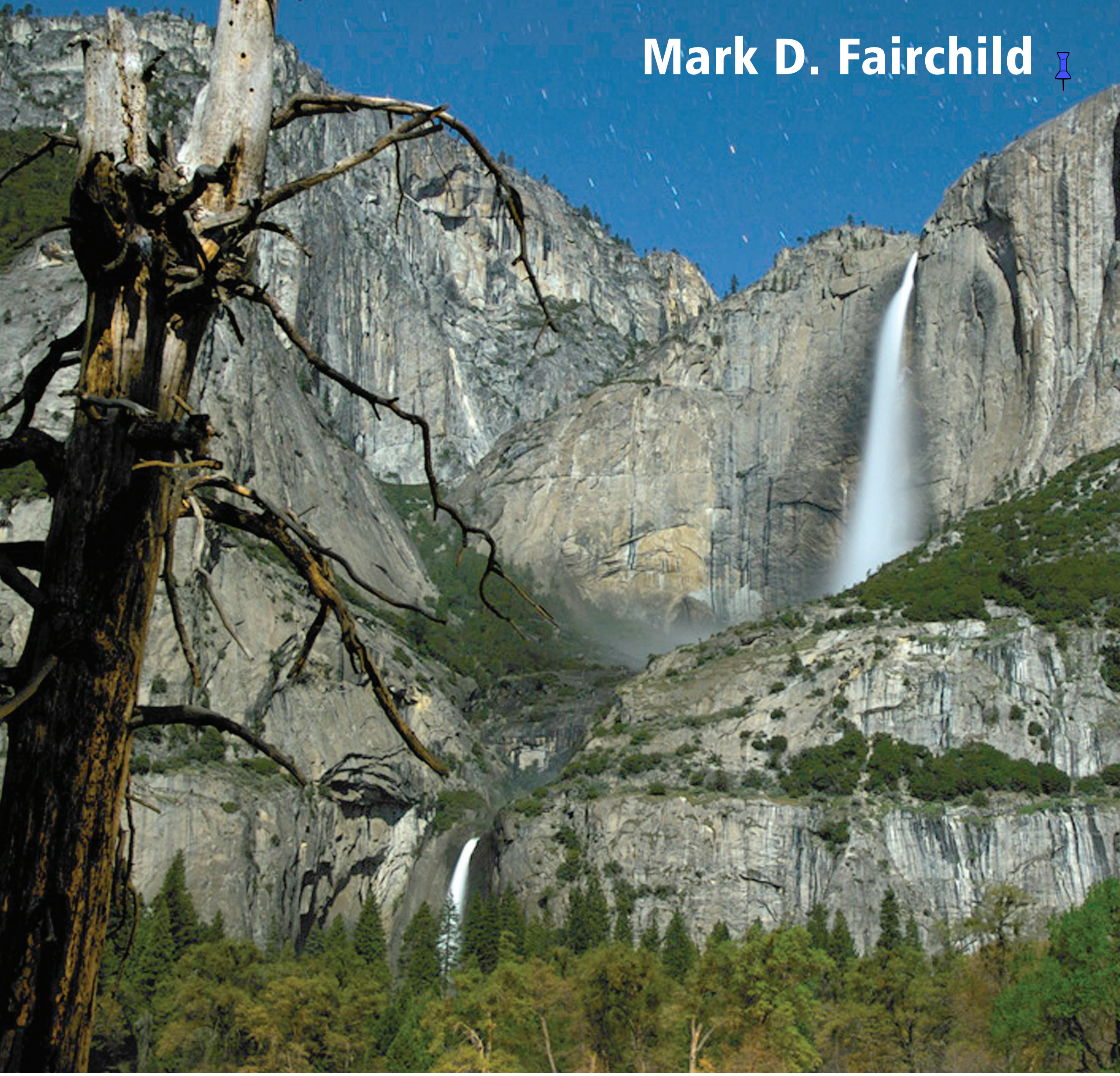
Mark D. Fairchild



COLOR APPEARANCE MODELS

Third Edition

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Published in Association with the Society for Imaging Science and Technology

Color Appearance Models

Third Edition

Mark D. Fairchild

Rochester Institute of Technology, USA

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To those that remind me that
a journey of a thousand miles begins
with a single step:

Lisa, Acadia, Ellie.

And to all the other animals that fill our lives.

How much of beauty—of color
as well as form—on which our eyes daily rest
goes unperceived by us?

