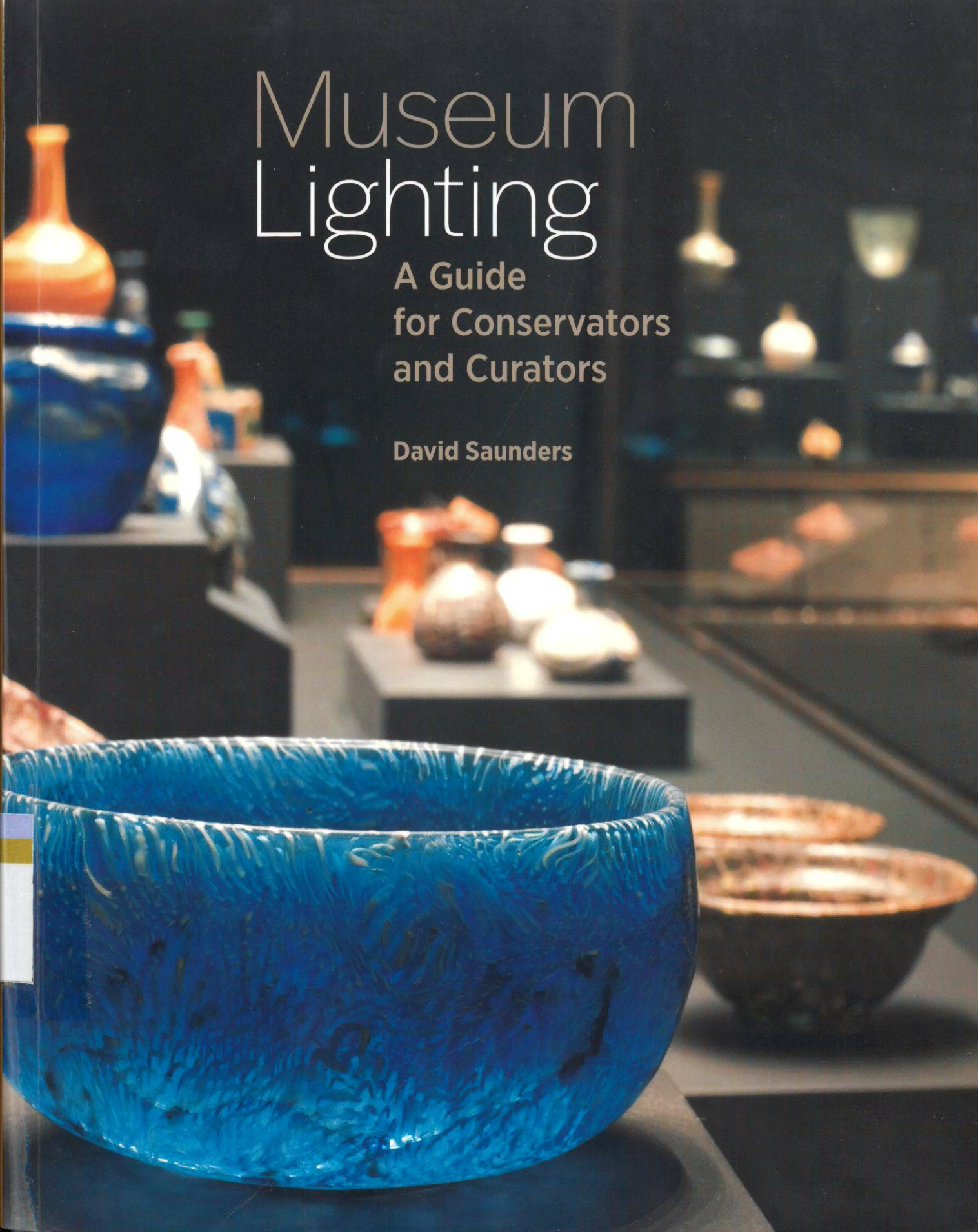


Museum Lighting

A Guide
for Conservators
and Curators

David Saunders



Museum Lighting

The Getty Conservation Institute | Los Angeles

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FOREWORD

In order to view and appreciate collections in museums, galleries, and historic homes, we rely on light. That light, however, is one of the greatest threats to the longevity of museum collections. Collections—ranging from drawings on paper, paintings, and photographs to costumes, rugs, and upholstery—fade and deteriorate from exposure to visible light and ultraviolet radiation. This phenomenon leads curators, conservators, conservation scientists, and collections managers to spend a significant amount of their professional time working to assure the highest levels of safety for light-sensitive objects while maintaining the visitors' pleasurable viewing experience.

Managing light in museums was comprehensively addressed in Garry Thomson's benchmark publication, *The Museum Environment* (1978, revised 1986), in which Thomson addressed how various environmental factors, including pollution, humidity, temperature, and, of course, light, can affect museum collections. Although much of this information remains valid today, we were pleased when author David Saunders proposed this new volume, *Museum Lighting: A Guide for Conservators and Curators*. With a greater focus on sustainability issues, a shift toward preventive conservation and risk assessment, and the introduction of new technologies such as LEDs (light-emitting diodes), this book offers a fresh perspective on lighting practices and guidelines for museums and collections of all kinds.

David's book proposal very happily coincided with the launch by the Getty Conservation Institute (GCI) of its Managing Collections Environment Initiative. This multiyear project addresses research questions and issues pertaining to the control and management of collection environments and includes a research component on museum lighting. We are fortunate to be able to count this book as an important contribution to that initiative.

In *Museum Lighting*, David has provided a broad and comprehensive guide that can be used by conservators, curators, and other museum professionals to assess, prevent, and minimize damage caused by light. The audience for this book is wide, for light affects objects displayed in museums and galleries of every kind and size.

Over his decades-long career as a conservation professional, David has served as a scientist at the National Gallery, London; keeper of conservation and scientific research at the British Museum, London; vice president for the International Institute for Conservation of Historic and Artistic Works (IIC); and for the last five years, chairman of the U.K.-based Anna Plowden Trust, which supports education and training in heritage conservation. He was a GCI scholar in 2016, during which time much of this volume was structured and written. In recognition of his passion, energy, and contributions to the conservation field, in 2017 he was named the first recipient of the Getty Rothschild Fellowship, which was established to support innovative scholarship in the history of art, collecting, and conservation.

We thank David for his generosity as a colleague and friend to the GCI, for his lifelong dedication to the field, and for this book. We anticipate that this volume will set a new standard for museum lighting, and we hope that it can benefit professionals and collections for many years to come.

