1 Introduction

1.1 What is color imaging science?

Color imaging science is the study of the formation, manipulation, display, and evaluation of color images. Image formation includes the optical imaging process and the image sensing and recording processes. The manipulation of images is most easily done through computers in digital form or electronic circuits in analog form. Conventional image manipulation in darkrooms accounts only for a very small fraction of the total images manipulated daily. The display of color images can use many different media, such as CRT monitors, photographic prints, half-tone printing, and thermal dye-transfer prints, etc. The complete imaging chain from capture, through image processing, to display involves many steps of degradation, correction, enhancement, and compromise. The quality of the final reproduced images has to be evaluated by the very subjective human observers. Sometimes, the evaluation process can be automated with a few objectively computable, quantitative measurements.

The complexity of color imaging science stems from the need to understand many diverse fields of engineering, optics, physics, chemistry, and mathematics. Although it is not required for us to be familiar with every part of the process in detail before we can work in and contribute to the color imaging science field, it is often necessary for us to have a general understanding of the entire imaging chain in order to avoid making unrealistic assumptions in our work. For example, in digital image processing, a frequently used technique is histogram-equalization enhancement, in which an input image is mapped through a tonal transformation curve such that the output image has a uniformly distributed histogram of image values. However, the technique is often applied without knowing what the units of the digital images really are. The same image can be digitized in terms of film density or image exposure. Depending on which way it is digitized, the resulting histogram can differ widely. Writing that an image has been processed by the "histogram-equalization" technique without saying in which metric the histogram was equalized does not allow the reader to draw any meaningful conclusion. If we have a general understanding of the practice of image scanning and display, we can easily avoid this type of error. Sometimes, causes of errors can be more subtle and it requires understanding of a different kind to avoid them. For example, the geometrical theory of optical imaging tells us that the out-of-focus point spread function is a uniform disk. However, if we understand that the fundamental assumption of geometrical optics is not valid around the image focus area, we are more careful in using the uniform disk as a blur model. In this case, basic knowledge of the assumptions underlying various approximations made by theories lets us watch out for potential pitfalls. For these reasons, this book aims at providing the needed general understanding of the entire color imaging chain whilst making the various assumptions and approximations clear.

1.2 Overview of the book

This book is written based on the belief that for a beginning color imaging scientist or engineer, a basic, broad understanding of the physical principles underlying every step in the imaging chain is more useful than an accumulation of knowledge about details of various techniques. Therefore, on the one hand, some readers may be surprised by many of the topics in the book that are not traditionally covered by textbooks on color science and imaging science. On the other hand, some readers may be disappointed that no comprehensive surveys are provided for various algorithms or devices. If we truly understand the nature of a problem, we can often come up with very creative and robust solutions after some careful thinking. Otherwise, even if we know all the existing tricks and methods to solve a problem, we may be at a loss when some critical constraints are changed. The following is an overview of the book.

1.2.1 Measurement of light and color

Since color images are formed by light, we first describe, in Chapter 2, the nature and properties of light as we understand them today. The history of how we came to achieve that understanding is fascinating, but it would take up too much space to give a full account of the intellectual struggle which involved some of the brightest minds in human history. However, properties of light, such as the wave train, its quantum nature, coherence, and polarization, come up in color imaging frequently enough that we have to at least understand these basic concepts involved in characterizing the light. Before we explain in Chapter 5 how light interacts with matter, we have to understand how we quantify and measure the energy propagation of light.

The scientific basis of color imaging starts from the defining concepts of how light can be measured. These are the topics of radiometry (Chapter 3) and photometry (Chapter 4). In these two chapters, we describe how the flow of light energy can be quantified in a physical system and how our “brightness” sensation can be related to the measurement. With proper knowledge of radiometry, we then come back to study the light–matter interaction, which is often very complex from a theoretical point of view and, in its full detail, not easy to comprehend. We, therefore, have to treat many aspects of the interaction phenomenologically. Thus, in Chapter 5, we discuss dispersion, refraction, reflection, scattering, transmission, absorption, and diffraction, basically following the traditional and historical development.

