

R.W.G. Hunt
M.R. Pointer



MEASURING COLOUR

Fourth Edition

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Measuring Colour

Fourth Edition

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A John Wiley & Sons, Ltd., Publication

This edition first published 2011
© 2011, John Wiley & Sons, Ltd

Previous Editions:

1st Edition ISBN 0 7458 01250 0, Ellis Horwood, Chichester, 1987
2nd Edition ISBN 0 13 567686 X, Ellis Horwood, Chichester, 1991
3rd Edition ISBN 0 86343 387 1, Fountain Press, Kingston-upon-Thames, 1998

Registered office

John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

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Library of Congress Cataloging-in-Publication Data

Hunt, R.W.G. (Robert William Gainer), 1923-
Measuring colour / R.W.G. Hunt, M.R. Pointer. – 4th ed.
p. cm. – (The Wiley-IS&T series in imaging science and technology)
Includes bibliographical references and index.
ISBN 978-1-119-97537-3 (hardback)
1. Colorimetry. I. Pointer, Michael, Ph. D. II. Title.
QC495.H84 2011
535.6028'7 – dc23

2011018730

A catalogue record for this book is available from the British Library.

Print ISBN: 978-1-119-97537-3
ePDF ISBN: 978-1-119-97573-1
oBook ISBN: 978-1-119-97559-5
ePub ISBN: 978-1-119-97840-4
Mobi ISBN: 978-1-119-97841-1

Set in 10/12pt Times by Laserwords Private Limited, Chennai, India.

Prologue

This is the story of Mister Chrome
who started out to paint his home.
The paint ran out when half way through
so to the store he quickly flew
to buy some more of matching hue,
a delicate shade of egg-shell blue.
But when he tried this latest batch,
he found it simply didn't match.
No wonder he was in a fix,
for of the colours we can mix,
the major shades and those between,
ten million different can be seen.

You foolish man, said Missis Chrome,
you should have taken from the home
a sample of the colour done;
you can't remember every one.
Taking care that she had got
a sample from the early pot,
she went and bought her husband more
of better colour from the store.
Before she paid, she checked the shade,
and found a perfect match it made.
In triumph now she took it home,
and gave it straight to Mister Chrome.
He put it on without delay,
and found the colour now okay.

But, after dark, in tungsten light,
they found the colour still not right.
So to the store they both went now,
with samples clear, and asked them how

a paint that matched in daylight bright
could fail to match in tungsten light.
The man's reply to their complaint
was that the pigments in the paint
had been exchanged, since they had bought,
for others of a different sort.
To solve the problem on their wall,
he gave them paint to do it all
from just one batch of constant shade,
and then at last success was made.

To compensate them for their trouble,
the store sent to them curtains double.
They hung them up with great delight;
they matched in tungsten and daylight.
A neighbour then did make a call
and fixed his eye upon the wall;
the paint, he said was all one colour,
but clearly saw the curtains duller!

Though colours strange at times appear,
the moral of this tale is clear:
to understand just what we see,
object, light, and eye, all three,
must colour all our thinking through
of chronic problems, old or new!

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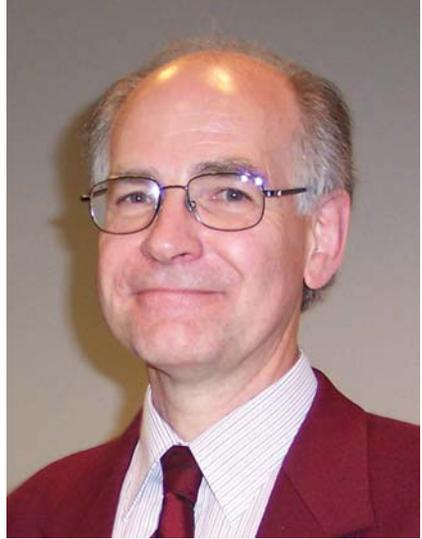
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About the Authors

