1 The Origins of Modern Color Science

J. D. Mollon

Department of Experimental Psychology
University of Cambridge, Downing Street, Cambridge CB2 3EB, UK

Jove's wondrous bow, of three celestial dyes,
Placed as a sign to man amid the skies

Pope, *Iliad*, xi: 37

CHAPTER CONTENTS

The Science of Color
ISBN 0–444–512–519

Each newcomer to the mysteries of color science must pass through a series of conceptual insights. In this, he or she recapitulates the history of the subject. For the history of color science is as much the history of misconception and insight as it is of experimental refinement. The errors that have held back our field have most often been category errors, that is, errors with regard to the domain of knowledge within which a given observation is to be explained. For over a century, for example, the results of mixing colored lights were explained in terms of physics rather than in terms of the properties of human photoreceptors. Similarly, in our own time, we remain uncertain whether the phenomenological purity of certain hues should be explained in terms of hard-wired properties of our visual system or in terms of properties of the world in which we live.

1.1 NEWTON

Modern color science finds its birth in the seventeenth century. Before that time, it was commonly thought that white light represented light in its pure form and that colors were modifications of white light. It was already well known that colors could be produced by passing white light through triangular glass prisms, and indeed the long thin prisms sold at fairs had knobs on the end so that they could be suspended close to a source of light. In his first published account of his 'New Theory of Colors,' Isaac Newton describes how he bought a prism 'to try therewith the celebrated *Phaenomena* of *colours*' (Newton, 1671). In the seventeenth century, one of the great trade fairs of Europe was held annually on Stourbridge Common, near the head of navigation of the river Cam. The fair was only two kilometers from Trinity College, Cambridge, where Newton was a student and later, a Fellow. In his old age, Newton told John Conduitt that he had bought his first prism at Stourbridge Fair in 1665 and had to wait until the next fair to buy a second prism to prove his 'Hypothesis of colours'. Whatever the accuracy of this account and its dates – the fair in fact was cancelled in 1665 and 1666, owing to the plague (Hall, 1992) – the story emphasizes that Newton did not discover the prismatic spectrum: His contribution lies in his analytic use of further prisms.

Allowing sunlight to enter a small round hole in the window shutters of his darkened chamber, Newton placed a prism at the aperture and refracted the beam on to the opposite wall. A spectrum of vivid and lively colors was produced. He observed, however, that the colored spectrum was not circular as he expected from the received laws of refraction, but was oblong, with semi-circular ends.

Once equipped with a second prism, Newton was led to what he was to call his *Experimentum Crucis*. As before, he allowed sunlight to enter the chamber through a hole in the shutter and fall on a triangular prism. He took two boards, each pierced by a small hole. He placed one immediately behind the prism, so its aperture passed a narrow beam; and he placed the second about 4 meters beyond, in a position that allowed him to pass a selected portion of the spectrum through its aperture. Behind the second aperture, he placed a second prism, so that the beam was refracted a second time before it reached the wall (Figure 1.1). By rotating the first prism around its long axis, Newton was able to pass different portions of the spectrum through the second aperture. What he observed was that the part of the beam that was more refracted by the first prism was also more refracted by the second prism.

Moreover, a particular hue was associated with each degree of refrangibility: The least refrangible rays exhibited a red color and the most refrangible exhibited a deep violet color. Between these

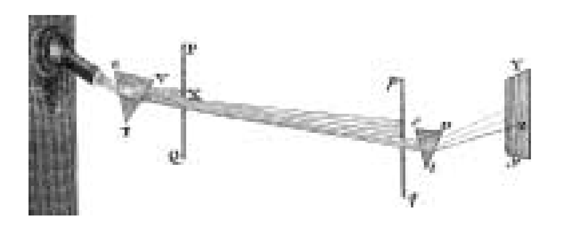


Figure 1.1 **An eighteenth-century representation of Newton's *Experimentum crucis*. As the left-hand prism is rotated around its long axis, the beam selected by the two diaphragms is constant in its angle of incidence at the second prism. Yet the beam is refracted to different degrees at the second prism according to the degree to which it is refracted at the first. (From Nollet's *Leçons de Physique Expérimentale*).**

two extremes, there was a continuous series of intermediate colors corresponding to rays of intermediate refrangibility. Once a ray of a particular refrangibility has been isolated in variants of the *Experimentum Crucis*, there was no experimental manipulation that would then change its refrangibility or its color: Newton tried refracting the ray with further prisms, reflecting it from various colored surfaces, and transmitting it through colored mediums, but such operations never changed its hue. Today we should call such a beam 'monochromatic': It contains only a narrow band of wavelengths – but that was not to be known until the nineteenth century.

Yet there was no individual ray, no single refrangibility, corresponding to white. White light is not homogeneous, Newton argued, but is a 'Heterogeneous mixture of differently refrangible Rays.' The prism does not modify sunlight to yield colors: Rather it separates out the rays of different refrangibility that are promiscuously intermingled in the white light of a source such as the sun. If the rays of the spectrum are subsequently recombined, then a white is again produced.

In ordinary discourse, we most often use the word 'color' to refer to the hues of natural surfaces. The color of a natural body, Newton argued, is merely its disposition to reflect lights of some refrangibilities more than others. Today we should speak of the 'spectral reflectance' of a surface – the proportion of the incident light that is reflected at each wavelength. As Newton observed, an object that normally appears red in broadband, white light will appear blue if it is illuminated by blue light, that is, by light from the more refrangible end of the spectrum.

The mixing of colors, however, presented Newton with problems that he never fully resolved. Even in his first published paper, he had to allow that a mixture of two rays of different refrangibility could match the color produced by homogeneous light, light of a single refrangibility. Thus a mixture of red and yellow make orange; orange and yellowish green make yellow; and mixtures of other pairs of spectral colors will similarly match an intermediate color, provided that the components of the pair are not too separated in the spectrum. 'For in such mixtures, the component colours appear not, but, by their mutual allaying each other, constitute a midling colour'(Newton, 1671). So colors that looked the same to the eye might be 'original and simple' or might be compound, and the only way to distinguish them was to resolve them with a prism. Needless to say, this complication was to give difficulties for his contemporaries and successors (Shapiro, 1980).

White presented an especial difficulty. In his first paper, Newton wrote of white: 'There is no one sort of Rays which alone can exhibit this. 'Tis ever compounded, and to its composition are requisite all the aforesaid primary colours' (Newton, 1671). The last part of this claim was quickly challenged by Christian Huygens, who suggested that two colors alone (yellow and blue) might be sufficient to yield white (Huygens, 1673). There do, in fact, exist pairs of monochromatic lights that can be mixed to match white (they are now called 'complementary wavelengths'), but their existence was not securely established until the nineteenth century (see section 1.7.1). Newton himself always denied that two colors were sufficient, but the exchange with Huygens obliged him to modify his position and to allow that white could be compounded from a small number of components.

In his *Opticks*, first published in 1704, Newton introduces a forerunner of many later 'chromaticity diagrams,' diagrams that show quantitatively the results of mixing specific colors (Chapters 3 and 7). On the circumference of a circle (Figure 1.2) he represents each of the seven principal colors of the spectrum. At the center of gravity of each, he draws a small circle proportional to 'the number of rays of that sort in the mixture under consideration.' Z is then the center of gravity of all the small circles and represents the color of the mixture. If two separate mixtures of lights have a common center of gravity, then the two mixtures will match. If, for example, all seven of the principal spectral colors are mixed in the proportions in which they are present in sunlight, then Z will fall in the center of the diagram, and the mixture will match a pure white. Colors that lie on the circumference are the most saturated ('intense and florid in the highest degree'). Colors that lie on a line connecting the center with a point on the circumference will all exhibit the same hue but will vary in saturation.

This brilliant invention is a product of Newton's mature years: It apparently has no

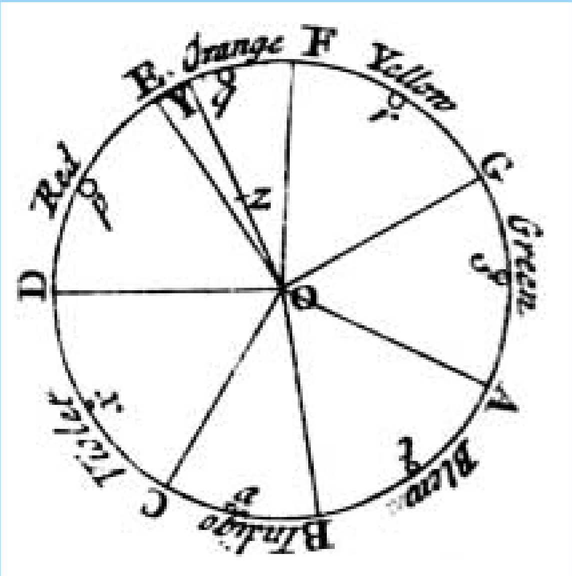


Figure 1.2 **Newton's color circle, introduced in his *Opticks* of 1704.**

antecedent in his published or unpublished writings (Shapiro, 1980). However, as a chromaticity diagram it is imperfect in several ways. First, Newton spaced his primary colors on the circumference according to a fanciful analogy with the musical scale, rather than according to any colorimetric measurements. Secondly, the two ends of the spectrum are apparently made to meet, and thus there is no way to represent the large gamut of distinguishable purples that are constructed by mixing violet and red light (although in the text, Newton does refer to such purple mixtures as lying near the line OD and indeed declares them 'more bright and more fiery' than the uncompounded violet). Thirdly, the circular form of Newton's diagram forbids a good match between, say, a spectral orange and a mixture of spectral red and spectral yellow – a match that normal observers can in fact make.