Timothy P. Whalen
John E. and Louise Bryson Director
The Getty Conservation Institute



Museum Lighting

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and Curators

David Saunders

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Timothy P. Whalen, *John E. and Louise Bryson Director*
Jeanne Marie Teutonico, *Associate Director, Programs*

The Getty Conservation Institute (GCI) works internationally to advance conservation practice in the visual arts—broadly interpreted to include objects, collections, architecture, and sites. The Institute serves the conservation community through scientific research, education and training, field projects, and the dissemination of information. In all its endeavors, the GCI creates and delivers knowledge that contributes to the conservation of the world's cultural heritage.

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Back cover: Red Drawing Room, Waddesdon Manor in Buckinghamshire, England (see figure 10.7).

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For reasons of style and consistency, some spellings have been changed in reprinted materials.

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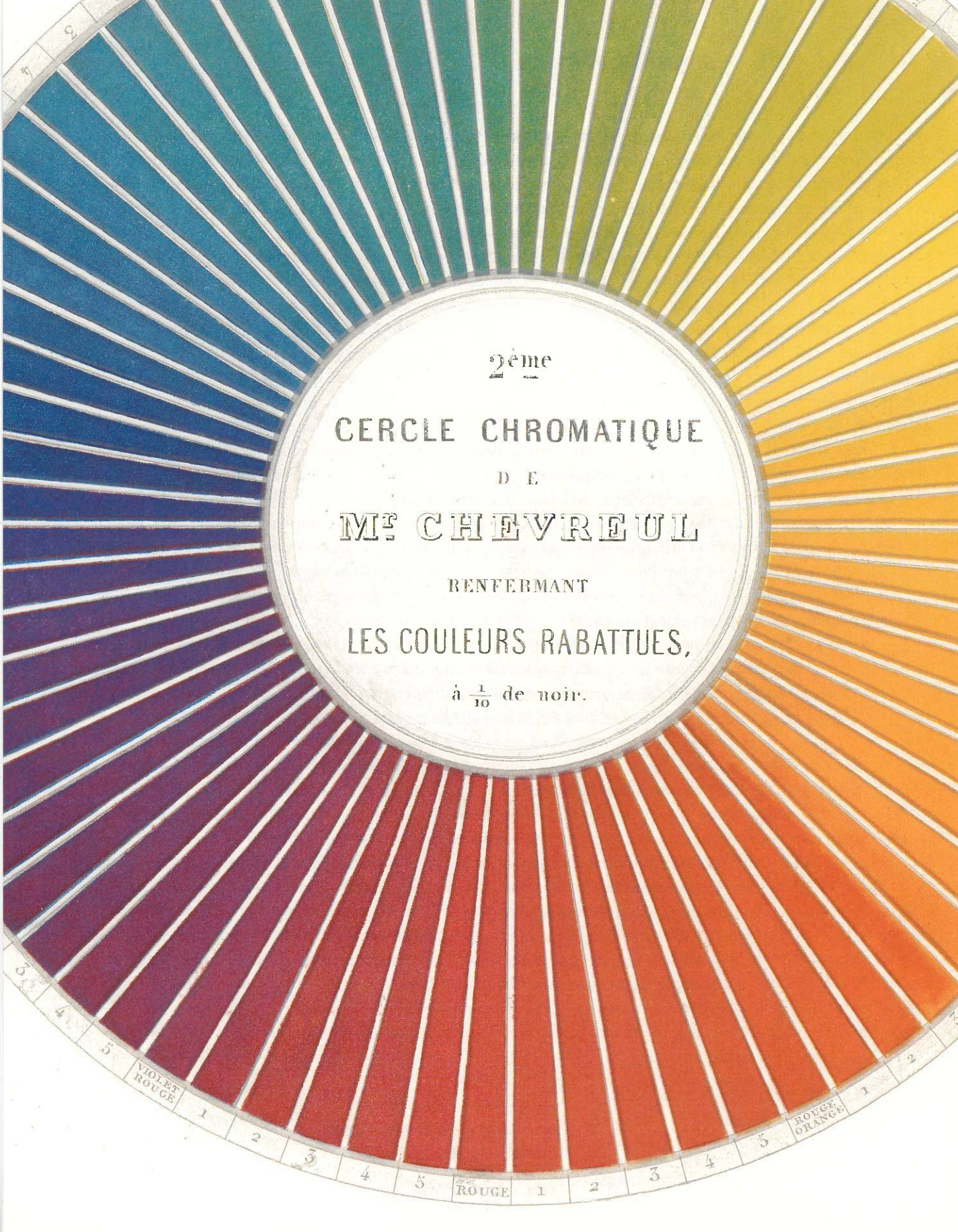
The book might, however, have remained a “project” without the opportunity offered by the Getty Conservation Institute (GCI) to spend a period at the Getty Center as a guest scholar in 2016 to undertake the background research, and a second fellowship from the Getty Foundation and Rothschild Foundation that allowed me both to return to the GCI in 2017 and to spend several months living and working at Waddesdon Manor in the U.K. as the inaugural Getty Rothschild fellow. In addition to the Getty and Rothschild foundations, I am immensely grateful to colleagues at the GCI (particularly Tim Whalen, Tom Learner, and Jeanne Marie Teutonico) and Waddesdon (Pippa Shirley, Colette Warbrick, and Jane Finch) for making me so welcome and ensuring I was able to make the best use of my time. My time at the GCI was made infinitely more productive by the expertise of Anna Duer in the Information Center and more enjoyable through the stimulating and irreverent company of fellow GCI scholars Thea van Oosten and Colm Murray.

In addition to colleagues already mentioned above, I would like to thank Sharon Cather, Rosie Grayburn, Catherine Higgitt, and Anna Laganà for critically reading, and commenting on, drafts of sections on specialist materials and technical issues at the limit of my experience.

A great many of the examples and illustrations in the book are drawn from the work, experience, or collections of others, and I am grateful to Melanie Bauernfeind, Rickard Beckén, Nigel Blades, Charlotte Eng, Troels Filtenborg, Pia Gottschaller, William Hall, Mia Jackson, Denise King, Capucine Korenberg, Joanna Kosek, Dale Kronkright, Florence Lam, Katy Lithgow, John Mardaljevic, Jane Munro, Shayne Rivers, Nicola Tinsley, Giovanni Verri, Steve Weintraub, Colin Williamson, and many of those already named above for their willingness to share information and images.

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Finally, researching and writing this book would not have been possible without the complete support of my wife, Alison, who listened sympathetically during the inevitable setbacks and uncomplainingly accepted my periodic protracted disappearances to the other side of the Atlantic.



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CERCLE CHROMATIQUE

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RENFERMANT

LES COULEURS RABATTUES,

à $\frac{1}{10}$ de noir.