Dr Robert W. G. Hunt received his Ph.D and DSc from the University of London. He was a research scientist at the Kodak Research Laboratories, where he worked on factors affecting the quality of colour images, and devices for making reflection prints from both negative and positive images on film; he was finally Assistant Director of Research. Since 1982 he has worked as an independent colour consultant, and has taken a leading role in the development of colour appearance models. He has written over 100 papers on colour vision, colour reproduction, and colour measurement, and his other book, *The Reproduction of Colour*, is now in its sixth edition. He has been awarded the Newton Medal of the Colour Group (Great Britain) (1974), the Progress Medal of the Royal Photographic Society (1984), the Judd-AIC Medal of the International Colour Association (1987), the Gold Medal of the Institute of Printing (1989), the Johann Gutenberg Prize of the Society for Information Display (2002), the Godlove Award of the Inter-Society Color Council, U.S.A (2007), and Honorary Fellowship of the Society of Dyers and Colourists (2009). In 2009 he was appointed an Officer of the British Empire (OBE) for ‘services to the field of colour science and to young people through Crusaders’.



Dr Michael R. Pointer received his Ph.D from Imperial College, London, working with David Wright. He then worked in the Research Division of Kodak Limited on fundamental issues of colour science applied to the photographic system. After periods at the University of Westminster and the National Physical Laboratory, he is now a Visiting Professor at the University of Leeds, as well as working as a consultant scientist. In 1997, he received the Fenton Medal, The Royal Photographic Society's award for services to the Society. In 2004, he received a Silver Medal from the Society of Dyers and Colourists for 'contributions to colour science'. He has authored over 100 scientific papers, is a Fellow of The Royal Photographic Society and the Institute of Physics, Secretary of CIE Division 1 Vision & Colour, and UK Associate Editor of the journal, *Color Research & Application*.



Series Preface

Imagine Alice in Wonderland saying this: ‘I wonder if I’ve changed *colour* in the night? Let me think. Was I the same *hue* when I got up this morning? I almost think I can remember feeling a little *less saturated*. But if I’m not the same *x-y value*, the next question is ‘*What Lab value* in the world am I?’ Ah, that’s the great puzzle!’

The fourth edition of *Measuring Colour* by Dr Robert W.G. Hunt and Dr Michael R. Pointer is the eleventh book in the Wiley-IS&T Series in Imaging Science and Technology. This excellent text, while not solving the complex puzzle of colour, provides readers with the means to solve their colour puzzle.

The 17-chapter book starts with the basic concepts of colour vision then covers the methodology of converting a spectrum to CIE values (*XYZ* or *Lab*) so one can match colours and detect metamers. Visual models are then used to indicate how colour changes under different viewing conditions and to explain why surface characteristics influence the perception of a given spectrum. The details of using digital cameras to measure colour are an important addition in the fourth edition, as the authors recognise that the CCD and CMOS sensors in digital cameras, together with colour filter arrays and digital signal processing, present a new opportunity to measure spatial variation in colour.

Human beings are very sensitive to colour changes or differences and find it difficult to decide, from a set of colours, for example on a paint palette, which one is wanted. People have a strong sense of memory of preference for the colour of green grass, blue skies or pink sunsets. They notice when a photographic image (from a film or digital camera) of a red tablecloth comes out wrong or when the sweater that was bought in a shopping mall under tungsten (fluorescent) light looks different in daylight.

Neural scientists can use Functional Magnetic Resonance Imaging to locate where in the brain the perceptions of the colours of the visible spectrum are located. Colour scientists know that each colour has an exact spectral power distribution which can be measured to a high degree of accuracy. Why, then, is colour such a puzzle?

What Alice did not know when she fell down the rabbit hole was that the human visual system can play a lot of tricks on how we perceive colour. The perception of colour depends not just on its native spectrum but also on the spectra of the direct illumination, the ambient illumination and the near and far surround colours. Geometrical patterns can cause local colour changes as seen by the observer, as can adaptation to a uniform colour field. So how can the puzzle called colour be solved when there are so many variables and boundary conditions?

The Mock Turtle might have said: ‘*What is the use of **studying** all that **colour** stuff, if you **can’t measure** it as you go on? It’s by far the most confusing thing I ever heard!*’

But then, he was not privy to the fourth edition of *Measuring Colour* which provides a welcome and major contribution to the continuing understanding of the puzzle that is colour.