Henry David Thoreau

Contents

Series Preface

Color is a subject that has fascinated scientists, philosophers and people in general for thousands of years. Virtually all people are familiar with the concepts of color and are fluent in its semantic description. However numerical descriptions of color and its manipulation using mathematical models is a field familiar to relatively few scientists and engineers. Indeed, color has only had a well defined mathematical basis for less than 100 years. The field of colorimetry was the first comprehensive mathematical description of color. The use of colorimetry, however, is limited to a description of whether colors appear to match one another under a defined set of viewing conditions. Colorimetry has enabled the precise control of color in many industrial applications including textile and paint manufacture, printing, photography, cinema, lighting and television and displays. Colorimetry however cannot provide us with a numerical description of the relative appearance of colors or how the appearance of colors will change in different viewing environments. This is the domain of color appearance modeling.

Scientific interest in color appearance modeling began with the observation that colors could change their appearance depending on the background they were seen against, the intensity and spectral properties of the illumination and many other factors. We have all experienced these phenomena, often realized when the fabric or paint that looked so perfect in the showroom doesn't quite look right when we bring it home. The first tentative steps towards a model of color appearance can be traced back to 1976 when the CIE introduced the CIELAB and CIELUV uniform color spaces. These color spaces allowed, for the first time, numerical correlates of lightness, hue, chroma and, in the case of CIELUV, saturation. Interest in color appearance modeling grew rapidly from this point. In the early 1980s leading color scientists including R.W.G. Hunt and Y. Nayatani developed the first versions of their color appearance models, designed to predict numerical correlates of all the perceptual attributes of color under a wide range of viewing conditions. Shortly after, Mark Fairchild developed the RLAB color appearance model. RLAB was a major advance in developing color appearance models for practical use in imaging applications. In 1997 the CIE proposed a simplified color appearance model, CIECAM97s, incorporating a number of features and approaches developed in the earlier models, as well as contributions by M.R. Luo and several others. Five years later CIECAM97s was succeeded by an improved, simpler and better model, CIECAM02. This model has now found widespread application in the imaging and printing industries, and an understanding of it is essential for scientists and engineers working in these areas.

The first two editions of *Color Appearance Models* are among the most significant and indispensable texts in the field of color science. This is because the author, Mark Fairchild, provides a technically detailed and comprehensive approach to the subject of color modeling. Mark's academic background, having postgraduate degrees in both imaging science and vision science, make him exceptionally qualified in this area. He has studied under, collaborated with and educated many of today's leading color scientists. Consequently, his treatment of the subject provides all the necessary context and background required for a full understanding of color appearance models. The book provides an explanation of how color phenomena arise from the anatomy and physiology of the human visual system. It summarizes the methodologies, from the field of psychophysics, that allow us to obtain numerical measures of perceptual phenomena such as color. Colorimetry – the foundation of all color appearance models – is explained clearly and thoroughly. Fairchild provides descriptions and explanations of a very broad range of color appearance phenomena that are addressed by color appearance models. The book also takes us on a historical and technical journey, visiting each of the major advances in color appearance modeling in turn, until finally arriving at today's most used model – CIECAM02. Fairchild provides a full technical explanation of all the major models as well as expert guidance on the strengths, weaknesses and uses of each model. The latter third of the book covers applications of color appearance modeling, with a strong focus on imaging science and technology. The third edition of *Color Appearance Models* extends the treatment of applications to the field of high dynamic-range (HDR) imaging. This is one of the important new challenges in imaging science and photography. Color appearance models provide the important scientific insights required for development and refinement of new HDR technologies.

Mark Fairchild is counted among the world's finest and most influential color imaging scientists and educators. His third edition of *Color Appearance Models* is destined to become a classic color science textbook. The Society for Imaging Science and Technology (IS&T) and John Wiley & Sons Ltd are proud to be able to make this outstanding book available to students, scientists and engineers working in color related fields.

Geoffrey J. Woolfe
Canon Information Systems Research Australia
Publications Vice President, Society for Imaging Science and Technology

Preface

The law of proportion according to which the several colors are formed, even if a man knew he would be foolish in telling, for he could not give any necessary reason, nor indeed any tolerable or probable explanation of them.