VIOLET
ROUGE

ROUGE
ORANGE

ROUGE

Introduction

In October 1999, Sweden's Nationalmuseum and Nordiska Akvarellmuseet (Nordic Watercolor Museum) jointly organized a conference on daylight and lighting in art museums (Nordiska Akvarellmuseet 2000). The wonderfully alliterative title of this gathering, "Ljuset förför, ljuset förstör," is perhaps best rendered in English as "Seductive light, destructive light." In Swedish or English it perfectly captures the conundrum central to the use of light in museums, galleries, and historic houses.¹ We need light to see our collections so that we can enjoy and study them. We love light for its ability to animate and enhance objects and spaces. But we dread light because it can steal image, color, and even form.

Viewing is about the present—instantaneous conditions or short-term variations are key in providing comfortable, interesting, and "seductive" lighting. But preservation is a longer-term business; today's light levels are half the story, and we must look not only at the levels tomorrow and beyond but consider for how long each day we might light our collections.

Thus in museums we have a complex relationship with light: how to reconcile these opposing emotions and positions so that we can use and appreciate collections, yet still pass objects with meaning and sense to future generations. And how can we do this consensually, so that we avoid a situation where one group sees itself as advocates for the collection's future preservation and another for its present use.

As it is sometimes the curator or conservator who is cast in one of these roles, a principal aim of this book is to present professional museum staff with enough background information and practical advice to make choices and arrive at solutions that best suit their circumstances. There is no single answer, but we will explore both the experimental and experiential studies that help to set appropriate light levels for seeing and appreciating the collections and the evidence of damage that allows us to develop lighting protocols that best preserve objects.

In 1978, Garry Thomson's book *The Museum Environment* brought together research that had been conducted over the course of three decades to provide an up-to-date overview of the effect of various environmental parameters on museum objects and to offer

1. Throughout the text of this book, *museum* is used to cover all manner of museums, galleries, historic houses, and other cultural heritage institutions that house collections. If comments apply to a specific type of setting, for example, a historic house museum, then this is stated specifically.

a description of then-current practices for protecting collections containing different types of materials from these risks. *The Museum Environment* includes sections that offer a description of the damaging effects of light (and ultraviolet radiation) on materials and present guidelines for the lighting of such objects in ways that minimize deterioration during display and study.

Over the decades since *The Museum Environment* was revised and updated in 1986, many of its recommendations have been the subject of heated discussion, but despite much subsequent research, no publication has appeared that satisfactorily replaces its broad coverage of the hazards and risks that affect museum collections or its pragmatic setting of guidelines for the avoidance of such effects. This lack might be explained by two factors.

First, the sheer volume of research that has been conducted in these various areas over the last 30 years means that it is now difficult to maintain a broad overview of the wide range of disciplines necessary to allow up-to-date advice and guidelines to be offered across all the environmental parameters. Even a guide focusing only on lighting cannot hope to cover in detail every aspect from fundamental physics to developing practice and policy. For example, the sections covering the susceptibility of different classes of museum objects in chapter 5 of this book provide only a series of overviews.

Second, the field feels itself to have moved on. The phrase *preventive conservation* was barely used 30 years ago, having only come into common use around the time of the 1994 International Institute for Conservation (IIC) Congress in Ottawa on that theme. *The Museum Environment* grew out of a series of international meetings and committees that considered lighting and climate in museums, with most attention focused on the effects of light, humidity, and pollution, with less frequent mention of biodeterioration and physical forces. Now we consider a broad range of threats to collections, not simply those that were the traditional province of conservators but institution-wide issues such as fire, flood, and theft, summarized through the work of the Canadian Conservation Institute (CCI 2017a) as the 10 “Agents of deterioration.”

10 Agents of Deterioration

Light, ultraviolet, and infrared	Physical forces
Incorrect temperature	Fire
Incorrect relative humidity	Water
Pests	Thieves and vandals
Pollutants	Dissociation

Source: CCI 2017a.

This increasing awareness of the need to consider a wider range of factors that may affect collections necessitated a reassessment of priorities and prioritization that led to the adoption of risk-based methodologies in preventive conservation (Waller 1994; Ashley-Smith 1999). Risk assessment now forms an indispensable part of preventive

conservation and collections management practice, with well-developed tools—such as the ABC (Michalski and Pedersoli 2016) and QuiskScan methods (Brokerhof and Bülow 2016)—to assist with the identification, categorization, and prioritization of risks. These risk-assessment frameworks, which take into account not only the likelihood and severity of risks and the vulnerability of objects but also consider the loss of value or significance that may result, help to place individual sources of deterioration within the context of institutional concerns and priorities.

Nevertheless, once risks have been identified and prioritized there usually remains the need to act or react. Current approaches to reducing the risks to collections focus on a sequence of actions, summarized by CCI as “avoid, block, detect, respond, recover” or by Brokerhof and colleagues (Brokerhof, Ankersmit, and Ligterink 2017:50) as “avoid, block, detect, react, treat.” Good preventive conservation practice first seeks to avoid risks—or to block them by placing a barrier between their source and the collection. Understanding and detecting these risks, or their consequences, allows practice to be improved in response (rather than preemptively). Recovery or treatment is a last resort, although it will not always be an option; for example, faded colors cannot be re-created.

Those responsible for acting or reacting—who in most cases are not preventive conservators or scientists—require information about the nature of deterioration that might be expected, upon which they can then base their decisions and practical guidelines about the environment in which objects should be stored or displayed.

Focusing on the effects of light on materials found in museums and other collections, this guide attempts to describe some of the most common deterioration phenomena, identify the types of objects that are most at risk, offer guidelines for their exposure to light that take their fragility into account, and suggest some practical measures for minimizing damage while allowing collections to be studied and enjoyed.

Unlike other environmental factors that have the potential to damage museum collections, most notably relative humidity, decisions about lighting are made simpler because the starting point is that the total exclusion of all light is the simplest method of minimizing light-induced damage. While exclusion—or near exclusion—of light is possible outside museum opening hours or when objects are in store (with some caveats discussed later), measures taken to reduce light damage in displays are often contentious, with many friendly and not-so-friendly discussions arising from the perceived tension between the conservator’s wish to minimize damage through limiting light exposure and the need to present objects attractively and visibly.

A second aim of this guide is, therefore, to give conservators and curators the basic information, and where possible practical guidelines, needed to make decisions about lighting their collections under most circumstances, balancing the conservation of objects with the needs of visitors, students, and professionals; the resources available; and the long-term maintenance and energy efficiency of the possible solutions. This guide does not, however, offer detailed information concerning architectural or engineering solutions, or technical details—beyond those necessary to understand their operation—of electric light sources or control systems. These become out of date very quickly as technology improves, such as developments focused at increased energy efficiency.