MICHAEL A. KRISS

*Formerly of the Eastman Kodak Research
Laboratories and the University of Rochester, USA*

Preface

To the First Edition

This book is intended to provide the reader with the basic facts needed to measure colour. It is a book about principles, rather than a guide to instruments. With the continual advances in technology, instruments are being improved all the time, so that any description of particular colorimeters, spectroradiometers, or spectrophotometers is likely to become out of date very quickly. For such information, manufacturers' catalogues are a better source of information than books. But the principles of measuring colour are not subject to rapid change, and are therefore appropriate for treatment in the more permanent format offered by books.

Recommendations about the precise way in which the basic principles of colour measurement should be applied have for over 50 years been the province of the International Commission on Illumination (CIE). The second edition of its publication *No. 15, Colorimetry*, includes several new practices, and it is therefore timely to restate the basic principles of colorimetry together with these latest international recommendations on their application; this is the aim of *Measuring Colour*.

Colour is, of course, primarily a sensation experienced by the individual. For this reason, the material has been set in the context of the colour vision properties of the human observer: the first chapter is a review of our current knowledge of colour vision; and the last chapter provides a description of a model of colour vision that can be used to extend colour measurement, beyond the territory covered by the CIE at present, to the field of colour appearance.

To the Second Edition

The second edition contains all the material of the first edition, together with four new chapters. Two of these chapters provide entirely new material: one is on light sources and the other is on precision and accuracy in colorimetry. The other two new chapters provide expanded treatments of metamerism and of the colorimetry of fluorescent materials. Extensive revisions have been made to the chapter on the model of colour vision, so as to present it in its latest version. Finally, minor revisions have been made to the rest of the book to improve the treatment in various respects.

To the Third Edition

The following changes have been made to this third edition. The chapter on metamerism has been expanded to include a discussion of corresponding colours, colour constancy and a description of a colour inconstancy index. The material in Chapter 11 of the second edition, entitled 'Miscellaneous topics', has been included at the end of Chapter 3. Chapter 11 now provides a discussion of the way in which the colours of colorant mixtures can be evaluated. Chapter 12 has been updated to provide the colour appearance model adopted internationally, designated CIECAM97s. Two new Appendices have been added: Appendix 7 provides illuminant-observer weights for band-pass corrected data, and Appendix 8 provides illuminant-observer weights for band-pass uncorrected data. In addition, various minor changes have been made to update the text.

To the Fourth Edition

For this fourth edition Dr Michael R. Pointer has become a joint author. Much of the book is concerned with CIE procedures, and, as current secretary of CIE Division 1 Colour and Vision, Dr Pointer has enabled the important features of the latest CIE publications to be covered; he has also provided new chapters on 'Factors affecting the appearance of coloured objects' and 'Colorimetry with digital cameras'. The first of these chapters covers the important topics of gloss, translucency and texture, which were not previously included; the second of these chapters covers the technology that enables colorimetry to be carried out on objects with complicated shapes or patterns, and which has been developed since publication of the third edition. The important topic of colour rendering by light sources now has its own chapter, and this includes descriptions of alternatives to the current CIE Colour Rendering Index. Additions to the Appendices include the recent CIE procedure for mesopic photometry, and the spectral reflectance factors for the Munsell colours used in the CIE Colour Rendering Index. For the current state of CIE publications see www.CIE.co.at. As with previous editions, various minor changes have been made to update the text. An important change in this fourth edition is the availability of colour printing on every page; this has made it possible to improve the clarity of many figures, and to position colour reproductions at their appropriate positions in the text, instead of being grouped into a section of colour plates. Since the publication of the third edition in 1998, the measurement of colour has become increasingly important in many areas, including science, medicine and manufacturing, and this fourth edition provides a more up-to-date and comprehensive treatment of this fascinating subject.