And in his text, Newton continues to deny one critical set of matches that his diagram does allow. The color circle implies that white could be matched by mixing colors that lie opposite one another on the circumference, but he writes:

> if only two of the primary Colours which in the circle are opposite to one another be mixed in an equal proportion, the point Z shall fall upon the centre O, and yet the Colour compounded of these two shall not be perfectly white, but some faint anonymous Colour. For I could never yet by mixing only two primary Colours produce a perfect white. Whether it may be compounded of a mixture of three taken at equal distances in the circumference, I do not know, but of four or five I do not much question but it may. But these are Curiosities of little or no moment to the understanding the Phaenomena of Nature. For in all whites produced by Nature, there uses to be a mixture of all sorts of Rays, and by consequence a composition of all Colours.
>
> (Newton, 1730)

In this unsatisfactory state, Newton left the problem of color mixing. To understand better his dilemma, and to understand the confusions of his successors, we must take a moment to consider the modern theory of color mixture. For the historian of science must enjoy a conceptual advantage over his subjects.

1.2 THE TRICHROMACY OF COLOR MIXTURE

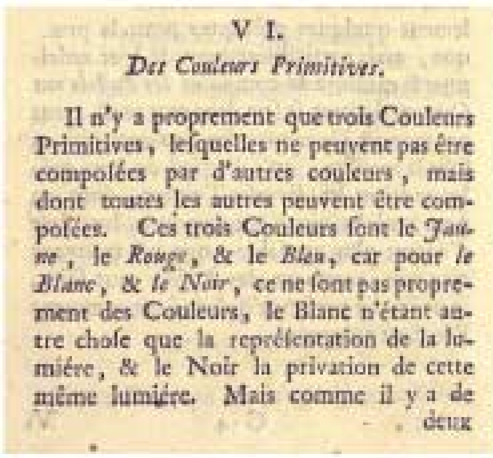
The most fundamental property of human color vision is *trichromacy*. Given three different colored lights of variable intensities, it is possible to mix them so as to match any other test light of any color. Needless to say, this statement comes with some small print attached. First, the mixture and the test light should be in the same context: If the mixture were in a dark surround and the test had a light surround, it might be impossible to equate their appearances (see Chapter 4). Two further limitations are (a) it should not be possible to mix two of the three variable lights to match the third, and (b) the experimenter should be free to mix one of the three variable lights with the test light.

There are no additional limitations on the colors that are to be used as the variable lights, and they may be either monochromatic or themselves broadband mixtures of wavelengths. Nevertheless, the three variable lights are traditionally called 'primaries'; and much of the historical confusion in color science arose because a clear distinction was not made between the primaries used in color mixing experiments and the colors that are primary in our phenomenological experience. Thus, colors such as red and yellow are often called 'primary' because we recognize in them only one subjective quality, whereas most people would recognize in orange the qualities of both redness and yellowness.

The trichromacy of color mixture in fact arises because there are just three types of cone receptor cell in the normal retina. They are known as long-wave, middle-wave and short-wave cones, although each is broadly tuned and their sensitivities overlap in the spectrum (Chapter 3). Each type of cone signals only the total number of photons that it is absorbing per unit time – its rate of 'quantum catch.' So to achieve a match between two adjacent patches of light, the experimenter needs only to equate the triplets of quantum catches in the two adjacent areas of the observer's retina. This, in essence, is the trichromatic theory of color vision, and it should be distinguished from the fact of trichromacy. The latter was recognized, in a simplified form, during Newton's lifetime. But for more than a century before the three-receptor theory was introduced, trichromacy was taken to belong to a different domain of science. It was taken as a physical property of light rather than as a fact of physiology. This category error held back the understanding of physical optics more than has been recognized.

The basic notion of trichromacy emerged in the seventeenth century. Already in 1686, Waller published in the *Philosophical Transactions of the Royal Society* a small color atlas with three primary or simple colors. A rather clear statement is found at the beginning of the eighteenth century in the 1708 edition of an anonymous treatise on miniature painting (Figure 1.3):

TRAITÉ
DE LA
PEINTURE
EN
MIGNATURE.
Pour apprendre aisément à Peindre sans Maître.
Ouvrage corrigé & augmenté sur le plan de l'ancien de diverses Instructions Préliminaires sur la Peinture en général, & de Préceptes sur le Dessein pour en faciliter l'Etude & la Pratique.
AUQUEL ON A AJOÛTÉ
Un petit Traité de la Peinture au Pastel, avec la Méthode de composer les Pastels.
La Maniére de Laver proprement toutes sortes de Plans.
Le Secret de faire les plus belles Couleurs, l'Or Bruny, l'Or en Coquille, & le Vernis de la Chine.
Avec une Explication par ordre Alphabetique de tous les Termes propres au Dessein & à la Peinture.
A LA HAYE,
Chez Louis & Henry van Dole, Marchands Libraires, dans le Pooten.
M. DCCVIII.



V I.
Des Couleurs Primitives.

Il n'y a proprement que trois Couleurs Primitives, lesquelles ne peuvent pas être composées par d'autres couleurs, mais dont toutes les autres peuvent être composées. Ces trois Couleurs sont le *Jaune*, le *Rouge*, & le *Bleu*, car pour *le Blanc*, & *le Noir*, ce ne sont pas proprement des Couleurs, le Blanc n'étant autre chose que la représentation de la lumiére, & le Noir la privation de cette même lumiére. Mais comme il y a de
deux

Figure 1.3 **An early statement of trichromacy, from an anonymous treatise on miniature painting, published at The Hague in 1708.**

> Strictly speaking there are only three primitive colors, that cannot themselves be constructed from other colors, but from which all others can be constructed. The three colors are yellow, red and blue, for white and black are not truly colors, white being nothing else but the representation of light, and black the absence of this same light.
> (Anonymous, 1708)

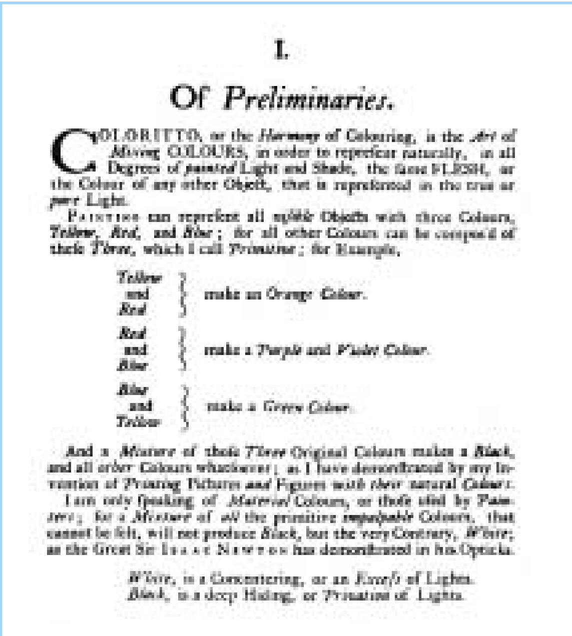
1.2.1 TRICHROMACY AND THE DEVELOPMENT OF THREE-COLOR REPRODUCTION

It is trichromacy – a property of ourselves – that makes possible relatively cheap color reproduction, by color printing, for example, and by color televisions and computer monitors (see Chapter 8). Three-color printing was developed nearly a century before the true nature of trichromacy was grasped. It was invented – and brought to a high level of perfection at its very birth – by Jacques Christophe Le Blon. This remarkable man was born in 1667 in Frankfurt am Main. It is interesting that Le Blon was working as a miniature painter in Amsterdam in 1708, when the anonymous edition of the *Traité de la Peinture en Mignature* was published at the Hague; and we know from unpublished correspondence, between the connoisseur Ten Kate and the painter van Limborch, that Le Blon was experimenting on color mixture during the years 1708–12 (Lilien, 1985).