Rather more detail is provided in two particular specialist publications: the Society of Light and Lighting's guide *Lighting for Museums and Art Galleries* (SLL 2015) and the Illuminating Engineering Society of North America's *Recommended Practice for Museum Lighting* (IESNA 2017).

In addition to a number of related publications that explore aspects of light, color, visual perception, light-induced deterioration, and museum practice in greater detail, there is, unsurprisingly, a wealth of data available on the internet. Although the rate of development of new technologies and approaches to lighting has been incredibly rapid over the last three decades, it has been eclipsed by the increased availability of information about these advances. The second edition of *The Museum Environment* was published in 1986, five years before the first web pages appeared, but now we can access authoritative, and not so authoritative, data at our desks. Much of the information in this book can be found freely on the web and will go out of date less quickly if these sites and data are maintained. Several relevant web resources, notably the CCI Light, Ultraviolet, and Infra-red web page (Michalski 2018) and the resource for analyzing light sources provided by the National Gallery, London (Padfield n.d.) are frequently updated and are used widely in this book.

Chapter 1

Light, Radiation, and Human Vision

Light and color, and the way we perceive, describe, and measure them, are much studied and well covered in thorough and very readable texts on the subject. These include Hunt and Pointer's *Measuring Colour* (2011); *Billmeyer and Saltzman's Principles of Color Technology*, which has been comprehensively updated by Berns (Berns, Billmeyer, and Saltzman 2000); and Berns's own recent *Color Science and the Visual Arts* (2016). The first three chapters of this book focus, therefore, only on some of the fundamental concepts of light that are needed to understand how it interacts with objects and viewers in a museum context. These chapters need not be read from beginning to end. For some the topics they cover will already be familiar; others may need to refer to those sections that describe the fundamental properties of light and color that are necessary to understand matters introduced later in the book. Together they are constructed to provide a staged introduction to the science that underpins color and light in a museum context.

In this chapter, we will see how light makes objects visible to our eyes and how our brains process the signals generated by the eye so that we can interpret the form, brightness, and color of scenes and make judgments based not only on the information received but also on previous and innate experience.

1.1 The Nature of Light

Before considering light specifically, it is helpful to look more generally at electromagnetic radiation. The term *light* is applied to a subset of electromagnetic radiation and is characterized by the very human consideration that it is the portion of this radiation that we can see with our eyes.

ELECTROMAGNETIC RADIATION

Electromagnetic radiation encompasses a broad range of types of radiation with which we might already be familiar to a greater or lesser extent, including X-rays, microwaves, and radio waves. The terms *rays* and *waves* applied to these phenomena give the impression of propagation and progression from an origin, and it can be useful to imagine each of these types of radiation in terms of ripples or waves originating from a point, rather in the manner that ripples proceed from the point at which a stone is dropped into still water (figure 1.1). Different types of radiation with which we might be familiar differ in the length

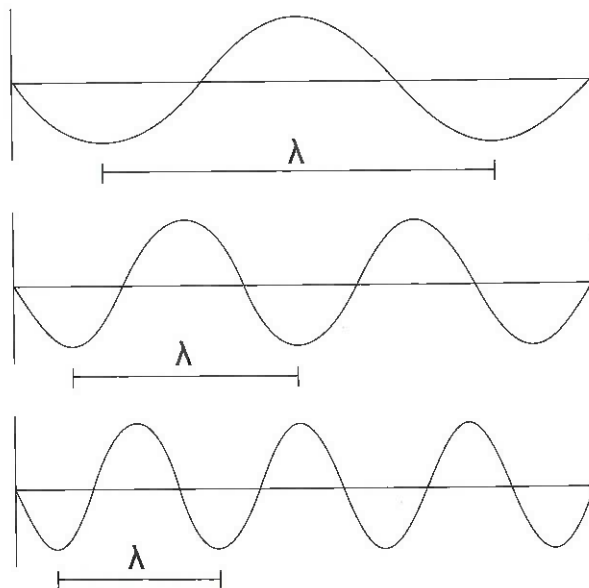
Figure 1.1. Ripples propagating from two points. Where wave peaks meet, they are reinforced, but where a peak and trough meet, they cancel each other out.



of these waves, measured as the distance between successive wave crests. This distance, known as the *wavelength* and usually represented by the Greek letter λ , characterizes particular varieties of radiation (figure 1.2). The wavelength can vary from many meters—or kilometers in the case of radio or broadcast TV waves—to billionths of a meter for X-rays or cosmic rays; figure 1.3 shows this relationship between wavelength and the type of radiation for many commonly encountered examples.

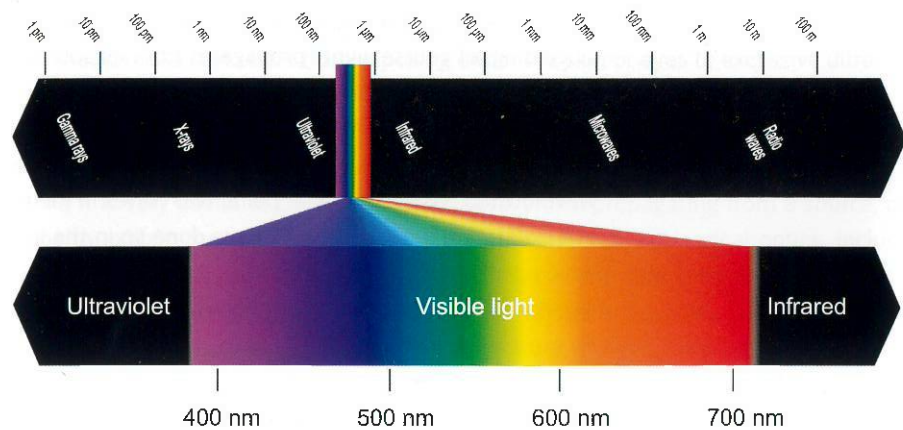
Light, as can be seen from figure 1.3, is that portion of this broader range of types of radiation to which our eyes are sensitive, as will be seen in section 1.2. Although there is some variation between individuals, most human eyes are sensitive to radiation with a wavelength in the range from approximately 400 to 700 nm.² Thus, we generally refer to the region between c. 400 and 700 nm as the *visible spectrum*.

Figure 1.2. Three waveforms with different wavelengths (λ).



2. A nanometer (nm) is one billionth of a meter.

Figure 1.3. The electromagnetic spectrum, showing in more detail the portion of the spectrum to which the eye is sensitive.