Acknowledgements

For the First Edition

I am most grateful to Dr M. R. Pointer of Kodak Limited for kindly making many helpful comments on the text, for providing some of the numerical data, and for help with the proof reading. My grateful thanks for help are also due to Dr A. Hård in connection with the section on the NCS, to Dr H. Terstiege with that on the DIN system, and to Dr A. Nemcsics with that on the Coloroid system. For permission to reproduce figures, my thanks are due to the Institute of Physics for Figure 3.5; to John Wiley and Sons for Figures 7.5, 7.12, 7.19 and 8. 1; to Dr A. Hård for Figure 7.12; to Dr H. Terstiege for Figure 7.19; and to Academic Press for Figures 9.1, 9.2 and 9.3. I would also like to thank Dr J. Schanda for kindly supplying me with copies of recent CIE documents.

With regard to the colour plates, my thanks are due to the following for kindly supplying the originals: Dr A.A. Clarke and Dr M.R. Luo, of Loughborough University of Technology, for Plates 2 and 3; Dr A. Hård for Plate 5; Dr H. Terstiege for Plate 8; and Mr R. Ingalls for Plates 1, 6, and 7. I would also like to thank the Munsell Corporation for permission to reproduce Plate 4.

I am also most grateful to Mr A.J. Johnson, and some of his colleagues, of Crosfield Electronics Limited, for kindly supplying the separations for the colour illustrations.

Finally my grateful thanks are due to my wife for editorial assistance and for help with the proof reading.

For the Second Edition

I am very grateful for help that has kindly been given to me by experts on the subject matter of the new material in this second edition. Dr F.W. Billmeyer has made many suggestions for improving the new chapters on metamerism, on precision and accuracy in colorimetry, and on the colorimetry of fluorescent materials. Miss M.B. Halstead, Mr D.O. Wharmby and Dr M.G. Abeywickrama have helped with the new chapter on light sources. Dr R.F. Berns has helped with the section on correcting for errors in spectral data, and Dr W.H. Venable with the section on the computation of tristimulus values. I am indebted to Mr J.K.C. Kempster for the data on which Figure 6.2 is based. Once again, I am most grateful to Dr M.R. Pointer for general comments, for help with computations, and for proof reading, and to my wife for editorial help and for proof reading.

For the Third Edition

I am most grateful to Dr M. R. Pointer for kindly suggesting that publication of this third edition be assisted by The Tintometer Limited, a company which has been continuously involved with colour measurement for over a hundred years; in this connection Miss Nicola Pointer's word-processing help is much appreciated. As with the earlier editions, Dr Pointer has also provided much expert help by means of general comments, and proof reading, for which I am most grateful. The tables given in Appendices 7 and 8 were originally published by the American Society for Testing Materials in their Standard ASTM E 308 - 95, *Standard Practice for Computing the Colours of Objects by Using the CIE System*; their permission to reproduce these tables is acknowledged with thanks. For preparing the final text in such a helpful way, I am very grateful to Mr Dennis Shearman of Priory Publications, who also performed the same task for my other book *The Reproduction of Colour*. Finally my best thanks are due to my wife for editorial help and for proof reading.

For the Fourth Edition

We are grateful to Janos Schanda for help with Chapter 7, to Jan and Peter Morovic for help with Chapter 12, and to Ronnier Luo and Changjun Li with Chapter 15. References to Munsell® in this publication are used with permission from X-Rite Inc. References to NCS in this publication are used with permission from NCS Color AB.

For preparing the final text in such a helpful way, we are very grateful to the Wiley staff at Chichester, who also performed the same task for Dr Hunt's *The Reproduction of Colour*.

1

Colour Vision

1.1 INTRODUCTION

Ten million! That is the number of different colours that we can distinguish, according to one reliable estimate (Judd and Wyszecki, 1975). It is, therefore, no wonder that we cannot remember colours well enough to identify a particular shade. People are thus well advised to take samples of their clothing colours with them when purchasing accessories that are intended to match. They are also usually well aware that it is not enough to examine the colour match in just one type of light in a shop, but to see it in daylight as well as in artificial light. Finally, a second opinion about the match, expressed by a friend or a shop assistant, is often wisely sought.