In 1719, Le Blon was in London and he there secured a patent from George I to exploit his invention, which he called 'printing paintings.' Some account of his technique is given by Mortimer (1731) and Dossie (1758). To prepare each of his three printing plates, Le Blon used the technique of mezzotint engraving: a copper sheet was uniformly roughened with the finely serrated edge of a burring tool, and local regions were then polished, to varying degrees, in order to control the amount of ink that they were to hold. Much of Le Blon's development work went into securing three colored inks of suitable transparency; but his especial skill lay in his ability mentally to analyze into its components the color that was to be reproduced. Sometimes he used a fourth plate, carrying black ink. This manoeuvre, often adopted in modern color printing, allows the use of thinner layers of colored ink, so reducing costs and accelerating drying (Lilien, 1985).

In 1721, a company, The Picture Office, was formed in London to mass-produce color prints by Le Blon's method. Shares were issued at ten pounds and were soon selling at a premium of 150%, but Le Blon proved a poor manager and the enterprise failed. In 1725, however, he published a slender volume entitled *Coloritto*, in which he sets out the principle of trichromatic color mixing (Figure 1.4). It is interesting that he gives the same primaries in the same order (Yellow, Red, and Blue) as does the anonymous author of the 1708 text, and uses the same term for them, *Couleurs primitives*.

Notice that Le Blon distinguishes between the results of superposing lights and of mixing pigments. Today we should call the former 'additive color mixture' and the latter, 'subtractive color mixture.' Pigments typically absorb light predominantly at some wavelengths and reflect or transmit light at other wavelengths. Where Le Blon superposes two different colored inks, the light reaching the eye is dominated by those wavelengths that happen not to be absorbed by either of the inks. It was not until the nineteenth century that there was a widespread recognition that



I.

Of *Preliminaries.*

COLORITTO, or the *Harmony* of Colouring, is the *Art* of *Mixing* COLOURS, in order to represent naturally, in all Degrees of *painted* Light and Shade, the same FLESH, or the Colour of any other Object, that is represented in the true or pure Light.

PAINTING can represent all visible Objects with three Colours, *Yellow*, *Red*, and *Blue*; for all other Colours can be compos'd of these *Three*, which I call *Primitive*; for Example,

Yellow and *Red* } make an *Orange Colour*.

Red and *Blue* } make a *Purple* and *Violet Colour*.

Blue and *Yellow* } make a *Green Colour*.

And a *Mixture* of those *Three Original* Colours makes a *Black*, and all other Colours whatsoever; as I have demonstrated by my Invention of *Printing Pictures and Figures with their natural Colours*.

I am only speaking of *Material* Colours, or those used by *Painters*; for a *Mixture* of *all* the primitive *impalpable* Colours, that cannot be felt, will not produce *Black*, but the very Contrary, *White*; as the Great Sir ISAAC NEWTON has demonstrated in his Opticks.

White, is a Concentering, or an *Excess* of Lights.
Black, is a deep Hiding, or *Privation* of Lights.

Figure 1.4 **From J.C. Le Blon's *Coloritto* published in London in 1725.**

additive and subtractive mixture differ not only in the lightness or darkness of the product but also in the hue that may result (see section 1.7.1).

Le Blon himself explored a form of additive mixture. In his patent method of weaving tapestries, he juxtaposed threads of the primitive colors to achieve intermediate colors. An account is given by Cromwell Mortimer (1731):

> Thus Yellow and Red produce an Orange, Yellow and Blue a Green, Etc. which seems to be confirmed by placing two Pieces of Silk near together; viz. Yellow and Blue: When by intermixing of their reflected Rays, the Yellow will appear of a light Green, and the Blue of a dark Green; which deserves the farther Consideration of the Curious.

The phenomenon that Mortimer describes here is probably the same as the 'optical mixture' or 'assimilation' later exploited by Signac and the neo-impressionists (Rood, 1879; Mollon, 1992); and it still exercises the Curious (see Chapter 4). Some neural channels in our retina integrate over larger areas than do others, and this may be why, at a certain distance from a tapestry, we can see the spatial detail of individual threads while yet we pool the colors of adjacent threads. From Mortimer's account, it seems that Le Blon thought that the mixing was optical, and this will certainly be the case when the tapestry is viewed from a greater distance. However, a naturally-lit tapestry consisting of red, yellow, and blue threads can never simulate a white. For each of the threads necessarily absorbs some portion of the incident light, and in conventionally lit scenes we perceive as white only a surface that reflects almost all the visible radiation incident on it. In his weaving enterprise, Le Blon did not have the advantage of a white vehicle for his colors, such as he had when printing on paper. The best that he was able to achieve from adjacent red, yellow, and blue threads was a 'Light Cinnamon'. Similarly, since the three threads always reflect some light, it is impossible to simulate a true black within the tapestry. So Le Blon was obliged to use white and black threads in addition. And – Mortimer adds – 'tho' he found he was able to imitate any Picture with these five Colours, yet for Cheapness and Expedition, and to add a Brightness where it was required, he found it more convenient to make use of several intermediate Degrees of Colours.'

Sadly, Le Blon's weaving project did not prosper any better than the Picture Office. He was, however, still vigorous – at the age of 68 he fathered a daughter – and in 1737, Louis XV gave him an exclusive privilege to establish color printing in France. He died in 1741, but his printing technique was carried on by Jaques Gautier D'Agoty, who had briefly worked for him and who was later to claim falsely to be the inventor of the four-color method of printing, using three colors and black. Figure 1.5 – the first representation of the spectrum to be printed in color – was published by Gautier D'Agoty in 1752.

Le Blon himself did not acknowledge any contradiction between his practical trichromacy and Newtonian optics; but his successor, Gautier D'Agoty, was vehemently anti-Newtonian. He held that rays of light are not intrinsically colored or colorific. The antagonistic interactions of

Figure 1.5 **The first representation of Newton's spectrum to be printed in color. From the *Observations sur l'Histoire Naturelle* of Gautier D'Agoty, 1752.**

light and dark (‘*Les seules oppositions de l’ombre & de la lumiere, & leur transparence*’) produce three secondary colors, blue, yellow, and red, and from these, the remaining colors can be derived (Gautier D’Agoty, 1752).

1.2.2 TRICHROMACY IN OPPOSITION TO NEWTONIAN OPTICS

As the eighteenth century progressed, increasingly sophisticated statements of trichromacy were published, but their authors invariably found themselves in explicit or implicit opposition to the Newtonian account, in which there are seven primary colors or an infinity.

The anti-Newtonian Jesuit Louis Bertrand Castel (1688–1757) identified blue, yellow, and red as the three primitive colors from which all others could be derived. In his *Optique des Couleurs* of 1740, he gives systematic details of the intermediate colors produced by mixing the primaries. Father Castel was aware that phenomenologically there are more distinguishable hues between pure red and pure blue than between blue and yellow or between yellow and red – as is clear in the later Munsell system. By informal experiments he established a color circle of twelve equally spaced hues: Blue, celadon (sea-green), green, olive, yellow, fallow, nacarat (orange-red), red, crimson, purple, agate, purple-blue (Castel, 1740). These he mapped on to the musical scale, taking blue as the keynote, yellow as the third, and red as the fifth.

In his time, Castel was most celebrated for his scheme for a *clavecin oculaire* – the first color organ. For many years, the *clavecin oculaire* was a strictly theoretical entity, for Père Castel insisted that he was a *philosophe* and not an artisan. Nevertheless, there was much debate as to whether there could be a visual analogue of music. Tellemann wrote approvingly of the color organ, but Rousseau was critical, arguing that music is an intrinsically sequential art whereas colors should be stable to be enjoyed. Eventually, practical attempts seem to have been made to build a *clavecin oculaire* (Mason, 1958). A version exhibited in London in 1757 was reported to comprise a box with a typical harpsichord keyboard in front, and about 500 lamps behind a series of 50 colored glass shields, which faced back towards the player and viewer. The idea has often been revived in the history of color theory (Rimington, 1912).

One of the most distinguished trichromatists of the eighteenth century was Tobias Mayer, the Göttingen astronomer. He read his paper ‘*On the relationship of colors*’ to the Göttingen scientific society in 1758, but only after his death was it published, by G.C. Lichtenberg (Forbes, 1971; Mayer, 1775; Lee, 2001). He argued that there are only three primary colors (*Haupfarben*), not the seven of the Newtonian spectrum. The *Haupfarben* can be seen in good isolation, if one looks through a prism at a rod held against the sky: On one side you will see a blue strip and on the other a yellow and a red strip, without any mixed colors such as green (Forbes, 1970). Here Mayer, like many other eighteenth-century commentators, neglects Newton’s distinction between colors that look simple and colors that contain light of only one refrangibility. For an analysis of the ‘boundary colors’ observed by Mayer and later by Goethe, see Bouma (1947).