Although humans cannot necessarily see radiation outside the boundaries of the visible spectrum, the light sources that we will encounter later in this book often emit radiation with longer and shorter wavelengths than those to which the eye is sensitive, so it is useful to consider the regions of the electromagnetic spectrum immediately adjacent to the visible. To understand the way in which these regions are named, we need to jump forward slightly and consider how we refer to the color sensations produced by the eye and brain in response to different wavelengths within the visible spectrum. For now, it is enough to note that we refer to light with a wavelength of c. 400 nm as *violet* and light with a wavelength of c. 700 nm as *red*. These terms serve as the starting point for the convention of referring to radiation that has a wavelength somewhat longer than red light as *infrared* and that with a wavelength slightly shorter than violet light as *ultraviolet* (see figure 1.3).

It is interesting to note in passing that although human eyes are generally sensitive in the 400–700 nm region, the eyes of other species have adapted to perceive radiation outside this range—for example, many birds and bees can see ultraviolet radiation.

The terminology for infrared, visible, and ultraviolet radiation can cause heated discussion. As light is the visible portion of the spectrum, the use of *visible* as a prefix to light might be considered redundant; we ought simply to use *light* but sometimes find it convenient to say *visible light*. Ultraviolet and infrared radiation are not visible, so should not be referred to as ultraviolet *light* and infrared *light*—although they often are. The word *radiation* is frequently dropped, and we use *ultraviolet* and *infrared*.

FREQUENCY

A second property of electromagnetic radiation—its frequency—is sometimes used in its classification. The frequency, which by convention is represented by the Greek letter ν , is inversely related to the wavelength; that is, as the wavelength increases, so the frequency

decreases. This relationship is founded on the fact that all electromagnetic radiation (including, of course, light) propagates from its source at a constant speed, known conventionally as the *speed of light* and usually denoted by the letter c . We can envisage this relationship by reference to figure 1.2: if we imagine all three waveforms moving to the right at the same speed, we can see that in the time it takes for one peak in the top waveform to pass a particular point, two waves in the middle waveform will have passed this point, and three peaks will have done so in the lower example. The frequency with which peaks pass a point increases as the distance between peaks—the wavelength—decreases. The relationship between frequency, wavelength, and the speed of light can be expressed mathematically as:

$$v = c/\lambda$$

Equation 1.1

As the wavelength is expressed in meters and the speed of light in meters traveled per second, the unit of frequency will be *per second*—that is, the number of peaks passing a point each second, which is usually expressed in Hertz (Hz). So, for example, light with a wavelength of 550 nm in the center of the visible region can also be said to have a frequency of 5.45×10^{14} Hz.³

This alternative scale for defining radiation also helps to explain the origin of the terms *infrared* and *ultraviolet*, meaning “below red” and “beyond violet,” respectively—that is, having a frequency below that of red and beyond that of violet.

ENERGY

Another important fundamental relationship that will be of significance when considering the damage caused to materials by light and other radiation is that between wavelength (or frequency) and energy. The energy (E) of radiation with a specific frequency or wavelength can be calculated from equation 1.2 or 1.3, respectively.

$$E = hv$$

Equation 1.2

$$E = hc/\lambda$$

Equation 1.3

In both cases, the term h is used to represent Planck's constant, which has a fixed value of 6.626×10^{-34} Joule seconds, yielding an energy in Joules.

Crucially, these equations demonstrate that the shorter the wavelength of electromagnetic radiation—or the higher its frequency—the greater its energy. Considering only the visible spectrum and the ranges immediately surrounding it in figure 1.3, it will be clear that infrared radiation has a lower energy than light, while ultraviolet radiation has a higher energy than light. The implication of this simple relationship will become apparent in later chapters, where the higher energy intrinsic to ultraviolet radiation will

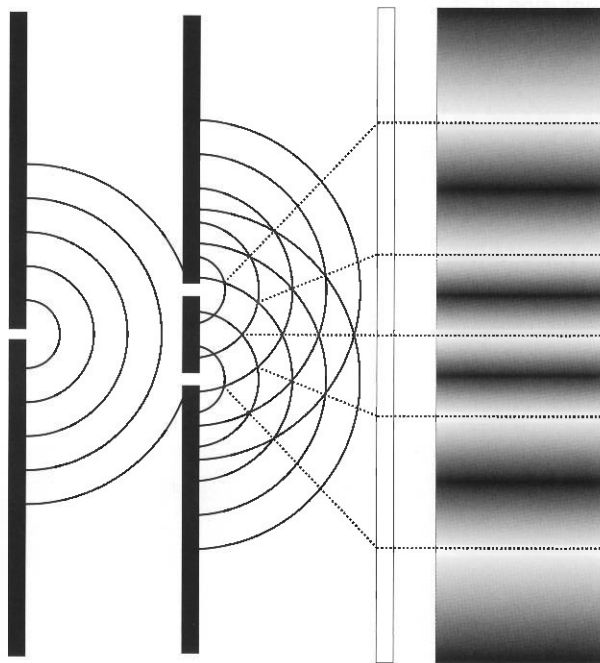
3. Very large or small numbers are often expressed using this convention, in which a number between 1 and 10 is multiplied by 10 raised to a certain power (10 multiplied by itself), indicated by a superscript numeral. Thus, 1,000 is expressed as 1×10^3 ; 5,000,000 as 5×10^6 ; and $1/1,000$ as 1×10^{-3} . The frequency expressed here as 5.45×10^{14} Hz would thus be written in full as 545,000,000,000,000 Hz.

be a recurring theme. Beyond conservation concerns, this higher energy lies behind long-term health risks that result from exposing either the skin or eyes to excessive ultraviolet radiation.

WAVES AND PARTICLES

While it is very useful to consider light as a waveform propagating from a source, as it helps to explain many of the properties of light observed in classical optics, including interference and refraction, that view represents only one side in the long-standing dispute as to the nature of light: whether it consists of rays or particles. Following centuries of debate in which most explanations of the nature of light, including Isaac Newton's corpuscular theory, presented light as a stream of particles, wave-based theories gained greater support in the 18th century, principally through the work conducted by Thomas Young and Augustin-Jean Fresnel on diffraction and interference. Young's double-slit

Figure 1.4. Young's double-slit experiment. The interference pattern cannot be explained by a particulate model of light but is analogous to the effect seen for waves on water in figure 1.1.



experiment is illustrated in figure 1.4. The particulate model for light fails to explain the pattern of brighter and darker fringes that are produced on the screen at the right of the figure by light that passes through the two slits in the central screen. If, however, light propagates from the two slits as waveforms that meet again at the screen, the pattern of bright interference fringes coincides with points where the peaks of waves from the two slits coincide and reinforce each other, while the dark fringes correspond to regions where a peak in one wave coalesces with a trough in the wave from the other slit, and they cancel each other out; a similar effect is seen for the ripples generated in figure 1.1.