Plato

Despite Plato's warning, this book is about one of the major unresolved issues in the field of color science, the efforts that have been made toward its resolution, and the techniques that can be used to address current technological problems. The issue is the prediction of the color appearance experienced by an observer when viewing stimuli in natural, complex settings. Useful solutions to this problem have impacts in a number of industries such as lighting, materials, and imaging. In lighting, color appearance models can be used to predict the color rendering properties of various light sources allowing specification of quality rather than just efficiency. In materials fields (coatings, plastics, textiles, *etc.*), color appearance models can be used to specify tolerances across a wider variety of viewing conditions than is currently possible and to more accurately evaluate metamerism. The imaging industries have produced the biggest demand for accurate and practical color appearance models. The rapid growth in color imaging technology, particularly the desktop publishing and digital photography markets, has led to the emergence of color management systems. It is widely acknowledged that such systems require color appearance models to allow images originating in one medium and viewed in a particular environment to be acceptably reproduced in a second medium and viewed under different conditions. While the need for color appearance models is recognized, their development has been at the forefront of color science and largely confined to the discourse of academic journals and conferences. This book brings the fundamental issues and current solutions in the area of color appearance modeling together in a single place for those needing to solve practical problems or looking for background for ongoing research projects.

Everyone knows what color is, but the accurate description and specification of colors is quite another story. In 1931, the Commission Internationale de l'Éclairage (CIE) recommended a system for color measurement establishing the basis for modern colorimetry. That system allows the specification of color matches through CIE XYZ tristimulus values. It was immediately recognized that more advanced techniques were required. The CIE recommended the CIELAB and CIELUV color spaces in 1976 to enable uniform international practice for the measurement of color differences and establishment of color tolerances. While the CIE system of colorimetry has been applied successfully for over 80 years, it is limited to the comparison of stimuli that are identical in every spatial and temporal respect and viewed under matched viewing conditions. CIE XYZ values describe whether or not two stimuli match. CIELAB values can be used to describe the perceived differences between stimuli in a single set of viewing conditions. Color appearance models extend the current CIE systems to allow the description of what color stimuli would look like under a variety of viewing conditions. The application of such models opens up a world of possibilities for the accurate specification, control, and reproduction of color.

Understanding color-appearance phenomena and developing models to predict them have been the topics of a great deal of research — particularly in the last 20–30 years. Color appearance remains a topic of much active research that is often being driven by technological requirements. Despite the fact that the CIE is not yet able to recommend a single color appearance model as the best available for all applications, there are many who need to implement some form of a model to solve their research, development, and engineering needs. One such application is the development of color management systems based on the International Color Consortium (ICC) Profile Format that continues to be developed by the ICC and incorporated into essentially all modern computer operating systems. Implementation of color management using ICC profiles requires the application of color appearance models with no specific instructions on how to do so. Unfortunately, the fundamental concepts, phenomena, and models of color appearance are not recorded in a single source. Generally, one interested in the field must search out the primary references across a century of scientific journals and conference proceedings. This is due to the large amount of active research in the area. While searching for and keeping track of primary references is fine for those doing research on color appearance models, it should not be necessary for every scientist, engineer, and software developer interested in the field. The aim of this book is to provide the relevant information for an overview of color appearance and details of many of the most widely used models in a single source. The general approach has been to first provide an overview of the fundamentals of color measurement and the phenomena that necessitate the development of color appearance models. This eases the transition into the formulation of the various models and their applications that appear later in the book. This approach has proven quite useful in various university courses, short courses, and seminars in which the full range of material must be presented in a limited time.

Chapters 1 through 3 provide a review of the fundamental concepts of human color vision, psychophysics, and the CIE system of colorimetry that are prerequisite to understanding the development and implementation of color appearance models. Chapters 4 through 7 present the fundamental definitions, descriptions, and phenomena of color appearance. These chapters provide a review of the historical literature that has led to modern research and development of color appearance models. Chapters 8 and 9 concentrate on one of the most important component mechanisms of color appearance, chromatic adaptation. The models of chromatic adaptation described in Chapter 9 are the foundation of the color appearance models described in later chapters. Chapter 10 presents the definition of color appearance models and outlines their construction using the CIELAB color space as an example. Chapters 11 through 13 provide detailed descriptions of the Nayatani *et al.*, Hunt, and RLAB color appearance models along with the advantages and disadvantages of each. Chapter 14 reviews the ATD and LLAB appearance models that are of increasing interest for some applications. Chapter 15 presents the CIECAM97s model established as a recommendation by the CIE just as the first edition of this book went to press (and included as an appendix in that edition). Also included is a description of the ZLAB simplification of CIECAM97s. Chapter 16 describes the recently formulated CIECAM02 model that represents a significant improvement of CIECAM97s and is the best possible model based on current knowledge. Chapters 17 and 18 describe tests of the various models through a variety of visual experiments and colorimetric applications of the models. Chapter 19 presents an overview of device-independent color imaging, the application that has provided the greatest technological push for the development of color appearance models. Finally, Chapters 20 and 21 introduce the concept of image appearance modeling as a potential future direction for color appearance modeling research, provide an overview of iCAM as one example of an image appearance model, and introduce new approaches to appearance prediction without color spaces and in high-dynamic-range environments.

