in a layer in radial and transversal directions. The information is conveyed along the radial direction of the receptors toward the bipolar cells and then toward the ganglion cells whose axons form the optic nerve.

Horizontal cells and amacrine cells form a transversal network, whose action modulates direct signals. Then, the signal travels in the form of trains of action potentials through the optic nerve toward the visual cortex, where a visual image is formed.

1.1.1. *The photoreceptors*

1.1.1.1. *Spectral sensitivity of cones, the monovariant response of a photoreceptor*

Each photon absorbed by a cone triggers a cascade of chemical reactions producing a signal at the output of the cone, regardless of the wavelength associated with that photon. As a result, the amplitude of the response of the cone to light depends only on the number of absorbed photons, and not on the wavelength associated with the photons. While light consist of wavelengths in the visible spectrum with wide energy distributions, the response of a single cone is monovariant, it varies only in amplitude. If the photon has energy close to that required for the isomerization of the photosensitive pigment included in the cone, this is absorbed by the cone. The probability of absorption is determined by the spectral sensitivity of the cone.

The *in vitro* measurements of the spectral sensitivity of the cones [DAR 83] showed the existence of three families of retinal cones with maxima at 419, 531 and 558 nm. This would correspond to *in vivo* measurements in a healthy eye, taking into account the filtering effect of the ocular media, which is about 440 nm for S cones sensitive to short wavelengths, 540 nm for M cones, sensitive to middle wavelengths,

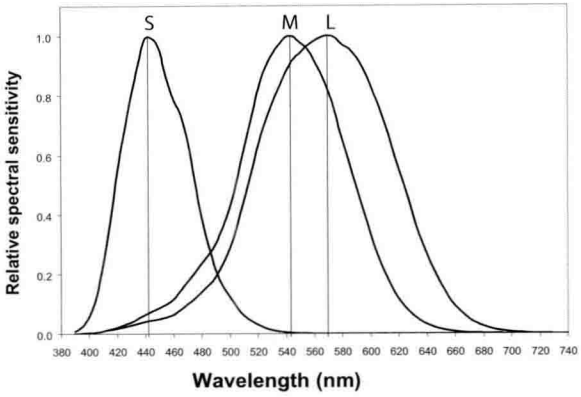

Figure 1.1. *Spectral sensitivity of the three families of cones*

and 565 nm for L cones, sensitive to longer wavelengths. The spectral sensitivity curves are widely spread over the visible spectrum, with the M and L cones being close to each other. It should be noted that there is no retinal cone whose maximum sensitivity lies in the part of the spectrum that appears red to the eye (beyond about 620 nm), indicating that the retinal cones are not simple color receptors. Red, like other colors, is reconstructed by the visual system. The M and L cones give to the eye its maximum light sensitivity of around 555 nm.

1.1.1.2. *The retinal mosaic*

Through optical or electronic microscopy, it is observed that the retina consists of two types of morphologically distinct photoreceptors: rods and cones. Rods are responsible for the vision at low illumination, and cones at higher illumination. The numerical density of cones is maximum in the fovea, that is to say in the central area of the retina, where images of the objects that we see are formed, and drops significantly toward the surrounding area. It is also possible to observe the cones *in vivo*, or at the back of the eye, using adaptive optics that neutralize the aberrations. We can also identify their corresponding families L, M or S [ROO 99, HOF 05]. Among the ten retinas that were examined, it was verified that the S cones were relatively few and that the numerical proportion of L and M cones was on average 2L for 1M, with surprising variations from

person to person ranging from 1L for 2M to 16L for 1M, for normal color vision.

1.1.2. *Retinal organization*

The extraction of the color signal is achieved by comparing the signals from a family of cones with those from another family of cones. This comparison is carried out by post-synaptic retinal neurons.

1.1.2.1. *Concept of receptive field of the neuron*

Each neuron of the visual system, wherever it is located in the hierarchy of the processing, corresponds to a given area of space seen by the subject. It also corresponds to all the requested photoreceptors, within which the bio-electrical behavior of the neuron is changed. This area is called the receptive field of the neuron.

The receptive fields are small in the fovea, and larger as we move away from it. Each neuron is only a small, circular part of the visual field and the encoding of the signal responsible for each neuron depends on its immediate environment.

A retinal neuron does not perform an absolute coding of the light contained in its receptive field, but a coding related to the light status in the near vicinity. Only a differential signal (contrast) generates a signal in the neuron, which is transmitted to the next neurones in the hierarchy of visual information processing. The contrast may relate both to a difference in light or to a difference in spectral content of light.

1.1.2.2. *Two parallel pathways from the retina to the cortex*

The chemical contact between photoreceptors, bipolar cells, and horizontal cells is carried out at the terminal portion of the cone and is called "synapse". The synapse type determines a fundamental functional dichotomy of the coding of the light signal. Some bipolar cells have synapses that maintain the polarity of the signal coming from the cone, others reverse it. The ON-bipolar cells indicate an increment of light at the center of the receptive field (relative to the surrounding fields). They initiate a neural pathway called the ON pathway. The OFF-bipolar cells

indicate a decrease in light at the center of the receptive field (relative to the surrounding fields). They initiate a neural pathway called the OFF pathway. These ON and OFF pathways run in parallel across each unit area of the visual space by encoding all the variations of light and remain independent up to the cortex.

1.1.2.3. *At the origin of konio, parvo and magnocellular pathways*

Different types of bipolar cells are at the origin of three separate neurophysiological pathways from the retina to the cortex: the koniocellular pathway dedicated to spectral differentiation; the parvocellular pathway dedicated to spectral differentiation and light differentiation; and the magnocellular pathway dedicated to light differentiation.

Midget bipolar (MB) cells are the most numerous. They receive signals from cones L and M. They are distinguished by the type of synapse, one belonging to the ON pathway, others to the OFF pathway (see next section).

For ease of nomenclature, a neuron whose receptive field center is ON (responding to an increase in light), will be encoded by "+", and a neuron whose receptive field center is OFF (responding to a decrease in light) will be encoded "−". The letter following the sign denotes the majority cone type in the center, either L or M (S cones will be discussed in the next section). Implicitly, the area of the receptive field receives signals from the other family of cones, either M or L, on an antagonist mode. For example, a neuron denoted +L will transmit a signal if the center is brighter than the surrounding area and/or if the spectral composition in the center favors large wavelengths. Thus, the midget bipolar cells are of four main types +L, −L, +M and −M. These neurons are the essential elements of the parvocellular pathway and the main initiators of the spectrum of colors and the range of forms and details.

Specific bipolar cells of S cones are the essential elements of the koniocellular pathway. They perform an encoding of the spectral antagonism by contrasting the signals of short wavelengths (S) to those of larger wavelengths (L and M), but are not involved in the encoding of variations in brightness.