By the late 19th century, observations made on the behavior of light had been placed within a theoretical context through the equations defining electromagnetic radiation

developed by James Clerk Maxwell. There were, however, several anomalous observations that could not be explained fully by the wave model—not least that certain reactions would not proceed if the light used to instigate the reaction was longer than a particular wavelength, no matter how intense the light. An explanation for this came in the early 20th century through Albert Einstein's work on the photoelectric effect (for which he won the Nobel Prize in 1921). Einstein showed that the energy delivered by light must be divided into discrete or *quantized* units, later termed *photons*. No matter how intense the light, the energy of these individual photons was determined and limited by the wavelength, as seen in equation 1.3. If their energy lay below that required to initiate a reaction or process, it would not occur—an important factor in considering the damage caused by light (see section 4.2).

At the present time photons are seen as exhibiting properties of both waves and particles, a paradox known as *wave-particle duality*. Although this dual nature of light may be confusing, it can be helpful to have both models available and to apply that which best explains particular properties and phenomena. For example, the wavelength properties of radiation are extremely helpful when investigating or defining light sources or colors, while the concept of the photon as a discrete “packet” of energy (sometimes termed a *quantum*) is useful when considering light-induced processes of degradation (see section 4.2).

WAVELENGTH AND COLOR

Sir Isaac Newton's experiments with daylight and prisms, described in his treatise *Opticks*, established that the light passing through a prism was itself divided into rays of different colors, rather than the color lying within the prism itself (figure 1.5). This well-known separation of “white” light into a spectrum (or rainbow) of colors from violet to red corresponds to the sequence illustrated in figure 1.3. While it is convenient to describe light of a certain

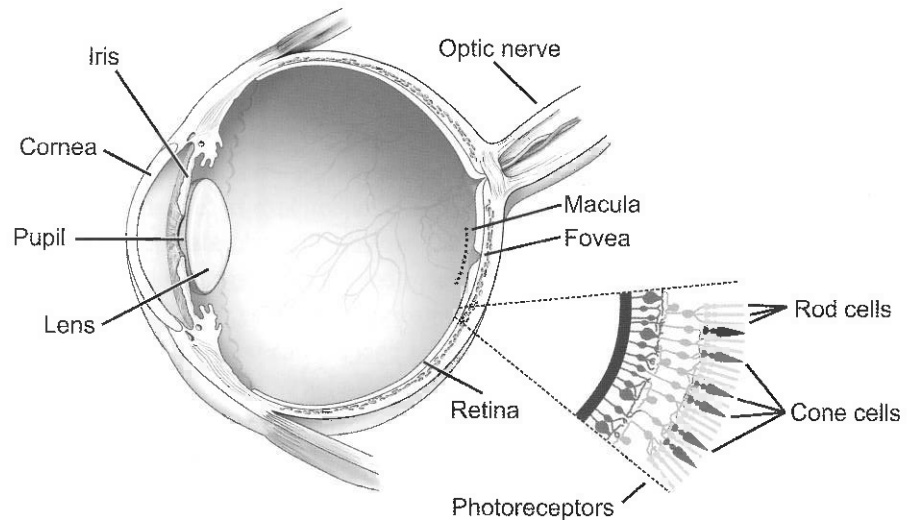
Figure 1.5. The classic demonstration—after Newton—that white light is composed of light of different wavelengths (colors).



wavelength as bearing a distinct color (e.g., red light at 700 nm), Newton cautioned “the rays to speak properly are not coloured. In them there is nothing else than a certain power and disposition to stir up a sensation of this or that Colour” (Newton 1704:90). In other words, it is only when light of a particular wavelength impinges upon the eye and the signals generated by the eye in response are interpreted by the brain that the sensation or notion of a particular color is produced. Despite Newton’s view that this was to describe color “grosly, and according to such conceptions as vulgar People . . . would be apt to frame,” it is convenient to apply color terms to rays with particular wavelengths, bearing in mind that the color terminology applied may differ among cultures and individuals.

1.2 Light, Color, and the Eye

Figure 1.6. Cross-section of the human eye showing the location of the photoreceptors in the retina.



All that we perceive of the color and form of our surroundings originates from the interaction of light with our eyes. The modern understanding that vision results from light entering the eye, rather than light emanating from the eye, can be traced to the *Kitāb al-Manāẓir* (Book of optics) written by ibn al-Haytham (CE 965–1039). A greatly simplified anatomy of the eye is shown in figure 1.6. Light enters the cornea and passes through the pupil (an aperture in the iris that can vary in diameter to allow more or less light into the eye, according to the amount of light available) before being focused by the lens onto the rear surface of the eye, the retina.

PHOTORECEPTORS

The retina contains cells specifically adapted to respond to light, the photoreceptors (see figure 1.6). The signals from these sensors provide the brain with spatial information—allowing the elements of a scene perceived by the eyes to be reconstructed—and