While the field of color appearance modeling remains young and likely to continue developing in the near future, this book includes extensive material that will not change. Chapters 1 through 10 provide overviews of fundamental concepts, phenomena, and techniques that will change little, if at all, in the coming years. Thus, these chapters should serve as a steady reference. The models, tests, and applications described in the later chapters will continue to be subject to evolutionary changes as research progresses. However, these chapters do provide a useful snapshot of the current state of affairs and provide a basis from which it should be much easier to keep track of future developments. To assist readers in this task, a webpage has been set up (www.cis.rit.edu/Fairchild/CAM.html), which lists important developments and publications related to the material in this book. A spreadsheet with example calculations can also be found there.

'Yes,' I answered her last night;
'No,' this morning sir, I say,
Colors seen by candle-light
Will not look the same by day.

Elizabeth Barrett Browning

Acknowledgments

A project like this book is never really completed by a single author. I particularly thank my family for the undying support that encouraged completion of this work. The research and learning that led to this book is directly attributable to my students. Much of the research would not have been completed without their tireless work, and I would not have learned about color appearance models were it not for their keen desire to learn more and more about them from me. I am deeply indebted to all of my students and friends — those that have done research with me, those working at various times at the Rochester Institute of Technology (RIT), and those that have participated in my university and short courses at all levels. There is no way to list all of them without making an omission, so I will take the easy way out and thank them as a group. I am also indebted to those that reviewed various chapters while the first edition of this book was being prepared and provided useful insights, suggestions, and criticisms as well as those who helped with revisions of the later editions. Thank you to Addison-Wesley for convincing me to write the first edition and then publishing it and to IS&T, the Society for Imaging Science and Technology, for having the vision to publish the second and third editions with Wiley. It has been a joy to work with all of the IS&T staff throughout my color imaging career. Thanks to all of the industrial and government sponsors of our research and education at RIT that lead to many of the results and analyses presented in this volume. I have been fortunate to work with a fascinating variety of students, staff, and faculty colleagues over the years; this edition would not have been possible without them.

M.D.F.
Honeoye Falls, NY

Ye'll come away from the links with a new hold on life,
that is certain if ye play the game with all yer heart.

Michael Murphy, *Golf in the Kingdom*

Introduction

Standing before it, it has no beginning;
even when followed, it has no end.
In the now, it exists; to the present apply it,
follow it well, and reach its beginning.

Tao Te Ching, 300–600 BCE

Like beauty, color is in the eye of the beholder. For as long as human scientific inquiry has been recorded, the nature of color perception has been a topic of great interest. Despite tremendous evolution of technology, fundamental issues of color perception remain unanswered. Many scientific attempts to explain color rely purely on the physical nature of light and objects. However, without the human observer there is no color. It is often asked whether a tree falling in the forest makes a sound if no one is there to observe it. Perhaps equal philosophical energy should be spent wondering what color its leaves are.

You can observe a lot by just watching.

Yogi Bera

WHAT IS A COLOR APPEARANCE MODEL?

It is common to say that certain wavelengths of light, or certain objects, are a given color. This is an attempt to relegate color to the purely physical domain. Instead it is proper to state that those stimuli are perceived to be of a certain color when viewed under specified conditions. Attempts to specify color as a purely physical phenomenon fall within the domain of spectrophotometry and spectroradiometry. When the lowest-level sensory responses of an average human observer are factored in, the domain of colorimetry has been entered. When the many other variables that influence color perception are considered, in order to better describe our perceptions of stimuli, one is within the domain of color appearance modeling — the subject of this book.

Consider the following observations:

- The headlights of an oncoming automobile are nearly blinding at night, but barely noticeable during the day.
- As light grows dim, colors fade from view while objects remain readily apparent.