Mayer introduced a color triangle, with the familiar red, yellow, and blue primaries at its corners. Along the sides, between any two *Haupfarben*, were 11 intermediate colors, each being described quantitatively by the amounts of the two primaries needed to produce them. Mayer chose this number because he believed that it represented the maximum number of distinct hues that could be discerned between two primaries. By mixing all three primary colors, Mayer obtained a total of 91 colors, with gray in the middle. By adding black and white, he extended his color triangle to form a three-dimensional color solid, having the form of a double pyramid. White is at the upper apex and black at the lower.

A difficulty for Mayer was that he was offering both a chromaticity diagram and a ‘color-order system.’ The conceptual distinction between these two kinds of color space had not yet been made. A chromaticity diagram tells us only what lights or mixtures of lights will match each other. Equal distances in a chromaticity diagram do not necessarily correspond to equal perceptual distances. A color-order system, on the other hand, attempts to arrange colors so that they are uniformly spaced in phenomenological experience (see Chapters 3, 4 and 7).

One advance came quickly from J.H. Lambert, the astronomer and photometrist, who realized that the chosen primary colors might not be equal in their coloring powers (*la gravité spécifique des couleurs*) and would need to be given different weightings in the equations (Lambert, 1770). He produced his own color pyramid (Figure 1.6), realized in practice by mixing pigments with wax (Lambert,1772). The apex of the pyramid was white. The triangular base had red, yellow, and blue primaries at its apices, but black in the middle, for Lambert's system was a system of subtractive color mixture (section 1.7.1). He was explicit about this, suggesting that each of his primary pigments gained its color by absorbing light corresponding to the other two primaries. He made an analogy with colored glasses: If a red, a yellow, and a blue glass were placed in series, no light was transmitted.

Other eighteenth-century trichromatists were Marat (1780) and Wünsch (1792). Particularly anti-Newtonian was J.P. Marat, who, rejected by the *Académie des Sciences*, became a prominent figure in the French Revolution. He had the satisfaction of seeing several *académiciens* go to the guillotine, before he himself died at the hand of Charlotte Corday.

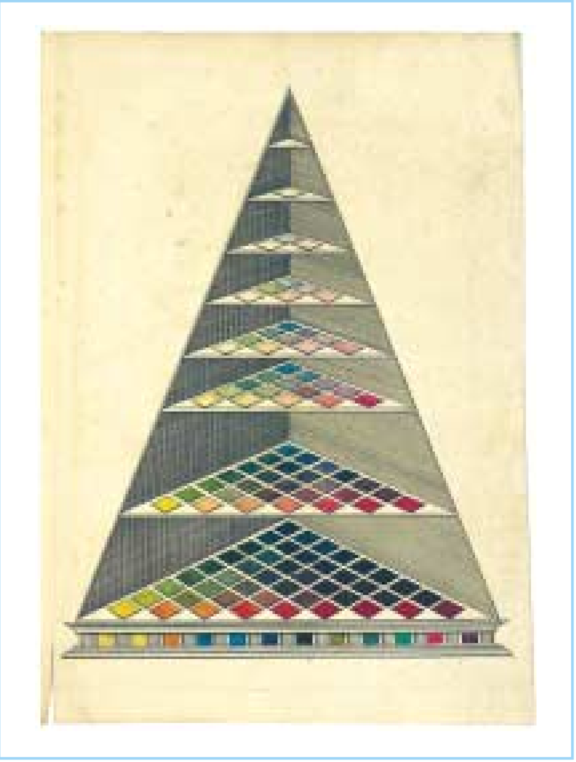


Figure 1.6 **The *Farbenpyramide* of J.H. Lambert (1772). Reproduced with permission of J.D. Mollon.**

1.2.3 THE MISSING CONCEPT OF A SENSORY TRANSDUCER

It has been said (Brindley, 1970) that trichromacy of color mixing is implicit in Newton's own color circle and center-of-gravity rule (see Figure 1.2). Yet this is not really so. If you choose as primaries any three points on the circumference, you can match only colors that fall within the inner triangle. To account for all colors, you must have imaginary primaries that lie outside the circle. And for Newton such imaginary primaries would have no meaning.

The reason is that Newton, and most of his eighteenth-century successors, lacked the concept of a tuned transducer, that is a receptor tuned to only part of the physical spectrum. It was generally supposed that the vibrations occasioned by a ray of light were directly communicated to the sensory nerves, and thence transmitted to the sensorium. Here are two characteristic passages from the *Queries* at the end of Newton's *Opticks*:

> *Qu* 12. Do not the Rays of Light in falling upon the bottom of the Eye excite Vibrations in the Tunica Retina? Which Vibrations, being propagated along the solid Fibres of the optick Nerves into the Brain, cause the Sense of seeing . . .
>
> *Qu*. 14. May not the harmony and discord of Colours arise from the proportions of the Vibrations propagated through the Fibres of the optick Nerves into the Brain, as the harmony and discord of Sounds arise from the proportions of the Vibrations of the Air? For some Colours, if they be view'd together are agreeable to one another, as those of Gold and Indigo, and others disagree . . .
>
> (Newton, 1730)

This was an almost universal eighteenth-century view: The vibrations occasioned by light were directly transmitted along the nerves. Since such vibrations could vary continuously in frequency, there was nothing in the visual system that could impose trichromacy. So the explanation of trichromacy was sought in the physics of the world.

Sometimes indeed, there was a recognition of the problem of impedance matching. Here is a rather telling passage from Gautier D'Agoty, written in commentary on his anatomical prints of the sense organs:

> The emitted and reflected ray is a fluid body, whose movement stimulates the nerves of the retina, and would end its action there, without causing us any sensation, if on the retina there were not nerves for receiving and communicating its movement and its various vibrations as far as our sense; but for this to happen, a nerve that receives the action of a ray composed of fluid matter (as is that of the fire that composes the ray) must also itself be permeated with the same matter, in order to receive the same modulation; for if the nerve were only like a rod, or like a cord, as some suppose, this luminous modulation would be reflected and could never accommodate itself to a compact and solid thread of matter . . .
>
> (Gautier D'Agoty, 1775)

An early hint of the existence of specific receptors can be found in a paper given to the St Petersburg Imperial Academy in July 1756 by Mikhail Vasil'evich Lomonosov. Both a poet and a scientist, Lomonosov established a factory that made mosaics and so he had practical experience of the preparation of colored glasses (Leicester, 1970). His paper concentrates on his physical theory of light. Space is permeated by an ether that consists of three kinds of spherical particle, of very different sizes. Picture to yourself, he suggests, a space packed with cannon balls. The interstices between the cannon balls can be packed with fusilier bullets, and the spaces between those with small shot. The first size of ether particle corresponds to salt and to red light; the second to mercury and to yellow light; and the third to sulfur and to blue light. Light of a given color consists in a gyratory motion of a given type of particle, the motion being communicated from one particle to another. In passing, Lomonosov suggests a physiological trichromacy to complement his physical trichromacy: the three kinds of particle are present in the 'black membrane at the bottom of the eye' and are set in motion by the corresponding rays (Lomonosov, 1757; Weale, 1957).