The above activity involves the three basic components of colour: sources of light, objects illuminated by them and observers. Colour, therefore, involves not only material sciences, such as physics and chemistry, but also biological sciences, such as physiology and psychology; and, in its applications, colour involves various applied sciences, such as architecture, dyeing, paint technology, and illuminating engineering. Measuring colour is, therefore, a subject that has to be broadly based and widely applied.

Without observers possessing the faculty of sight, there would be no colour. Hence it is appropriate to start by considering the nature of the colour vision provided by the human eye and brain. Before doing this, however, a brief description must be given of the way in which it is necessary to characterise the nature of the light which stimulates the visual system.

1.2 THE SPECTRUM

It is fair to say that understanding colour finds its foundations in the famous experiments performed by Isaac Newton in 1666. Before this date, opinions on the nature of colours and the relationships between them were most vague and of very little scientific use, but, after Newton's work became known, a way was open for progress based on experimental facts.

The historic experiments were performed in Trinity College, Cambridge, when Newton made a small hole, a third of an inch in diameter, in the shutter of an otherwise entirely

dark room; through this hole, the direct rays of the sun could shine and form an image of the sun's disc on the opposite wall of the room, like a pin-hole camera. Then, taking a prism of glass, and placing it close to the hole, he observed that the light was spread out fan-wise into what he was the first to call a *spectrum*: a strip of light, in this case about ten inches long, and coloured red, orange, yellow, green, blue, indigo, and violet, along its length. The natural conclusion, which Newton was quick to draw, was that white light was not the simple homogeneous entity which it was natural to expect it to be, but was composed of a mixture of all the colours of the spectrum.

The next question which arose was whether these spectral colours themselves, red, green, etc., were also mixtures and could be spread out into further constituent colours. A further experiment was performed to test this suggestion. A card with a slit in it was used to obscure all the light of the spectrum, except for one narrow band. This band of light, say a yellow or a green, was then made to pass through a second prism, but the light was then seen not to be spread out any further, remaining exactly the same colour as when it emerged from the slit in the card. It was, therefore, established that the spectral colours were in fact the basic components of white light.

The inclusion by Newton of indigo in the list of spectral colours is rather puzzling since, to most people, there appears to be a gradual transition between blue and violet with no distinct colour between them, as there is in the case of orange between red and yellow. Several explanations of the inclusion of indigo have been suggested, but the most likely is that Newton tried to fit the colours into a scale of tones in a way analogous to the eight-tone musical scale; to do this he needed seven different colours to correspond to the seven different notes of the scale (McLaren, 1985).

In Figure 1.1, the main bands of colour in the spectrum are shown against a scale of the *wavelength* of the light. Light is a form of electro-magnetic radiation, as is also the case for x-rays, radar, and radio waves, for instance, and the property of this radiation that gives it particular characteristics is its wavelength. Radio waves have quite long wavelengths, typically in the range from about a metre to several kilometres, whereas x-rays

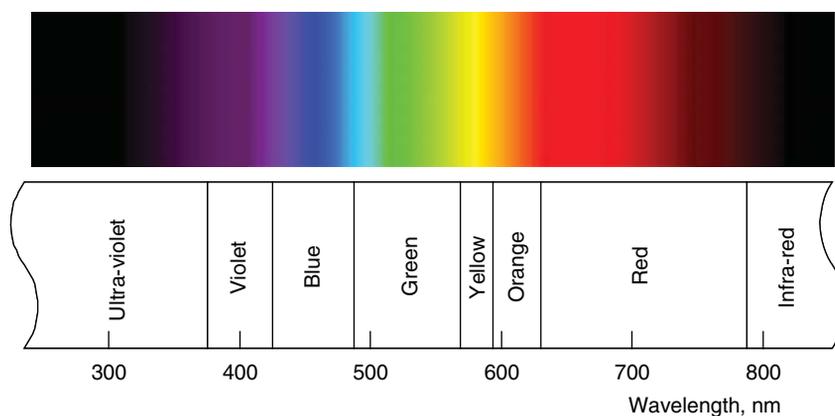


Figure 1.1 The colour names usually given to the main regions of the spectrum. Because of the limitations of printing, the colours of the spectrum cannot be shown accurately, but their general layout is displayed adequately