- Stars disappear from sight during the daytime.
- The walls of a freshly painted room appear significantly different from the color of the sample that was used to select the paint in a hardware store.
- Artwork displayed in different color mat board takes on a significantly different appearance.
- Printouts of images do not match the originals on a self-luminous display (*e.g.*, computer monitor, tablet, smart phone, television).
- Scenes appear more colorful and of higher contrast on a sunny day than on an overcast day.
- Blue and green objects (*i.e.*, board-game pieces) become indistinguishable under dim incandescent illumination.
- It is nearly impossible to select appropriate socks (*e.g.*, black, brown, or blue) in the early morning light.
- There is no such thing as a gray, or brown, lightbulb.
- There are no colors described as reddish-green or yellowish-blue.

None of the above observations can be explained by physical measurements of materials and/or illumination alone. Rather, such physical measurements must be combined with other measurements of the prevailing viewing conditions and models of human visual perception in order to make reasonable predictions of these effects. This aggregate is precisely the task that color appearance models are designed to manage. Each of the observations outlined above, and many more like them, can be explained as instances of various color appearance phenomena and predicted by color appearance models. They cannot be explained by the established techniques of color measurement, sometimes referred to as basic colorimetry. Hutchings (1999), in the first chapter of his book on food color and appearance, provides a delightful review of the complexities of specifying the appearance of stimuli that all enjoy perceiving. This book details the differences between basic colorimetry and color appearance models, provides fundamental background on human visual perception and color appearance phenomena, and describes the application of color appearance models to current technological problems such as digital color reproduction. Upon completion of this book, a reader should be able to fairly easily explain the causes of, if not the physiological mechanisms for, each of the appearance phenomena listed above. Fairchild (2011a) and <*whyiscolor.org*> provide an introductory and inquisitive look at the fundamental questions of color appearance and color science from the perspectives of students ranging from pre-school to graduate school.

Basic colorimetry provides the fundamental color measurement techniques that are used to specify stimuli in terms of their sensory impact for an average human observer. These techniques are absolutely necessary as the foundation for color appearance models. However, on their own, the techniques of basic colorimetry can only be used to specify whether or not two stimuli, viewed under identical conditions, match in color for an average observer. Advanced colorimetry aims to extend the techniques of basic colorimetry to enable the specification of color difference perceptions and ultimately color appearance. There are several established techniques for color difference specification that have been formulated and refined over the past several decades. These techniques have also reached the point that a few, agreed upon, standards are used throughout the world while research continues to fine-tune, improve, and extend them. Color appearance models aim to go the final step. This would allow the mathematical description of the appearance of stimuli in a wide variety of viewing conditions. Such models have been the subject of much research in the late twentieth and early twenty-first centuries and have become required for practical applications. There are a variety of models that have been proposed. These models have found their way into color imaging systems through the refinement and extension of color management techniques. Techniques derived from color appearance models are even found in the image capture and display algorithms of popular smart phones. Such applications require an ever-broadening array of scientists, engineers, programmers, imaging specialists, and others to understand the fundamental philosophy, construction, and capabilities of color appearance models as described in the ensuing chapters.

Learning is best accomplished with positive feedback to assure that new ideas are assimilated and replace pre-existing misunderstandings. As such, and so as not to make the learning process too difficult, here are some clues to the explanations of the color appearance observations listed near the beginning of this introduction.

- The change of appearance of oncoming headlights can be largely explained by the processes of light adaptation and described by Weber's law.
- The fading of color in dim light while objects remain clearly visible is explained by the transition from trichromatic cone vision to monochromatic rod vision.
- The incremental illumination of a star on the daytime sky is not large enough to be detected, while the same physical increment on the darker nighttime sky is easily perceived, because the visual threshold to luminance increments has changed between the two viewing conditions.
- The paint chip does not match the wall due to changes in the size, surround, and illumination of the stimulus and due to inter-reflections among adjacent walls that serves to increase perceived saturation.
- Changes in the color of a surround or background profoundly influence the appearance of stimuli. This can be particularly striking for photographs and other artwork.
- Assuming the display and printer are accurately calibrated and characterized, differences in media, white point, luminance level, image size, and surround can still force the printed image to look significantly different from the original.
- The Hunt effect and Stevens effect describe the apparent increase in colorfulness and contrast of scenes with increases in illumination level.
- Low levels of incandescent illumination do not provide the energy required by the short-wavelength sensitive mechanisms of the human visual system (the least sensitive of the color mechanisms) to distinguish green objects from blue objects.

- In the dim early morning light, the ability to distinguish dark colors is diminished.
- The perceptions of gray and brown only occur as related colors, thus they cannot be observed as light sources that are normally the brightest element of a scene.
- The hue perceptions red and green (or yellow and blue) are encoded in a bipolar fashion by our visual system and thus cannot exist together.