In Chapter 6, we cover the topic of colorimetry, which starts with the physical specification of stimuli that our visual system perceives as colors. The word color, as we use it in our daily conversation, implicitly refers to human color vision. In studying color imaging systems, a spectrum of incident light can be specified with respect to any physical sensing system that can sense more than one spectral component. Colorimetry can be established for any such system. For example, when we wish to study how other animals or insects see the world, separate colorimetric systems can be constructed according to their spectral sensing mechanisms. From this perspective, we can appreciate how color imaging can be thought of as a branch of science that relates different physical systems with the same basic laws. For human color perception, the colorimetry system established by the Commission Internationale de l'Eclairage (CIE) is the most widely accepted system today. Much of Chapter 6 is devoted to explaining what the CIE system is and how it was derived. It is of fundamental importance that we understand this system thoroughly.

Since the spectral composition of the light reflected from an object surface is the product of the spectral composition of the light incident on the surface and the spectral reflectance factor of the surface, the spectral characteristics of light sources directly (through direct illumination) or indirectly (through mutual reflection) affect the spectral composition of the optical image formed at the sensor(s) of a color imaging system. Therefore, it is necessary for us to have a good knowledge of the nature of the various light sources that are involved in color imaging applications. This is the subject of Chapter 7.

The colorful contents of natural scenes are the results of the complex interaction of light and objects. The quantitative description of such interactions is called scene physics, and is the subject of Chapter 8. It is important to note that such quantitative description is a very difficult problem to formulate. The concept of the bidirectional reflectance distribution function (BRDF) is one formulation that has been widely accepted because of its practical applicability and usefulness, although it certainly is not valid for every conceivable light–matter interaction. Various models for reflective and transmissive materials are discussed following this basic concept. In addition to color imaging applications, these models often find use in color image synthesis, colorant formulation, the printing industry, and computer vision. These fields are closely related to color imaging and color imaging research benefits from ideas and results from them. The chapter also includes a general overview of the physical and optical properties of some of the common materials that we encounter in color imaging applications. The chapter ends with a summary of some statistical properties of natural scenes. These properties are empirical, but they are useful for at least two purposes: (1) Many practical color imaging problems, such as white balance and exposure determination, are open research problems that seem to have no provable, deterministic solutions. Statistical properties of natural scenes can be used as *a priori* knowledge in any Bayesian estimate. (2) The statistical properties reveal certain regularities in the natural scenes and thus form a very rich source of research topics that will increase our understanding of how the physical world behaves.

1.2.2 Optical image formation

The next component in the events of an imaging chain is the formation of the optical images on the sensor. Within the visible wavelength range, optical imaging can be very well described by treating light as rays, neglecting its wave and photon characteristics most of the time. Such an approximation is called geometrical optics, in which Snell's law plays the most important role. However, when discontinuous boundaries exist, such as an aperture stop in a camera, light's wave nature (diffraction) becomes an important factor to consider. For example, in geometrical optics, the image of an object point in an aberration-free system is always

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assumed to be an ideal image point, independently of the aperture size. This is simply not true. From electromagnetic wave theory, we can derive the so-called "diffraction-limited" point spread function, which turns out to have a fairly complicated spatial distribution. The description of the optical image formation through wave theory is called wave optics or physical optics. Chapters 9 and 10 cover the basic concepts in both geometrical optics and physical optics. The geometrical theory of optical imaging is quite general and, as far as color imaging science is concerned, the most interesting result is that the mapping between the object space and the image space is a projective transformation. This leads naturally to the matrix method for paraxial ray tracing that allows us to do quick and simple calculations of the basic characteristics of most optical imaging systems. The most fundamental tool for analyzing the image quality of an imaging system is the optical transfer function (OTF). The relationship between the OTF and the wavefront aberration can be derived from diffraction theory, which is the foundation of physical optics for image formation.

In the sensing and recording of optical images, it is very important to calculate how much light (image irradiance) is collected on the sensor plane, as a function of focal length, object distance, and aperture size. In Chapter 10, the image irradiance equations, like the theory of radiometry, are derived from geometrical optics. These equations are very important for all practical optical imaging systems and should be understood well. A more detailed desciption of the light distribution in the image space has to be derived from physical optics. The results from geometrical optics and physical optics are compared using a case study of the blur caused by defocus. The conclusion is that when the defocus is severe, the predictions of both theories are quite similar. However, when the defocus is slight, the predictions are very different. Physical optics even predicts, against our intuition, that the center of the point spread function can become zero at a certain defocus distance. This rather counterintuitive prediction has been confirmed by experiments.