have extremely short wavelengths, typically about a millionth of a millimetre or shorter. Light waves have wavelengths in between, ranging from slightly above to slightly below a half a millionth of a metre. To obtain convenient numbers for the wavelengths of light, the unit used for expressing them is the *nanometre* (abbreviation, *nm*), which is a millionth of a millimetre, or 10^{-9} of a metre; this is the unit used in Figure 1.1. It must be emphasised that the colour names and wavelength boundaries given in Figure 1.1 are only intended as a rough guide; each colour gradually merges into the next so that there is really no exact boundary; moreover, the colour appearance of light of a given wavelength depends on the viewing conditions, and is also liable to be slightly different from one observer to another. Even so, the names given in Figure 1.1 are useful to bear in mind when considering data that are presented as functions of wavelength. Radiation having wavelengths longer than those of the visible spectrum and less than about 1 mm is called *infrared*; and that having wavelengths shorter than those of the visible spectrum and longer than about 100 nm is called *ultraviolet*. These radiations can provide radiant energy that tans the skin or warms the body, for instance, but they cannot normally be seen as light. In colour science, although it is the long-established practice to identify different parts of the spectrum by using wavelength, it would be more fundamental to use *frequency*. This is because, for light from any part of the spectrum, as it passes through a medium, its wavelength decreases by being divided by the refractive index of that medium; however, the velocity also decreases in the same proportion, so that the frequency (the velocity divided by the wavelength) remains constant. The values of wavelength quoted are usually as measured in air, and, although those measured in vacuum would be more fundamental, they differ by only about 3 parts in 10 000. (The velocity of light in vacuum is about 2.998×10^8 metres per second.)

1.3 CONSTRUCTION OF THE EYE

A diagrammatic representation of a cross-section of the human eye is given in Figure 1.2. Most of the optical power is provided by the curved surface of the *cornea*, and the main function of the *lens* is to alter that power by changing its shape, being thinner for viewing

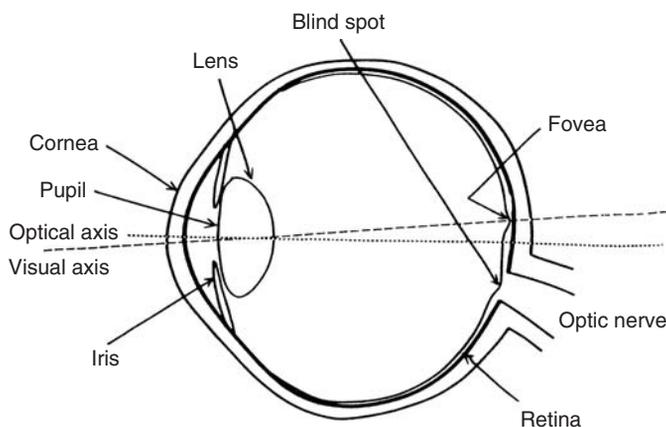


Figure 1.2 Cross-sectional diagram of the human eye

distant objects and thicker for near objects. The cornea and lens acting together form a small inverted image of the outside world on the *retina*, the light-sensitive layer of the eye. The *iris*, the annular-shaped coloured part of the eye that we see from the outside, changes its shape, having a central aperture that is only about 2 mm in diameter in bright light, but which is larger in dim light, having a maximum diameter of about 8 mm. The aperture referred to is called the *pupil*, and is the area through which the light passes. The iris, by changing its diameter, provides some compensation for changes in the level of illumination under which objects are seen; however, this compensation only amounts to a factor of about 8 to 1, rather than the 16 to 1 to be expected from the ratio of the squares of the diameters, because rays that pass through the edge of the pupil are less effective in stimulating the retina than those that pass through the centre, a property known as the *Stiles-Crawford effect*.