Given those clues, it is time to read on and further unlock the mysteries of color appearance. All of the topics in these examples are explored in more detail, and from various perspectives, throughout the text.

1
Human Color Vision

Color appearance models aim to extend basic colorimetry to specify the perceived color of stimuli in a wide variety of viewing conditions. To fully appreciate the formulation, implementation, and application of color appearance models, several fundamental topics in color science must first be understood. These are the topics of the first few chapters of this book. Since color appearance represents several of the dimensions of our visual experience, any system designed to predict correlates to these experiences must be based, to some degree, on the form and function of the human visual system. All of the color appearance models described in this book are derived with human visual function in mind, although most also include some empirical modeling of the visual system as a "black box." It becomes much simpler to understand the formulations of the various models if basic visual anatomy, physiology, and performance of the visual system are understood. Thus, this book begins with a treatment of the human visual system.

As necessitated by the limited scope available in a single chapter, this treatment of the visual system is an overview of the topics most important for an appreciation of color appearance modeling. The field of vision science is immense, complex, and fascinating. Readers are encouraged to explore the literature and the many useful texts with differing perspectives on human vision in order to gain further insight and details. Of particular note are the review paper on the mechanisms of color vision by Lennie and D'Zmura (1988), the text on human color vision by Kaiser and Boynton (1996), the more general text on the foundations of vision by Wandell (1995), the comprehensive treatment by Palmer (1999), and edited collections on color vision by Backhaus *et al.* (1998) and Gegenfurtner and Sharpe (1999). Other interesting and more recent texts on vision include the extensive and complete volume by Chalupa and Werner (2004), the revision of Dowling's (2012) classic on the retina, Livingstone's (2002) interesting treatment of the relationships between art and biology of seeing, Mausfeld and Heyer's (2003) book focused on perception,

Color Appearance Models, Third Edition. Mark D. Fairchild.

Schwab's (2012) discussion of the evolution of vision, and Valberg's (2005) revised edition covering all of vision, but with some more focus on color. General texts on sensation and perception, such as Wolfe *et al.* (2012), are also excellent sources for learning fundamental aspects of the human visual system. Johnsen (2012) provides a slightly different perspective on visual systems and other optical phenomena in nature. The material that is briefly summarized in this chapter is treated in more detail in those references.

1.1 OPTICS OF THE EYE

Our visual perceptions are initiated and strongly influenced by the anatomical structure of the eye. Figure 1.1 shows a schematic representation of the optical structure of the human eye with some key features labeled. The human eye can be thought of as acting like a camera. The cornea and lens act together like