1.2.3 *In the eye of the beholder*

The beauty of color images is in the eye of the beholder. Thus, it is necessary for us to understand the function and the characteristics of the human visual system, so that color imaging systems can be efficiently optimized. We examine the optics of the eye in Chapter 11. Basic anatomical structures and optical models of the eye are described. Its optical properties, such as the modulation transfer function (MTF), acuity, and accommodation, are summarized. A computational model of the OTF of the eye as a function of viewing parameters is then discussed, based on the wavefront aberrations of the pupil function. This type of approach is very useful when we want to model the optical performance of the eye under viewing conditions very different from the laboratory settings. In Chapter 12, we discuss how the visual signal is sensed and processed in our visual pathways from retina to brain. The physiology and the anatomy of the visual system presented in this chapter help us to understand the practical constraints and the general features of our visual perception. In Chapter 13, we shift our attention to the basic issues in the psychophysics of visual perception. Here we try to clarify one of the most confused areas in color imaging. The basic approach is to describe how psychophysical experiments are conducted, so that color imaging scientists and engineers will think more carefully about how to apply the psychophysical data to their work. In this chapter, we have chosen to discuss the concepts of brightness and lightness in some detail because they show us how complicated the computation can be even for some things that sound intuitively obvious. We also discuss at length the perception of images when they are stabilized on our retinas. The finding that the perceived images quickly fade when they are stabilized on the observer's retina clearly demonstrates that the visual perception is more a task of reconstruction from visual features than a job of mapping the optical images directly to our mind.

After we have studied the human visual system in Chapters 11–13, we are well prepared to explore the basic ideas and theories behind the various color order systems in Chapter 14. We have delayed the discussion of this subject until now so that we can appreciate the motivation, the limitations, and the difficulties involved in any color order system. (For example, the concept of opponent color processes was developed to explain many psychophysical observations, and therefore it also plays an important role in the Ostwald and the NCS color order systems.) The idea of using a color atlas for everyday color specification seems an intuitive thing to do, but from the perspective of colorimetry, a color atlas may be a useless thing to have because the everyday illuminants are almost never as specified by the atlas. It is the powerful color processing of our visual system that does all the "auto" compensations that make a color atlas of any practical use.

1.2.4 *Tools for color imaging*

The practice of color imaging science requires physical and perceptual evaluation of color images. The tools for physical evaluation are spectroradiometers, spectrophotometers, densitometers, and other electrical and optical instruments. Chapter 15 covers physical color measurement tools and Chapter 16 mathematical tools.

The tools for perceptual evaluation are less well developed, but they fall into the general categories of tone reproduction (Chapter 17), color reproduction (Chapter 18), and image quality (mostly *ad hoc* measures of sharpness, resolution, noise, and contrast, as discussed in Chapter 21). There have been quite extensive studies of tone and color reproduction, and some general principles can be systematically summarized. Good tone reproduction is the number one requirement in the perceived image quality. In the past, research has been focused on the tone reproduction characteristics of an imaging system as a whole. As digital processing becomes common practice for most imaging applications, a general theory of image-dependent tone reproduction is needed. On the subject of color reproduction, there are fewer definitive studies. The major effort seems to be in working out a usable color appearance model. Although the current model is incomplete because it does not explicitly take spatial and temporal variations into consideration, it seems to produce reasonable measures for color reproduction.

1.2.5 *Color image acquisition and display*

Tremendous progress has been made since the 1970s in the development of new image acquisition and display devices. Photographic films and papers are still quite important, but in many applications, they are being replaced by digital cameras, scanners, and many printing/display devices. Chapter 19 discusses various color image acquisition media, devices, and systems, while Chapter 20 covers those for color image display. Basic understanding of the characteristics and working principles of the various input/output systems is very important in the practice of color imaging science. Even if we do not directly work on a particular device or medium, it is very likely we will encounter images that are acquired by that device or are to be displayed on that medium. Often, the solution to a color imaging problem for a given device may have been worked out for other devices. Understanding the problems and technology behind one type of system often helps us to solve problems in another type of system. A good example is the unsharp masking method for image enhancement, which has long been practised in photographic dark rooms. The same technique is now used extensively in digital imaging as well.