The retina lines most of the interior of the approximately spherically-shaped eye-ball, and this provides the eye with a very wide field of view. However, the retina is far from being uniform in sensitivity over its area. Colour vision is very limited for stimuli seen beyond about 40° off the visual axis (Hurvich, 1981), and in this area vision is used mainly for the detection of movement. Within the 40° on either side of the eye's axis, the ability to see both colour and fine detail gradually increases as the eye's axis is approached, the area of sharpest vision being termed the *fovea*, which comprises approximately the central 1.5° diameter of the visual field. An area within this, termed the *foveola*, corresponds to a field of about 1° . A curious feature of the fovea and foveola is that they are not centred on the *optical axis* of the eye, but lie about 4° to one side as shown in Figure 1.2, thus resulting in the visual axis being offset by this amount. About 10° to the other side of the optical axis (equivalent to about 14° from the fovea) is the *blind spot*, where the nerve fibres connecting the retina to the brain pass through the surface of the eye-ball, and this area has no sensitivity to light at all. There is also an area covering part of the fovea, called the *yellow spot* or *macula lutea*, containing a yellowish pigment. In addition to these spatial variations in the retina, there are changes in the types of light receptors present in different areas. In the foveola, the receptors are all of one type, called *cones*; outside this area, there is, in addition, another type, called *rods*. The ratio of cones to rods varies continuously from all cones and no rods in the foveola to nearly all rods and very few cones beyond about 40° from the visual axis. Finally, the individual cones and rods are connected to the brain by nerve fibres in very different ways, depending on their position: in the foveola, there are about the same number of nerve fibres as cones; but, as the angle from the visual axis increases, the number of nerve fibres decreases continuously until as many as several hundred rods and cones may be served by each nerve fibre.

1.4 THE RETINAL RECEPTORS

The function of the rods in the retina is to give monochromatic vision under low levels of illumination, such as moonlight and starlight. This *scotopic* form of vision operates when the stimuli have luminances of less than some hundredths of a candela per square metre (cd m^{-2} ; for a summary of photometric terms and units, see Appendix 1).

The function of the cones in the retina is to give colour vision at normal levels of illumination, such as daylight and typical indoor artificial light. This *photopic* form of vision operates when stimuli have luminances of several cd m^{-2} or more.

There is a gradual change from photopic to scotopic vision as the illumination level is lowered, and, for stimuli having luminances between several cd m^{-2} to some hundredths of a cd m^{-2} , both cones and rods make significant contributions to the visual response, and this is called *mesopic* vision. The wavelengths of the light to which the rods are most sensitive are shorter than is the case for most of the cones, and, as a result, as the illumination level falls through the mesopic range, the relative brightnesses of red and blue colours change. This can often be seen in a garden at the end of the day; red flowers that look lighter than blue flowers in full daylight look darker than the blue ones as the light fades. This is known as the *Purkinje phenomenon*.

The rods and cones are so named because of their shapes, but they are all very small, being typically about a five-hundredth of a millimetre in diameter, with a length of around a twenty-fifth of a millimetre. They are packed parallel to one another and face end-on towards the pupil of the eye so that the light is absorbed by them as it travels along their length. They are connected to nerve fibres via an extremely complicated network of cells situated immediately on the pupil-side of their ends. The nerve fibres then travel across the pupil-side of the retina to the blind spot where they are collected together to form the *optic nerve* which connects the eye to the brain. Hence, before the light reaches the receptors, it has to pass through the cells and nerve fibres, which are largely transparent. In each eye, there are about 6 million cones, 100 million rods, and 1 million nerve fibres.