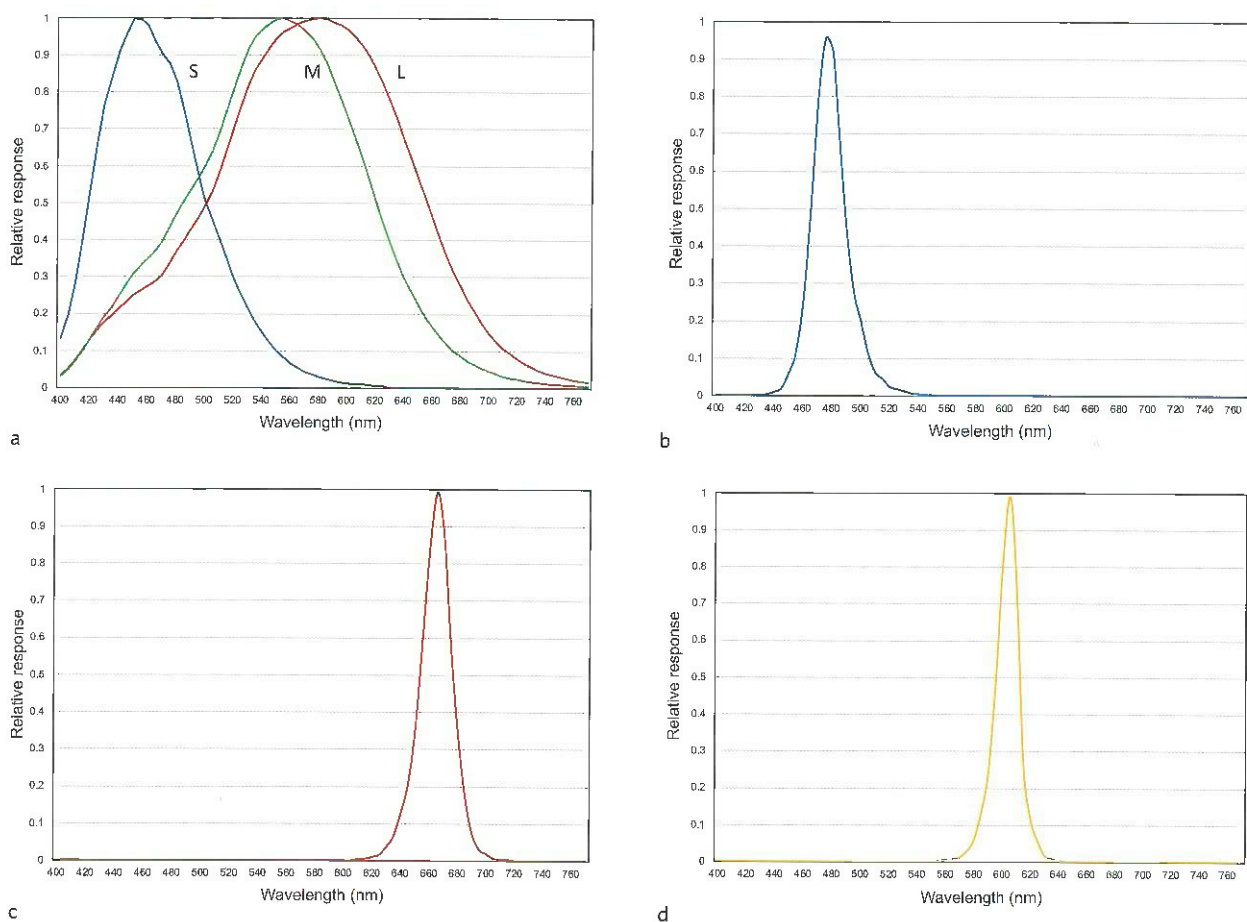


Figure 1.7. Spectral sensitivity curves for the short (S), medium (M), and long (L) wavelength cone sensors in the human eye (a) and the spectra of hypothetical blue (b), red (c), and orange (d) light sources.

information about the colors of those elements. There are a number of different types of photoreceptors, but those associated with color vision under reasonable light levels are the *cones*, so called because of the shape of these cells. Individuals with normal color vision have three types of cone cells. Each type contains a photosensitive pigment that is a modified form of the compound rhodopsin, but slight differences in the molecule make the pigments in the different cones responsive to different wavelengths of light.

The approximate responses of the three types of photoreceptors across the visible region from 400 to 700 nm, their *spectral sensitivity curves*, are labeled S, M, and L in figure 1.7a, corresponding to their response to short, medium, and long wavelengths of visible radiation. In other contexts they are referred to as blue, green, and red receptors, as these are the wavelengths to which they are most responsive. Traces that depict sensitivity across the visible spectrum (such as those in figure 1.7a) are also referred to as *spectral response curves*. A normal human eye contains around 6 million cones, which are randomly distributed across the retina but occur at a higher density in the region of the macula (see figure 1.6). It is estimated that the eye contains around twice as many L cones as M cones and that there are 20 times fewer S cones than M cones. These approximate

ratios are for those with normal color vision, since the absence or severe depletion of one or more types of cone cells is a frequent cause of abnormal color vision—sometimes termed *color blindness*.

When light of a particular color (range of wavelengths) impinges on the retina, only those photoreceptors that are sensitive in that range are stimulated. Figure 1.7b provides a graphical representation of the output of a blue light source, showing the amount (power) of light emitted as a function of wavelength; such representations of light sources are referred to as *spectral power distributions*. The degree to which a light source will stimulate a particular type of cone can be determined by assessing the extent to which its spectral power distribution overlaps with the spectral response of the photoreceptor. We see that the blue light represented in figure 1.7b will stimulate principally the S cones, while the red light in figure 1.7c will stimulate mainly the L cones. In practice, it is rare for only one type of cone to respond, and it is the ratio of stimulation of the three photoreceptors that is characteristic of a color. Both the red light in figure 1.7c and the orange light in figure 1.7d will stimulate the L cones, but the orange light will create a greater response in the M cones than the red light.

NIGHT VISION

The signal generated by the photoreceptors is proportional to the amount of light entering the eye. There is, as explored in section 1.6, a minimum amount of light required for the cones to operate efficiently; below that their response progressively becomes too feeble for a color image to be formed by the brain. Within the retina there is, however, another type of sensor cell that is approximately 10 to 15 times more numerous than the cone photoreceptors and can respond to very much lower light levels. While these *rod cells* allow vision at very low light levels (often termed *night vision*), they all contain the same photosensitive pigment mentioned earlier: rhodopsin. In consequence, they share a single spectral response, and it is not possible for us to differentiate between wavelengths under extremely low light levels where the eye has “switched” to night vision, so all scenes appear monochromatic.

OTHER PHOTORECEPTORS

A third type of photosensitive cell within the retina is not involved in the image-forming process; its main function appears to be the detection of light and dark to help regulate the circadian (day/night) rhythms and processes of the body. These cells are termed *intrinsically photosensitive retinal ganglion cells* and contain the photosensitive pigment melanopsin (indeed, the cells are sometimes referred to as *melanopsin-containing retinal ganglion cells*). Although these cells are not used in vision, their stimulation has been found to be important in regulating sleep patterns and maintaining levels of alertness (Pickard and Sollars 2012). Melanopsin is particularly sensitive to light at the blue end of the spectrum (its maximum absorption is at c. 480 nm), which is why lamps rich in blue radiation are often used to combat the effects of light deprivation, including seasonal affective disorder. (Their impact on the lighting used in museums is covered in chapter 6.)

1.3 White Light

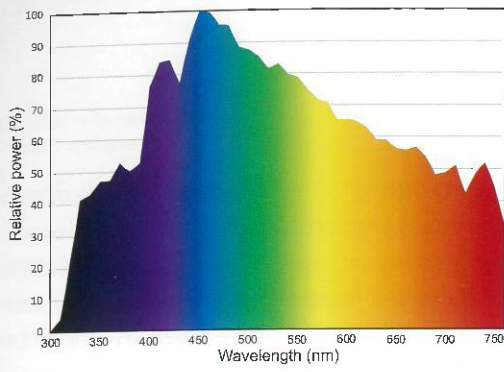
While the blue, orange, and red light sources whose spectral power distributions are represented in figures 1.7b–1.7d are useful to demonstrate the response of the eye to colored light, these *narrow-band sources* (those emitting all their power in a narrow range of wavelengths) are not representative of the light sources we encounter normally, which we often characterize as *white light sources*.