1.2.6 *Image quality and image processing*

Every imaging system, from its design to the finished product, involves many cost, schedule, and performance trade-offs. System optimization and evaluation are often based on the image quality requirements of the product. The metrics that are used to evaluate image quality, therefore, play a very important role in the system design and testing processes. In Chapter 21, we present the basic attributes and models for image quality. Objective measures, such as camera/sensor speed, image noise, and spatial resolution, are quickly becoming standardized. Subjective measures, such as contrast, sharpness, tone, and color reproduction, are less well defined physically and rely more on psychophysical experiments with human observers. It is necessary to understand what procedures can be used and what precautions we need to take.

Digital image processing can be used to correct some deficiencies in current imaging systems, such as noise reduction, image sharpening, and adaptive tone adjustment. Furthermore, algorithms can be used to increase the system performance, such as autofocus, autoexposure, and auto-white-balance. Basic algorithms in digital image processing are very well covered in existing textbooks. Unfortunately, some algorithms are too slow to be practical, and many others too fragile to be useful. Most good and fast algorithms tend to be proprietary and not in the public domain. They also tend to be hardware specific.

Color image processing is not simply repeating the same processing for three monochromatic images, one for each color channel. There are many new concepts and new problems that we do not encounter in gray scale images for two basic reasons: (1) color images are vector fields, and (2) our color vision has its own idiosyncracy – color information is represented and processed by our visual system in a specific way. In Chapter 22, we concentrate on only a few selected concepts, such as color space design, vector gradient, color segmentation, and statistics of directional data. These are concepts that have not received much discussion in the literature, but are very important for many practical applications to take into account. It is easy to be misled if we have not thought about the various issues by ourselves first.

1.3 The International System of Units (SI)

In this book, we use the terminology and units in the International System of Units (SI) and those recommended by the Commission Internationale de l’Eclairage (CIE). When there are

Table 1.1. *SI prefixes (from [942])*

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	μ
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a
10^{2}	hecto	h	10^{-21}	zepto	z
10^{1}	deca	da	10^{-24}	yocto	y

conflicts in symbols, we will use the CIE symbols for the units in radiometry, colorimetry, and photometry. The International System of Units is described in many standard documents (such as [942]) and the book by Ražnjević [787] provides good explanations. The CIE system is well described in its publication: *International Lighting Vocabulary* [187]. The International System of Units (SI) adopted by CGPM[1] is composed of basic units, derived units, and supplementary units. There are seven basic units: meter [m] for length, kilogram [kg] for mass, second [s] for time, ampere [A] for electric current, kelvin [K] for temperature, candela [cd] for luminous intensity, and mole [mol] for amount of substance. The meter is defined as the length of the path traveled by light in vacuum during a time interval of 1/299 792 458 second. The unit of plane angle, radian [rad], and the unit of solid angle, steradian [sr], are two of the supplementary units. Since they are dimensionless derived units, they do not need to be defined as a separate class of unit. Many SI derived units, such as watt [W], volt [V], hertz [Hz], and joule [J], are quite familiar to us. Other SI derived units, such as lux [lx] and lumen [lm], that we are going to use frequently in the book will be defined in detail later. When the numerical values are too large or too small, the SI prefixes in Table 1.1 can be used to form multiples and submultiples of SI units. It is a convention that a grouping formed by a prefix symbol and a unit symbol is a new inseparable symbol. Therefore, cm (centimeter) is a new symbol and can be raised to any power without using parentheses. For example, $2\ \mathrm{cm}^2 = 2\ (\mathrm{cm})^2$. Convention also requires that unit symbols are unaltered in the plural and are not followed by a period unless at the end of a sentence.