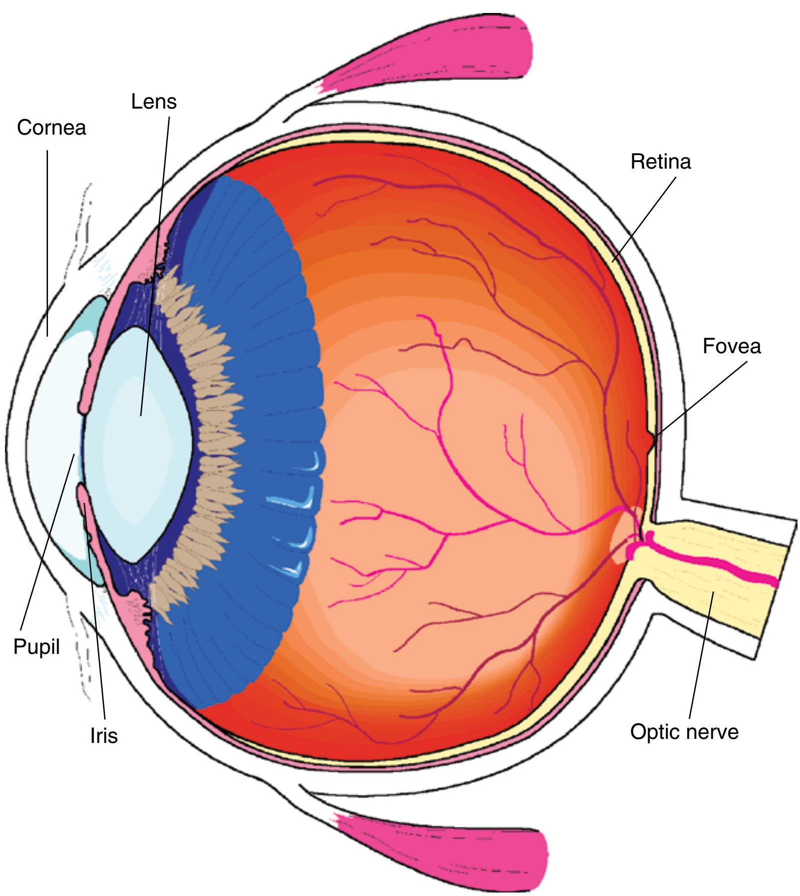

Figure 1.1 Schematic diagram of the human eye with some key structures labeled

a camera lens to focus an image of the visual world on the retina at the back of the eye, which acts like the image sensor (*e.g.*, CCD) of a camera. These and other structures have a significant impact on our perception of color.

The Cornea

The *cornea* is the transparent outer surface of the front of the eye through which light passes. It serves as the most significant image-forming element of the eye since its curved surface at the interface with air represents the largest change in index of refraction within the eye's optical system. The cornea is avascular, receiving its nutrients from marginal blood vessels and the fluids surrounding it. Refractive errors, such as nearsightedness (myopia), farsightedness (hyperopia), or astigmatism, can be attributed to variations in the shape of the cornea with respect to the location and the shape of the retina. These refractive errors are sometimes corrected with laser surgery to reshape the cornea.

The Lens

The *lens* serves the function of accommodation. It is a layered, flexible structure that varies in index of refraction. It is a naturally occurring gradient-index optical element with the index of refraction higher in the center of the lens than at the edges. This feature serves to reduce some of the aberrations that might normally be present in a simple optical system.

The shape of the lens is controlled by the ciliary muscles. When we gaze at a nearby object, the lens becomes "fatter" and thus has increased optical power to allow us to focus on the near object. When we gaze at a distant object, the lens becomes "flatter" resulting in the decreased optical power required to bring more distant objects into sharp focus. As we age, the internal structure of the lens changes, resulting in a loss of flexibility. Generally, when the age of about 45–50 years is reached, the lens has completely lost its flexibility and observers can no longer focus on near objects (this is called presbyopia, or "old eye"). It is at this point that most people must resort to reading glasses or bifocals.

Concurrent with the hardening of the lens is an increase in its optical density. The lens absorbs and scatters short-wavelength (blue and violet) energy. As it hardens, the level of this absorption and scattering increases. In other words, the lens becomes more and more yellow with age. Various mechanisms of chromatic adaptation generally make us unaware of these gradual changes. However, we are all looking at the world through a yellow filter that not only changes with age, but is significantly different from observer to observer. The effects are most noticeable when performing critical color matching or comparing metameric color matches with other observers. The effect is particularly apparent with purple objects and nearly monochromatic stimuli such as the primaries of wide-gamut displays. Since an older lens absorbs most of the blue energy reflected from a purple object but does not affect the reflected red energy, older observers will tend to report that the object is significantly more red than reported by younger observers. Important issues regarding the characteristics of lens aging and its influence on visual performance are discussed by Pokorny *et al.* (1987), Werner and Schefrin (1993), and Schefrin and Werner (1993) and in the Commission Internationale de l'Éclairage (CIE) (2006) report on physiological color matching functions.

The Humors

The volume between the cornea and the lens is filled with *aqueous humor*, which is essentially water. The region between the lens and the retina is filled with *vitreous humor*, which is also a fluid, but with a higher viscosity similar to that of gelatin. Both humors exist in a state of slightly elevated pressure (relative to air pressure) to assure that the flexible eyeball retains its shape and dimensions in order to avoid the deleterious effects of wavering retinal images. The flexibility of the entire eyeball serves to increase its resistance to injury. It is much more difficult to break a structure that gives way under impact than one of equal "strength" that attempts to remain rigid. Since the indices of refraction of the humors are roughly equal to that of water, and those of the cornea and lens are only slightly higher, the rear surface of the cornea and the entire lens have relatively little optical power (in comparison with the front surface of the cornea).

The Iris

The *iris* is the sphincter muscle that controls pupil size. The iris is pigmented, giving each of us our specific eye color. Eye color is determined by the concentration and distribution of melanin within the iris. The pupil, which is the hole in the middle of the iris through which light passes, defines the level of illumination on the retina. Pupil size is largely determined by the overall level of illumination, but it is important to note that it can also vary with nonvisual phenomena such as arousal. (This effect can be observed by enticingly shaking a toy in front of a cat and paying attention to its pupils.) Thus it is difficult to accurately predict pupil size from the prevailing illumination. In practical situations, pupil diameter varies from about 3 to 7 mm. This change in pupil diameter results in approximately a five-fold change in pupil area and therefore retinal illuminance. The visual sensitivity change with pupil area is further limited by the fact that marginal rays are less effective at stimulating visual response in the cones than central rays (the Stiles–Crawford effect). The change in pupil diameter alone is not sufficient to explain excellent human visual function over prevailing illuminance levels that can vary over 10 orders of magnitude or more.