1.5 SPECTRAL SENSITIVITIES OF THE RETINAL RECEPTORS

The rods and the cones are not equally sensitive to light of all wavelengths. In the case of the rods, the initial step in the visual process is the absorption of light in a photosensitive pigment called *rhodopsin*. This pigment absorbs light most strongly in the blue-green part of the spectrum, and decreasingly as the wavelength of the light becomes either longer or shorter. As a result, the spectral sensitivity of the scotopic vision of the eye is as shown by the broken curve of Figure 1.3. This curve is obtained by having observers adjust the strength of a beam of light of one wavelength until the perception it produces has the same intensity as that produced by a beam of fixed strength of a reference wavelength. If the strength of the variable beam had to be, for example, twice that of the fixed beam, then the scotopic sensitivity at the wavelength of the variable beam would be regarded as a half of that at the wavelength of the fixed beam. These relative sensitivities are then plotted against wavelength to obtain the broken curve of Figure 1.3, the maximum value being made equal to 1.0 by convention. To obtain a sensitivity curve representing scotopic vision, it is necessary to use beams of sufficiently low intensity to be entirely in the scotopic range, and the curve of Figure 1.3 was obtained in this way. It is based on results obtained from about 70 observers (22 in a study by Wald, 1945; and 50 in a study by Crawford, 1949) and represents scotopic vision of observers under 30 years of age; above this age, progressive yellowing of the lens of the eye makes the results rather variable. The curve represents the scotopic sensitivity for light incident on the cornea, and thus the effects of any absorption in the ocular media are included. The strengths of the beams can be evaluated in various ways, but the convention has been adopted to use the amount of power (energy per unit time) per small constant-width wavelength interval. If the beams used have the same small width of wavelength throughout the spectrum, then all that is required is to know the relative power

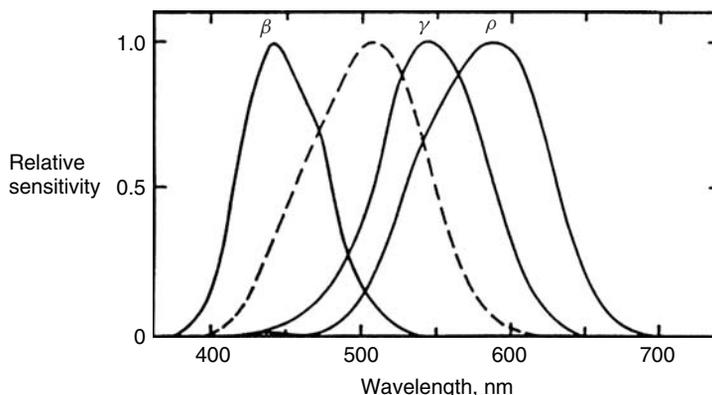


Figure 1.3 Broken line: the spectral sensitivity of the eye for scotopic (rod) vision. Full lines: spectral sensitivity curves representative of those believed to be typical of the three different types of cones, ρ , γ , and β , of the retina that provide the basis of photopic vision. The sensitivities are for equal power per small constant-width wavelength interval

in each beam. However, if the beams have different widths of wavelength, then the values of the relative power per unit wavelength interval have to be determined for each beam.

A system having a single spectral sensitivity function, such as that shown by the broken line in Figure 1.3, cannot, on its own, provide a basis for colour vision. Thus, although, for example, light of wavelength 500 nm would result in a response about 30 times as great as the same strength of light of wavelength 600 nm, the two responses could be made equal simply by increasing the strength of the 600 nm beam by a factor of about 30 times. The system is thus not able to distinguish between changes in wavelength and changes in intensity, and this is what is needed to provide a basis for colour vision. Scotopic vision therefore provides only shades of whites, greys, and blacks, as occur in moonlight.

In the case of the cones of the human retina, it has proved difficult to extract the photosensitive pigments, and our knowledge of them has had to be obtained largely by indirect means. These include very careful measurements of the light absorbed at each wavelength of the spectrum by individual cones removed from eyes that have become available for study (Dartnall, Bowmaker, and Mollon, 1983), and deductions from experiments on colour matching together with data (Estévez, 1979) on colour defective vision (to be discussed in Section 1.10). Also the genes for the pigments have been expressed in tissue cultures, enabling the pigments to be produced for study (Nathans, Merbs, Sung, Weitz, and Wang, 1992). As a result of these studies, sets of curves typified by those shown by the full lines of Figure 1.3 have been obtained. (See also Stockman, Sharpe and Fach, 1999; Stockman and Sharpe, 2000; Stockman, 2008.)

The exact shapes of the curves that best typify the spectral sensitivities of the cones are still a matter of some debate, and in some sets the right-hand curve peaks at about 565 nm (Smith and Pokorny, 1972) instead of at about 585 nm as in Figure 1.3; but the set shown in Figure 1.3 shows all the important features of any reasonably plausible set, and is adequate for our present descriptive purposes. These curves represent the spectral