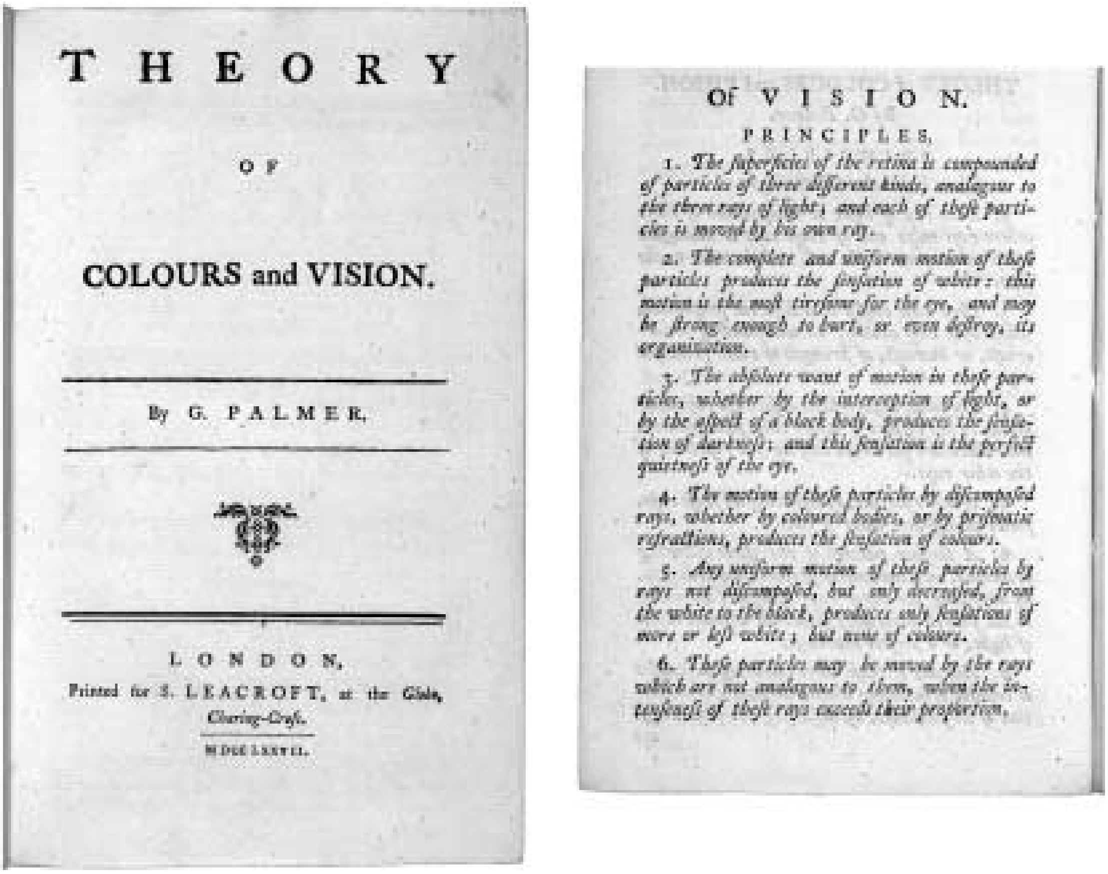
In the *Essai de Psychologie* of Charles Bonnet (1755) we find the idea of retinal resonators combined with a conventionally Newtonian account of light. Bonnet, however, supposed that for every degree of refrangibility there must be a resonator, just as – he suggested – the ear contains many different fibers that correspond to different tones. So each local region of the retina is innervated by fascicles, which consist of seven principal fibers (corresponding to Newton's principal colors); the latter fibers are in turn made up of bundles of fibrillae, each fibrilla being specific for an intermediate nuance of color. Bonnet was not troubled that this arrangement might be incompatible with our excellent spatial resolution in central vision.

In the last quarter of the eighteenth century, the elements of the modern trichromatic theory emerge. Indeed, all the critical concepts were present in the works of two colorful men, who lived within a kilometer of each other in the London of the 1780s. Each held a complementary part of the solution, but neither they nor their contemporaries ever quite put the parts together.

1.2.3.1 George Palmer

One of these two men was George Palmer. Gordon Walls (1956), in an engaging essay, described his fruitless search for the identity of this man. It was Walls' essay that first prompted my own interest in the history of color theory. In fact, Palmer was a prosperous glass-seller and, like Lomonosov, a specialist in stained glass (Mollon, 1985, 1993). He was born in London in 1740 and died there in 1795. His business was based in St Martin's Lane, but for a time in the 1780s he was also selling colored glass in Paris. His father, Thomas, had supplied stained glass for Horace Walpole's gothick villa at Strawberry Hill and enjoys a walk-on part in Walpole's letters (Cunningham, 1857).

George Palmer represents an intermediate stage in the understanding of trichromacy, for he was, like Lomonosov, both a physical and a physiological trichromatist. In a pamphlet published in 1777 and now extremely rare, he supposes that there are three physical kinds of light and three corresponding particles in the retina (Palmer, 1777b). In later references, he speaks of three kinds of 'molecule' or 'membrane'. The uniform motion of the three types of particle produces a sensation of white (Figure 1.7). His



THEORY

OF

COLOURS and VISION.

By G. PALMER.

LONDON,
Printed for S. LEACROFT, at the Globe, Charing-Cross.
MDCCLXXVII.

OF VISION.

PRINCIPLES.

1. The superficies of the retina is compounded of particles of three different kinds, analogous to the three rays of light; and each of these particles is moved by his own ray.

2. The complete and uniform motion of these particles produces the sensation of white: this motion is the most tiresome for the eye, and may be strong enough to hurt, or even destroy, its organization.

3. The absolute want of motion in these particles, whether by the interception of light, or by the effect of a black body, produces the sensation of darkness; and this sensation is the perfect quietness of the eye.

4. The motion of these particles by discomposed rays, whether by coloured bodies, or by prismatic refractions, produces the sensation of colours.

5. Any uniform motion of these particles by rays not discomposed, but only decreased, from the white to the black, produces only sensations of more or less white; but none of colours.

6. These particles may be moved by the rays which are not analogous to them, when the intenseness of these rays exceeds their proportion.

Figure 1.7 **George Palmer's proposal that the retina contains three classes of receptor, in his *Theory of Colours and Vision* of 1777. Only four copies of this monograph are known to survive.**

1777 essay attracted little support in Britain. The only review of this proto-trichromatic theory was one line in the *Monthly Review*: 'A *visionary* theory without *colour* of truth or probability.' In the French-speaking world, however, his ideas were better received: A translation of the pamphlet (Palmer, 1777a) attracted an extravagant review in the *Journal Encyclopédie*.

Once equipped with the idea of a specific receptor, Palmer ran with it. In 1781 in a German science magazine, his explanation of color blindness is discussed, although his name is there given mysteriously as 'Giros von Gentilly' while 'Palmer' is said to be a pseudonym (Voigt, 1781). He is reported to say that color blindness arises if one or two of the three kinds of molecules are inactive or are constitutively active (Mollon, 1997). In a later pamphlet published in Paris under his own name (Palmer, 1786), Palmer suggests that complementary color aftereffects arise when the three kinds of fiber are differentially adapted – an explanation that has been dominant ever since. To explain the 'flight of colors,' the sequence of hues seen in the afterimage of a bright white light, Palmer proposes that the different fibers have different time constants of recovery. And to explain the *Eigenlicht*, the faint light that we see in total darkness, he invokes residual activity in the fibers.

Another modern concept introduced by George Palmer is that of artificial daylight. In 1784, the Genevan physicist Ami Argand introduced his improved oil-burning lamp (Heyer, 1864; Schrøder, 1969). In its day, the Argand lamp revolutionized lighting. It is difficult for us today to appreciate how industry, commerce, entertainment, and domestic life were restricted by the illuminants available until the late eighteenth century. Argand increased the brilliance of the oil lamp by increasing the flow of air past the wick. He achieved this by two devices. First, he made the wick circular so that air could pass through its center, and second, he mounted above it a glass chimney. Unable, however, to secure suitable heat-resistant glass in France, he went to England in search of the flint glass that was an English specialty at the time. While he was gone, the lamp was pirated in Paris by an apothecary called Quinquet, who was so successful a publicist that his name became an eponym for the lamps. For a time, however, Quinquet had a partner, no other than George Palmer – and Palmer's contribution was clever: He substituted blue glass for Argand's clear glass, so turning the yellowish oil light into artificial daylight. Characteristically, this novel idea was set out in a pamphlet given away to customers (Palmer, 1785). The selling line was that artisans in trades concerned with color could buy the Quinquet–Palmer lamp, work long into the night, and so outdo their competitors. Palmer even proposed a pocket version that would allow physicians correctly to judge the color of blood or urine during the hours of darkness. The concept of artificial daylight appears again in a monograph by G. Parrot (1791).

George Palmer never took the final step of realizing that the physical variable is a continuous one. Living only streets away from him in 1780 was another tradesman, John Elliot, who postulated transducers sensitive to restricted regions of a continuous physical spectrum – but who never restricted the number of transducers to three (Mollon, 1987; in press).

1.2.3.2 John Elliot MD

Elliot was a man of a melancholic disposition, the opposite of the outgoing entrepreneur, George Palmer. It was said of him that he was of a sallow complexion and had the appearance of a foreigner, although he was born in Chard in Somerset in 1747. At the age of 14, he was bound apprentice to an apothecary in Spitalfields, London. At the expiry of his time, he became assistant in Chandler's practice in Cheapside and – if we are to believe the *Narrative of the Life and Death of John Elliot MD* (Anonymous, 1787) – it was during this period that he first established a romantic attachment to Miss Mary Boydell, whose many attractions included an Expectation – to be precise, an expectation of £30 000 on the death of her uncle, Alderman Boydell. Miss Boydell encouraged and then rejected the clever young apothecary. By 1780, Elliot was in business on his own, first in Carnaby Market and then, as he prospered, in Great Marlborough Street (Partington and McKie, 1941).