If we reverse Newton's experiment to split white light into its component colored rays, we see that white light comprises radiation of many colors, or wavelengths. Because there is no single standard white light, its definition is illusive. The *Oxford English Dictionary* offers "apparently colourless light [that] contains all the wavelengths of the visible spectrum at equal intensity." This definition corresponds to a purely theoretical white light source that emits radiation of equal intensity throughout the visible region, termed the *equal-energy source*. However, most light sources that we would describe as white do not emit all wavelengths at equal intensity. The spectral power distributions of several such light sources are presented in figure 1.8. These have been chosen to represent classes of illuminants commonly found in museums and will serve as a point of reference for future discussions. The shape of the curves differs from source to source, but the feature they share is that each emits light across the spectrum in a way that stimulates all three of the cone photoreceptors to a similar—if not equal—extent.

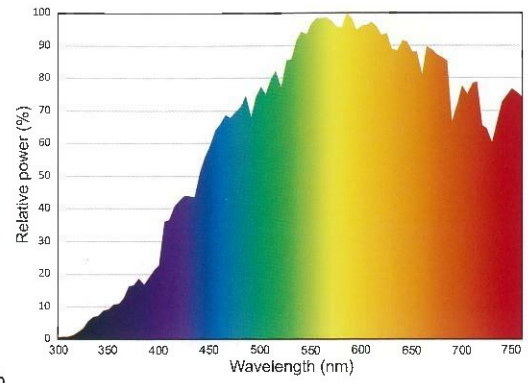
This loose definition based on the effect of "white" light on the eye's receptors is a useful starting point, although it might seem surprising that all the sources in figure 1.8, with their very different spectral distributions, produce such an effect, particularly those that have spectra with discrete peaks or spikes. Such spectra are often termed *discontinuous* to differentiate them from those that show a smooth curve across the visible region, referred to as *continuous spectra*. In figure 1.8, the most notable examples of discontinuous spectra are the fluorescent lamps, while daylight, incandescent, and halogen lamps produce continuous spectra. The reason sources with discontinuous spectra still appear white is that the spectral peaks generally correspond closely to the wavelengths at which the three photoreceptors in the eye are most sensitive, producing the near-equal stimulation that we have seen is characteristic of a white light source.

The potential merit of discontinuous sources is that when radiation is delivered principally in those regions of the spectrum to which the eye is sensitive, less energy is needed to provide a particular light level—a feature that was exploited in the 1970s to develop very energy-efficient fluorescent lamps (Thornton 1973). These lamps' shortcoming is that the lack of emission in certain regions of the spectrum can lead to color distortion. (These facets of discontinuous sources will be explored later; see sections 3.1 and 7.2.)

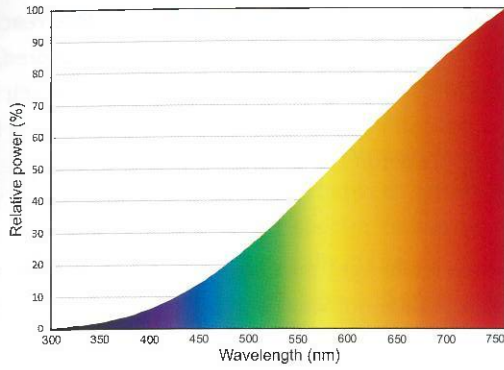
Figure 1.8. Spectral power distributions for representative light sources: north sky daylight (a), noon sunlight (b), incandescent lamp (c), halogen lamp (d), triphosphor fluorescent lamp (e), high color-quality fluorescent lamp (f), warm white LED (g), and cool white LED (h).



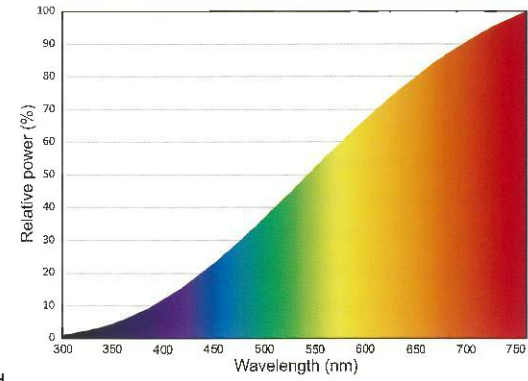
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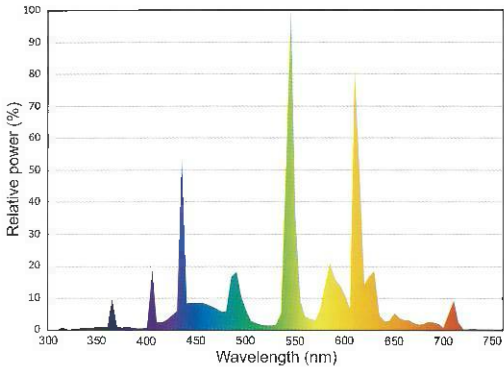
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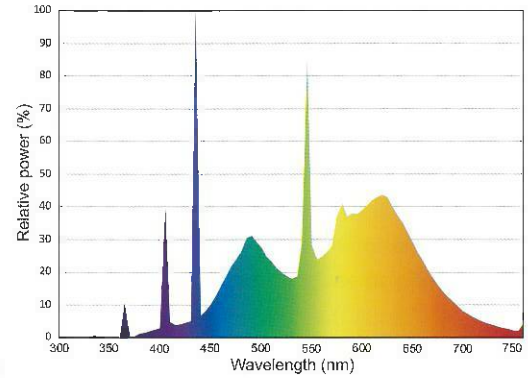
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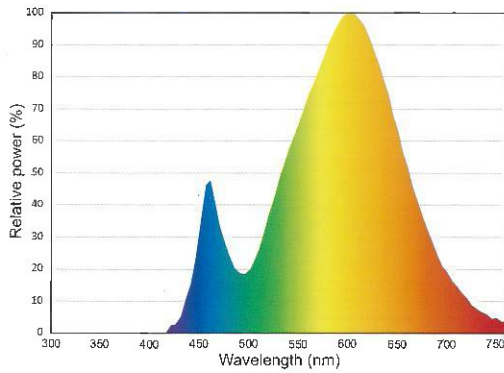
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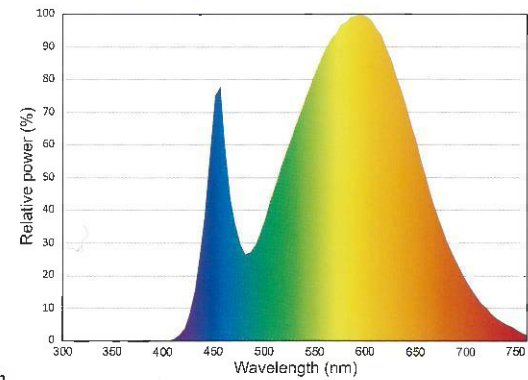
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f



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h