The Retina

The optical image formed by the eye is projected onto the retina. The *retina* is a thin layer of cells, approximately the thickness of tissue paper, located at the back of the eye and incorporating the visual system's photosensitive cells and initial signal processing and transmission "circuitry." These cells are neurons, part of the central nervous system, and can appropriately be considered a part of the brain. The photoreceptors, rods and cones, serve to transduce the information present in the optical image into chemical and electrical signals that can be transmitted to the later stages of the visual system. These signals are then processed by a network of cells and transmitted to the brain through the optic nerve. More detail on the retina is presented in "The retina."

Behind the retina is a layer known as the *pigmented epithelium*. This dark pigment layer serves to absorb any light that happens to pass through the retina without being absorbed by the photoreceptors. The function of the pigmented epithelium is to prevent light from being scattered back through the retina, thus reducing the sharpness and contrast of the perceived image. Nocturnal animals give up this improved image quality in exchange for a highly reflective tapetum that reflects the light back in order to provide a second chance for the photoreceptors to absorb the energy. This is why the eyes of a deer, or other nocturnal animal, caught in the headlights of an oncoming automobile appear to glow. They are acting like very efficient retro-reflectors by focusing the light from the car they are looking at through the animal's eyes and right back to the car itself.

The Fovea

Perhaps the most important structural area on the retina is the fovea. The *fovea* is the area on the retina where we have the best spatial and color vision. When we look at, or fixate, an object in our visual field, we move our head and eyes such that the image of the object falls on the fovea. As you are reading this text, you are moving your eyes to make the various words fall on your fovea as you read them. To illustrate how drastically spatial acuity falls off as the stimulus moves away from the fovea, try to read the preceding text in this paragraph while fixating on the period at the end of this sentence. It is probably difficult, if not impossible, to read the text that is only a few lines away from the point of fixation. The fovea covers an area that subtends about 2° of visual angle in the central field of vision. To visualize 2° of visual angle, a general rule is that the width of your thumbnail, held at arm's length, is approximately 1° of visual angle. (Also, the moon and sun each subtend almost exactly 0.5° of visual angle in the sky, an interesting coincidence that enhances the possibility of the Earth having both complete lunar and solar eclipses.)

The Macula

The fovea is also protected by a yellow filter known as the macula. The *macula* serves to protect this critical area of the retina from intense exposures to short-wavelength energy. It might also serve to reduce the effects of chromatic aberration that cause the short-wavelength image to be rather severely out of focus most of the time. Unlike the lens, the macula does not become more yellow with age. However, there are significant differences in the optical density of the macular pigment from observer to observer and in some cases between a single observer's left and right eyes. The yellow filters of the lens and macula, through which we all view the world, are the major source of variability in color vision between observers with normal color vision.

The Optic Nerve

A last key structure of the eye is the optic nerve. The optic nerve is made up of the axons (outputs) of the ganglion cells, the last level of neural processing in the retina. It is interesting to note that the optic nerve is made up of approximately one million fibers carrying information generated by approximately 130 million photoreceptors. Thus there is a clear compression of the visual signal prior to transmission to higher levels of the visual system. A one-to-one "pixel map" of the visual stimulus is never available for processing by the brain's higher visual mechanisms. This processing is explored in greater detail below. Since the optic nerve takes up all of the space that would normally be populated by photoreceptors, there is a small area in each eye in which no visual stimulation can occur. This area is known as the *blind spot*.

The structures described above have a clear impact in shaping and defining the information available to the visual system that ultimately results in the perception of color appearance. The action of the pupil serves to define retinal illuminance levels that, in turn, have a dramatic impact on color appearance. The yellow-filtering effects of the lens and macula modulate the spectral responsivity of our visual system and introduce significant inter-observer variability. The spatial structure of the retina serves to help define the extent and nature of various visual fields that are critical for defining color appearance. The neural networks in the retina reiterate that visual perception in general, and specifically color appearance, cannot be treated as simple point-wise image processing problems. Several of these important features are discussed in more detail in the following sections on the retina, visual physiology, and visual performance.