In his *Philosophical Observations on the Senses* (Elliot, 1780), he described simple experiments in which he mechanically stimulated his own eyes and ears, and was led to an anticipation of Johannes Mueller's 'Doctrine of Specific Nerve Energies' (Müller, 1840). Our sense organs, Elliot argued, must contain resonators – transducers – that are normally stimulated by their appropriate stimulus but can also be excited mechanically:

> there are in the retina different times of vibration liable to be excited, answerable to the time of vibration of different sorts of rays. That any one sort of rays, falling on the eye, excite those vibrations, and those only which are in unison with them . . . And that in a mixture of several sorts of rays, falling on the eye, each sort excites only its unison vibrations, whence the proper compound colour results from a mixture of the whole.
>
> (Elliot, 1780)

He develops his ideas in his *Elements of Natural Philosophy*, a work intended for medical students, which was first published in 1792 and then in a second edition in 1796. So modern is Elliot's account that it deserves quoting at length:

> The different colours, like notes of sound, may be considered as so many gradations of tone; for they are caused by vibrations of the rays of light beating on the eye, in like manner as sounds are caused by vibrations or pulses of the air beating on the ear. Red is produced by the slowest vibrations of the rays, and violet by the quickest . . .
>
> If the red-making rays fall on the eye, they excite the red-making vibrations in that part of the retina whereon they impinge, but do not excite the others because they are not in unison with them . . . From hence it may be understood that the rays of light do not cause colours in the eye any otherwise than by the mediations of the

> vibrations or colours liable to be excited in the retina; the colours are occasioned by the latter; the rays of light only serve to excite them into action. So likewise if blue- and yellow-making rays fall together on the same part of the retina, they excite the blue- and yellow-making vibrations respectively, but because they are so close together as not be distinguished apart, they are perceived as a mixed colour, or green; the same as would be caused by the rays in the midway between the blue- and yellow-making ones. And if all sorts of rays fall promiscuously on the eye, they excite all the different sorts of vibrations; and as they are not distinguishable separately, the mixed colour perceived is white; and so of other mixtures.
>
> We are therefore perhaps to consider each of these vibrations or colours in the retina, as connected with a fibril of the optic nerve. That the vibration being excited, the pulses thereof are communicated to the nervous fibril, and by that conveyed to the sensory, or mind, where it occasions, by its action, the respective colour to be perceived . . .
>
> (Elliot, 1786)

Elliot suggests that each of the several types of resonator is multiplied many times over, throughout the retina, the different types being completely intermingled. As we shall see later, his physiological insight was to lead him to the important physical insight that there might exist frequencies for which we have no resonators. Yet his life was to be brought to its unhappy end before he could make the final step of suggesting that there were only three classes of resonator in the retina.

The year 1787 found Elliot again obsessed with Miss Boydell and increasingly disturbed in his behavior. He bought two brace of pistols. He filled one pair with shot, and the other with blanks – or so the Defense claimed at the trial. On 9 July he came up behind Miss Boydell, who was arm in arm with her new companion, George Nichol. Elliot fired at Miss Boydell, but was seized by Nichol before he could shoot himself, as he apparently intended. By 16 July he was on trial at the Old Bailey. The prosecution insisted that the pistols had been loaded and that Miss Boydell had been saved only by her whalebone stays. The Jury found Elliot not guilty, but the Judge committed him to Newgate Gaol nevertheless, to be tried for assault (Hodgson, 1787). He died there on 22 July 1787.

1.2.3.3 Thomas Young

We have seen that all the conceptual elements of the trichromatic theory were available in the last quarter of the eighteenth century. However, the final synthesis was achieved only in 1801, by Thomas Young.

Young was born in Somerset in 1773, the eldest of ten children of a prosperous Quaker (Wood, 1954). His first scientific paper was on the mechanism of visual accommodation, a paper that secured his election to the Royal Society at the early age of 21. There is no evidence that Young himself ever performed systematic experiments on color mixing, but we do know that he was familiar with the evidence for trichromacy that had accumulated by the end of the eighteenth century. Intent on a medical career, he spent the academic year of 1795–96 at the scientifically most distinguished university in the realms of George III, the Georg-August University in Göttingen. We know from his own records that he there attended the physics lectures of G.C. Lichtenberg at 2 p.m. each day (Peacock, 1855); and from a transcript of these lectures got out by Gamauf (1811), we know that Young would have heard about the color-mixing experiments of Tobias Mayer, about the color triangle and the double pyramid formed from it, as well as about colored after-images and simultaneous color contrast.

After leaving Göttingen, Young spent a period at Emmanuel College, Cambridge, but by 1800 he was resident in London, having inherited the house and fortune of a wealthy uncle. In 1801, in a lecture to the Royal Society, he put forward the trichromatic theory of vision in a recognizable form. Adopting a wave theory of light, he grasped that the physical variable was wavelength and was continuous, whereas the trichromacy of color matching was imposed by the physiology of our visual system. The retina must contain just three types of sensor or resonator. Each resonator has its peak in a different part of the spectrum, but is broadly tuned, responding to a range of wavelengths.

> Now, as it is almost impossible to conceive each sensitive point of the retina to contain an infinite number of particles, each capable of vibrating in perfect unison with every possible undulation, it becomes necessary to suppose the number

> limited, for instance, to the three principal colours, red, yellow, and blue, of which the undulations are related in magnitude nearly as the numbers 8, 7, and 6; and that each of the particles is capable of being put in motion less or more forcibly, by undulations differing less or more from a perfect unison; for instance, the undulations of green light being nearly in the ratio of 6½, will affect equally the particles in unison with yellow and blue, and produce the same effect as a light composed of those two species: and each sensitive filament of the nerve may consist of three portions, one for each principal colour . . .
>
> (Young, 1802a)

Notice that in this first account Young does not refer explicitly to the trichromacy of color mixture; and he remains hesitant about the number of resonators. Later, in his article 'Chromatics' for *Encyclopaedia Britannica* (Young, 1817) he is firmer, now taking the three distinct 'sensations' to be red, green, and violet. The rays occupying intermediate places in the Newtonian spectrum excite mixed 'sensations,' so monochromatic yellow light excites both the red and green 'sensations' and monochromatic blue light excites the violet and the green 'sensations.' He is distinguishing here between the excitations of the nerves ('sensations of the fibres') and phenomenological experience: 'the mixed excitation producing in this case, as well as in that of mixed light, a simple idea only.' He realized – and it took others a long time to follow – that we cannot assume that the phenomenologically simplest hues (say, red, yellow, blue) necessarily correspond to the peak sensitivities of the receptors.

Thomas Young did not accurately know the spectral sensitivities of the three receptors, but he had overcome the category error that had held back color science since Newton. Clerk Maxwell was later to say, in a lecture to the Royal Institution: 'So far as I know, Thomas Young was the first who, starting from the well-known fact that there are three primary colours, sought for the answer to this fact, not in the nature of light, but in the constitution of man' (Maxwell, 1871).

1.3 INTERFERENCE COLORS

Yet Thomas Young's insight into sensory physiology was secondary to his contribution to color physics. Of his several legacies to modern science, none has been more significant than his generalized concept of interference. The colors of thin plates – the colors observed in soap bubbles and films of oil – had intrigued Hooke and Boyle and were measured systematically by Newton. But Newton, although he applied the concept of interference to explain the anomaly of tides in the Gulf of Tonking (Newton, 1688), and although he knew that the colors of thin films were periodic in character, did not make the leap that Thomas Young was to make a century later.

In order to quantify the conditions that gave rise to the colors of thin films, Newton pressed a convex lens of long focal length against a glass plate (Figure 1.8). Knowing the curvature of the convex surface, he could estimate accurately the thickness of the air film at a given distance from the point of contact. When white light was

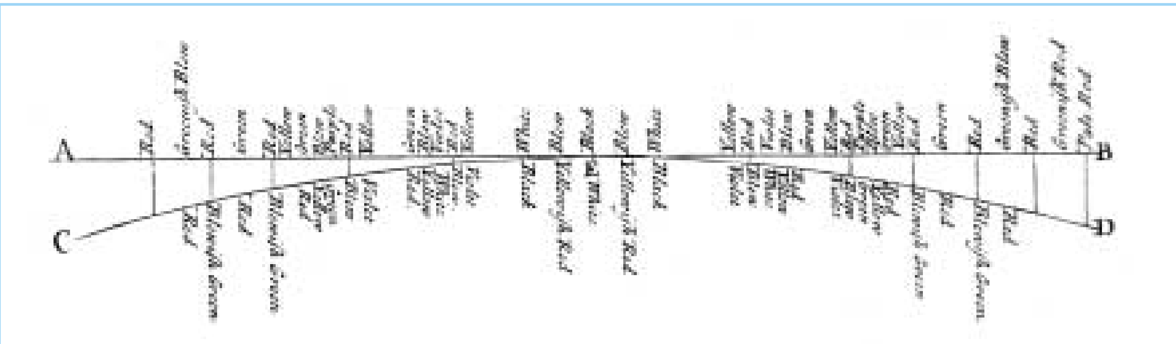


Figure 1.8 **Newton's representation of the colors seen when a convex lens is pressed against a glass plate.**

allowed to fall normally on the air film, Newton observed several series of concentric rings of color. If observations were made of light that had passed through both the lens and the plate, then colored rings were again seen, but these were complementary in hue to those seen by reflection from the plate. If light from only one part of the spectrum were used, then isolated bright bands were seen at certain distances from the central point. Newton supposed that each of the constituent colors of white light produced its own system of rings and that the colors seen with a white illuminant were due to the overlapping of the individual components. When using light of one color only, he could measure about 30 successive rings; and he found that in moving from one ring to the next, the corresponding thickness of the air film always increased by the same amount (Newton, 1730). Newton's own explanation was in terms of 'fits of easy reflection' and 'fits of easy transmission.' He supposed that a ray of light in a refracting medium alternates between two states ('fits'). In one state, the light is disposed to be reflected, in the other it is disposed to be transmitted. The rate of alternation between the two states varied with the color of the light (Shapiro, 1993).