Unfortunately, there are many instances when one standard symbol could represent more than one physical quantity. For example, E is used both for the electric field strength [$\mathrm{V\,m^{-1}}$] and for irradiance [$\mathrm{W\,m^{-2}}$]. Similarly, H is used for the magnetic field strength [$\mathrm{A\,m^{-1}}$] and also for exposure [$\mathrm{J\,m^{-2}}$]. Since this happens very frequently and since changing standard symbols for various physical quantities can create more confusion, we decided that the best way to avoid ambiguity is to specify the units when it is not clear from the context which physical quantity is used. This will free us to use the same, widely accepted, standard symbol for different physical quantities in our discussion throughout the book. In

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[1] CGPM stands for Conférence Générale des Poids et Measures. Its English translation is: General Conference on Weights and Measures. It is the decision-making body of the Treaty of the Meter, signed in 1875. The decisions by CGPM legally govern the international metrology system among all the countries that signed the Treaty.

Table 1.2. *Some important physical constants used in this book*

Quantity	Symbol	Value
speed of light in vacuum	c	$299\,792\,458$ m s^{-1}
permeability of vacuum	μ_0	$4\pi \times 10^{-7}$ m kg s^{-2} A^{-2}
permittivity of vacuum	ϵ_0	$\frac{1}{\mu_0 c^2}$ m^{-3} kg^{-1} s^4 A^2
Planck constant	h	$6.626\,075\,5 \times 10^{-34}$ J s
Boltzmann constant	k	$1.380\,658 \times 10^{-23}$ J K^{-1}
electron volt	eV	$1.602\,177\,33 \times 10^{-19}$ J

almost all cases, the context and the name of the physical quantity will make the meaning clear. The physical constants shown in Table 1.2 will be useful in our later discussion.

1.4 General bibliography and guide to the literatures

Color imaging science cuts across many different disciplines. For further details on any specific topic, the reader is encouraged to consult books and papers in that field. There are many excellent books in each field. Since every person has a different style of learning and a different background of training, it is difficult to recommend books that will be both useful and interesting to everyone. A short bibliography is compiled here. No special criteria have been used for selection and the list represents only a tiny fraction of the excellent books available on the various topics. Hopefully, it may be useful for you. If you know some experts in the field you are interested in, you should ask them for more personalized recommendations.

Radiometry and photometry

Radiometry and the Detection of Optical Radiation, by R.W. Boyd [127].
Optical Radiation Measurements, Volume I, by F. Grum and R.J. Becherer [369].
Reliable Spectroradiometry, by H.J. Kostkowski [525].
Illumination Engineering – From Edison's Lamp to the Laser, by J.B. Murdoch [687].
Self-Study Manual on Optical Radiation Measurements, edited by F.E. Nicodemus [714].
Geometrical Considerations and Nomenclature for Reflectance, by F.E. Nicodemus, J.C. Richmond, J.J. Hsia, I.W. Ginsberg, and T. Limperis [715].
Thermal Radiation Heat Transfer, by R. Siegel and J.R. Howell [872].
Introduction to Radiometry, by W.L. Wolfe [1044].

Color science

Billmeyer and Saltzman's Principles of Color Technology, 3rd edition, by R.S. Berns [104].
Principles of Color Technology, 2nd edition, by F.W. Billmeyer and M. Saltzman [111].
Measuring Colour, by R.W.G. Hunt [430].
Color: An Introduction to Practice and Principles, by R.G. Kuehni [539].
Color Measurement, by D.L. MacAdam [620].
Colour Physics for Industry, 2nd edition, edited by R. McDonald [653].

Handbook of Color Science, 2nd edition, edited by Nihon Shikisaigakkai (in Japanese) [716].
The Science of Color, 2nd edition, edited by S.K. Shevell [863].
Industrial Color Testing: Fundamentals and Techniques, by H.G. Völz [989].
Color Science, 2nd edition, by G. Wyszecki and W.S. Stiles [1053].

Human visual perception

The Senses, edited by H.B. Barlow and J.D. Mollon [54].
Handbook of Perception and Human Performance, Volumes I and II, edited by K.R. Boff, L. Kaufman, and J.P. Thomas [118, 119].
Vision, by P. Buser and M. Imbert [153].
The Visual Neurosciences, edited by L.M. Chalupa and J.S. Werner [167].
Visual Perception, by T.N. Cornsweet [215].
The Retina: An Approachable Part of the Brain, by J.E. Dowling [264].
An Introduction to Color, by R.M. Evans [286].
Color Vision: From Genes to Perception, edited by K.R. Gegenfurtner and L.T. Sharpe [337].
Eye, Brain, and Vision, by D.H. Hubel [418].
Color Vision, by L.M. Hurvich [436].
Human Color Vision, 2nd edition, by P.K. Kaiser and R.M. Boynton [480].
Visual Science and Engineering: Models and Applications, by D.H. Kelly [500].
Vision: *A Computational Investigation into the Human Representation and Processing of Visual Information*, by D. Marr [636].
Images of Mind, by M.I. Posner and M.E. Raichle [774].
The First Steps in Seeing, by R.W. Rodieck [802].
Visual Perception: The Neurophysiological Foundations, edited by L. Spillmann and J.S. Werner [892].
Foundations of Vision, by B.A. Wandell [1006].
A Vision of the Brain, by S. Zeki [1066].