Thomas Young was led to the concept of interference by his study of acoustics (Mollon, 2002). At Göttingen in 1796, to satisfy one of the requirements for his degree, he gave a lecture on the human voice (Peacock, 1855). Proceeding to Emmanuel College, Cambridge, he planned to prepare a paper on this subject, but 'found himself at a loss for a perfect conception of what sound was' and so set about collecting all the information he could, from books and from experiment (Young, 1804). A contemporary at Emmanuel wrote of him 'His rooms had all the appearance of belonging to an idle man . . . I once found him blowing smoke through long tubes.' He was soon to use the concept of interference to explain auditory beats – the waxing and waning of loudness that is heard as two tones of very similar pitch drift in and out of phase (Young, 1800).

Legend holds that Young was prompted to think about interference by observing the ripples generated by a pair of swans on the pond in Emmanuel College, and certainly he explicitly sets out such a lacustrine model in the pamphlet he wrote to defend his theory against the criticisms of Henry Brougham:

> Suppose a number of equal waves of water to move upon the surface of a stagnant lake, with a certain constant velocity, and to enter a narrow channel leading out of the lake. Suppose then another similar cause to have excited another equal series of waves, which arrive at the same channel at the same time, with the same velocity, and at the same time as the first. Neither series of waves will destroy the other, but their effects will be combined: if they enter the channel in such a manner that the elevations of one series coincide with those of the other, they must together produce a series of greater joint elevations; but if the elevations of one series are so situated as to correspond to the depressions of the other, they must exactly fill up those depressions, and the surface of the water must remain smooth; at least I can discover no alternative, either from theory or from experiment.
>
> (Young, 1804)

By his own account, it was only in May 1801 that Young realized that interference could explain the colors of thin plates. He supposed that light consisted of waves in an all-pervading ether. Different wavelengths corresponded to different hues, the shortest wavelengths appearing violet, the longest, red. In his initial model, however, the undulations were longitudinal – that is, along the line of the ray – rather than transverse, as Fresnel was later to show them to be.

In his Bakerian Lecture of November 1801, Young proposed that the colors of thin films depended on constructive and destructive interference between light reflected at the first surface and light reflected at the second: When the peak of one wave coincides with the trough of another, the two will cancel, but when the path length of the second ray is such that the peaks coincide for a given wavelength, then the hue corresponding to that wavelength will be seen (Young, 1802a). The first published account is in the *Syllabus* of his Royal Institution lectures:

> When two portions of the same light arrive at the eye by different routes, either exactly or very nearly in the same direction, the appearance or disappearance of various colours is determined by the greater or less difference in the lengths of the paths: the same colour recurring, when the intervals are multiples of a length, which, in the same

> medium, is constant, but in different mediums, varies directly as the sine of refraction.
>
> (Young, 1802b)

By applying his interference hypothesis to Newton's measurements of the colors of thin films, Young achieved the first accurate mapping of colors to the underlying physical variable. Figure 1.9 reproduces his table of the wavelengths that correspond to particular hues (Young, 1802a). Once converted from fractions of an inch to nanometers, the estimates closely resemble modern values. Particularly striking is the wavelength given for yellow, since it is in this region of the spectrum that hue changes most rapidly with wavelength. Young's value converts to 576 nm and this is within a nanometer of modern estimates of the wavelength that appears 'unique' yellow, the yellow that looks neither reddish nor greenish to an average eye in a neutral state of adaptation (Ayama *et al.*, 1987). His values for orange, green, and violet are very reasonable. The value for blue, 497 nm, is a longer wavelength than would be taken as the exemplar of blue today, but Newton's 'blew,' in a spectrum that had to accommodate indigo, may have been close to cyan, resembling the modern Russian *golyboi*. Indeed, we may have here an interesting explanation for Newton's statement that a mixture of spectral yellow and spectral blue makes green (Newton, 1671), a statement that has exercised historians of science (Shapiro, 1980).

It is in the same Bakerian lecture that Young made the first suggestion that interference also

Colours.	Length of an Undulation in parts of an Inch, in Air.	Number of Undulations in an Inch.	Number of Undulations in a Second.	Wavelength nm
Extreme -	.0000266	37640	463 millions of millions	
Red - -	.0000256	39180	482	650
Intermediate	.0000246	40720	501	
Orange - -	.0000240	41610	512	609
Intermediate	.0000235	42510	523	
Yellow -	.0000227	44000	542	576
Intermediate	.0000219	45600	561 (= 2^{48} nearly)	
Green - -	.0000211	47460	584	536
Intermediate	.0000203	49320	607	
Blue - -	.0000196	51110	629	497
Intermediate	.0000189	52910	652	
Indigo - -	.0000185	54070	665	469
Intermediate	.0000181	55240	680	
Violet - -	.0000174	57490	707	444
Extreme - -	.0000167	59750	735	

Figure 1.9 **Thomas Young's table of the wavelengths corresponding to particular hues. Conversions to nanometers have been added to the right. (From his Bakerian Lecture published in 1802.)**

accounts for the colors seen when light falls on striated surfaces (Young, 1802a). Young noted the systematic variation in hue as he rotated a pair of finely ruled lines at different angles to an incident beam, so anticipating the diffraction gratings that are today widely used in monochromators and spectroradiometers (Chapter 7).

As far as I am aware, the earlier literature holds no approximations to the Table of Figure 1.9. Thomas Young reached modern values in one leap. Yet it is important to realize that his accuracy is a tribute to the precision of Newton's measurements, made in the seventeenth century. Although Young's two-slit demonstration of optical interference (Young, 1807) has probably been even more influential in modern physics than Newton's prismatic experiments, it has to be said that Young was not by inclination an experimentalist. His first biographer, Hudson Gurney records:

> he was afterwards accustomed to say, that at no period of his life was he particularly fond of repeating experiments or even of very frequently attempting to originate new ones; considering that, however necessary to the advancement of science, they demanded a great sacrifice of time, and that when the fact was once established, that time was better employed in considering the purposes to which it might be applied, or the principles which it might tend to elucidate.
>
> (Gurney, 1831)

1.4 THE ULTRA-VIOLET, THE INFRA-RED, AND THE SPECTRAL SENSITIVITY OF THE EYE

Something else was clear to Thomas Young in 1801 and that was the continuity of visible and infra-red radiation. He writes: 'it seems highly likely that light differs from heat only in the frequency of its radiations' (Young, 1802a).

For most of the eighteenth century, there was little suspicion that radiation existed outside the visible spectrum. In part, we can attribute this innocence to the anthropocentric world-view that still prevailed: the Creator would not have filled space with radiation that Man could not perceive. A more specific explanation, however, is the absence – discussed above – of the physiological concept of a tuned transducer: If all frequencies are directly communicated to the nerves, then we should perceive all frequencies that exist.

Historians of science often attribute to James Hutton in 1794 the first suggestion of the existence of invisible rays beyond the red end of the spectrum. The first empirical demonstration was by William Herschel, the astronomer, the year before Thomas Young's Bakerian lecture (Herschel, 1800a). Figure 1.10 shows one of his experiments. He used a glass prism to form a solar spectrum on a graduated surface, and placed a thermometer with a blackened bulb at different positions within and beyond the spectrum, noting the rise of temperature. He placed further thermometers to one side of the spectrum to control for any change in ambient temperature (Herschel, 1800b). He systematically showed that the invisible rays are reflected, refracted and absorbed by different media, much as are the visible ones. Yet he concluded that the two kinds of ray are quite different in nature. He was misled by a category error.