Optics

Handbook of Optics, Volumes I and II, edited by M. Bass [84].
Principles of Optics, 7th edition, by M. Born and E. Wolf [125].
Introduction to Matrix Methods in Optics, by A. Gerrard and J.M. Burch [341].
Statistical Optics, by J.W. Goodman [353].
Introduction to Fourier Optics, by J.W. Goodman [354].
Optics, 2nd edition, by E. Hecht [385].
Lens Design Fundamentals, by R. Kingslake [508].
Optics in Photography, by R. Kingslake [509].
Optics, 2nd edition, by M.V. Klein and T.E. Furtak [512].
Physiological Optics, by Y. Le Grand and S.G. El Hage [580].
Aberration Theory Made Simple, by V.N. Mahajan [626].
Optical Coherence and Quantum Optics, by L. Mandel and E. Wolf [631].
Geometrical Optics and Optical Design, by P. Mouroulis and J. Macdonald [682].

Introduction to Statistical Optics, by E.L. O'Neil [729].
Elements of Modern Optical Design, by D.C. O'Shea [733].
Applied Photographic Optics, 3rd edition, by S.F. Ray [786].
States, Waves and Photons: A Modern Introduction to Light, by J. W. Simmons and M.J. Guttmann [877].
The Eye and Visual Optical Instruments, by G. Smith and D.A. Atchison [884].
Modern Optical Engineering, 3rd edition, by W.J. Smith [887].
The Optics of Rays, Wavefronts, and Caustics by O.N. Stavroudis [899].

Scene physics

Absorption and Scattering of Light by Small Particles, by C.F. Bohren and D.R. Huffman [120].
The Cambridge Guide to the Material World, by R. Cotterill [217].
Light by R.W. Ditchburn [258].
Sensory Ecology, by D.B. Dusenbery [269].
Seeing the Light, by D.S. Falk, D.R. Brill, and D.G. Stork [297].
Color in Nature, by P.A. Farrant [301].
Color and Light in Nature, by D.K. Lynch and W. Livingston [615].
The Colour Science of Dyes and Pigments, by K. McLaren [654].
Light and Color in the Outdoors, by M. Minnaert [667].
The Physics and Chemistry of Color, by K. Nassau [693].
Light and Color, by R.D. Overheim and D.L. Wagner [736].
Introduction to Materials Science for Engineers, 4th edition, by J.F. Shackelford [853].
Colour and the Optical Properties of Materials, by R.J.D. Tilley [952].
Light and Color in Nature and Art, by S.J. Williamson and H.Z. Cummins [1036].
Color Chemistry, 2nd edition, by H. Zollinger [1071].

Image science

Foundations of Image Science, by H.H. Barrett and K.J. Meyers [64].
Image Science, by J.C. Dainty and R. Shaw [232].
Principles of Color Photography, by R.M. Evans, W.T. Hanson, and W.L. Brewer [289].
The Theory of the Photographic Process, 4th edition, edited by T.H. James [459].
Handbook of Image Quality, by B.W. Keelan [494].
Science and Technology of Photography, edited by K. Keller [495].
Image Technology Design: A Perceptual Approach, by J.-B. Martens [642].
Handbook of Photographic Science and Engineering, 2nd edition, edited by C.N. Proudfoot [779].
Fundamentals of Electronic Imaging Systems, 2nd edition, by W.F. Schreiber [841].
Imaging Processes and Materials, edited by J. Sturge, V. Walworth, and A. Shepp [923].
Photographic Sensitivity: Theory and Mechanisms, by T. Tani [936].