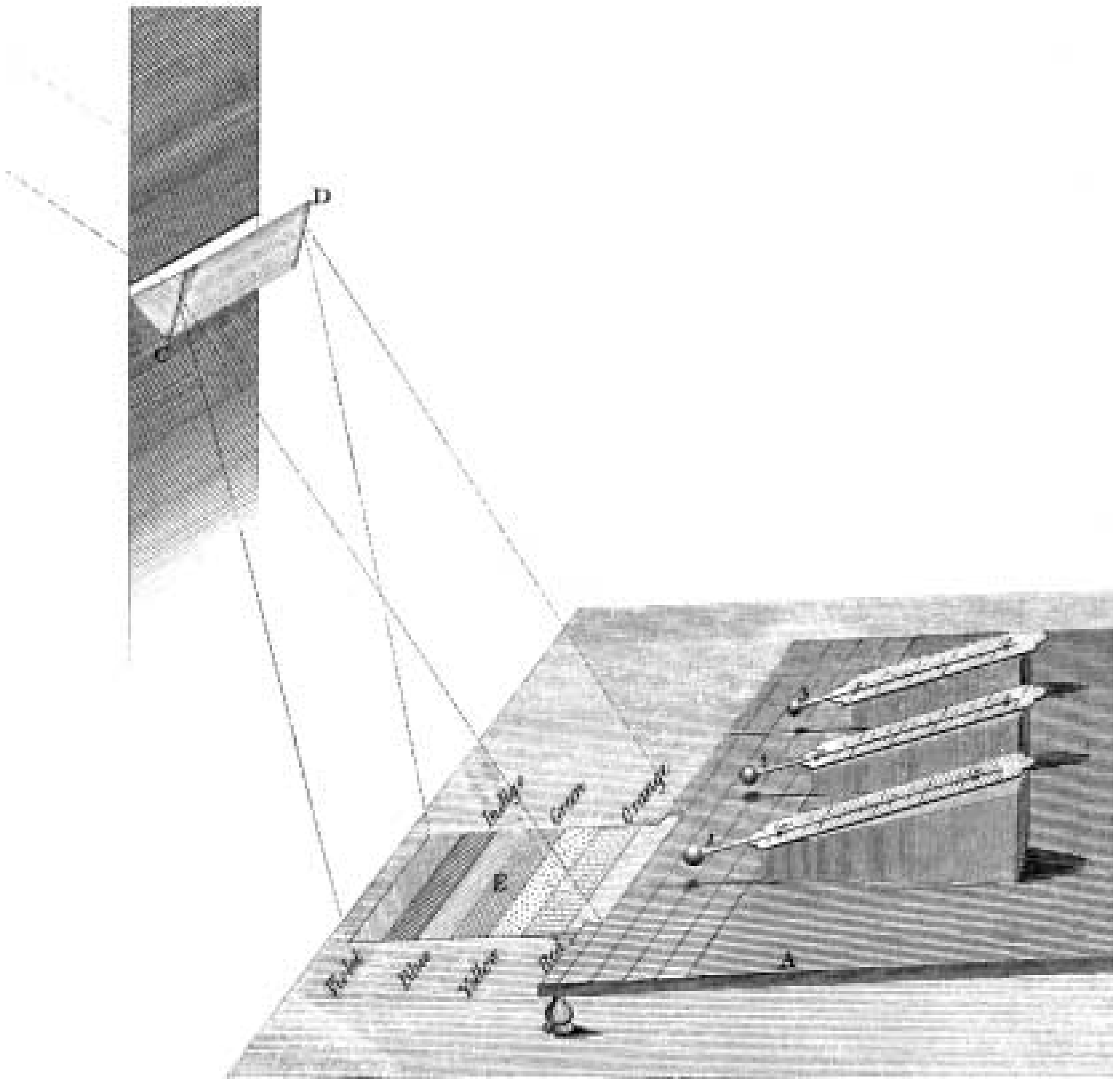


Figure 1.10 **An experimental arrangement used by Herschel to investigate the infra-red. A rise in temperature is recorded by a thermometer placed beyond the visible spectrum.**

Figure 1.11 shows Herschel's representation of the spectral efficiencies of the two types of ray. Certainly, he does deserve some credit for this plot. The very idea of a graph was still unusual in 1800; and this one may be the earliest ancestor of V_λ, the standard curve that represents the photopic sensitivity of the human eye (Chapter 3). The abscissa of Herschel's graph is refrangibility and will be dependent on the dispersive properties of the glass of the prism, as will the positions of the actual peaks. Notice that there is no ordinate for either of the two curves. For the thermal curve, it is the heating power as measured by the thermometer. To obtain the visual curve, Herschel scaled different colors by an acuity criterion, judging their ability to support the discrimination of spatial detail when light of different colors illuminated various objects under a microscope.

If he offered the second curve as a visual sensitivity curve, it would be rather impressive. But he doesn't. He offers it as a curve of the relative radiances of lights of different refrangibility, a spectral power distribution, and he offers a distinct curve for the calorific rays, which he supposes to be of a quite different quality. Operating with the wrong model of sensory transduction, Herschel is unable to grasp that the visible and invisible parts of the physical spectrum are continuous.

Yet the insight William Herschel lacked, had been provided in a work published 15 years earlier (Anonymous, 1786). The author of the latter work advances a vibratory theory of heat, and we can be sure of his identity, since it was printed with another essay that was rejected by the Royal Society. That careful body still retains the manuscripts that its referees rejected in the eighteenth century and hence we know that the author was John Elliot. And in a telling passage, Elliot writes:

> A writer on this subject has shewn (*Philosophical Observations on the Senses*, Etc) that colours may be excited in the eye, by irritating that organ, which do not at all depend on the rays of light . . . He therefore suggests that the rays of light excite colours in us only by the mediation of these internal colours. From whence it would follow, that if there are rays of light which have no

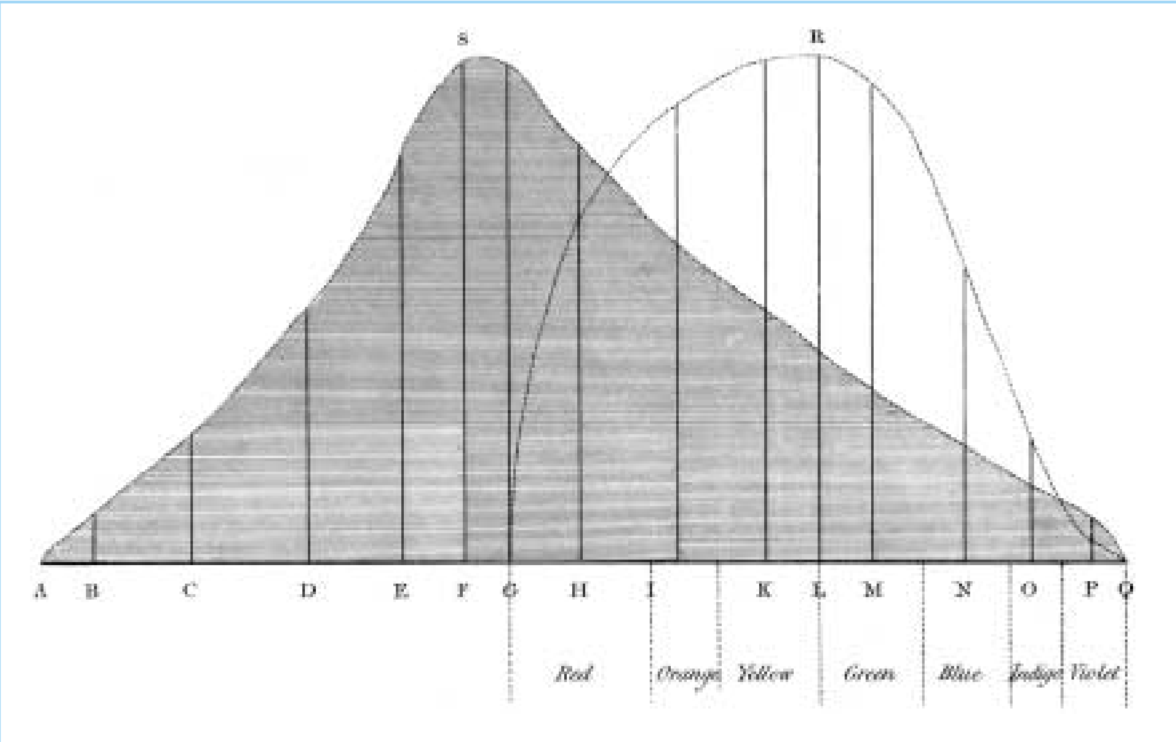


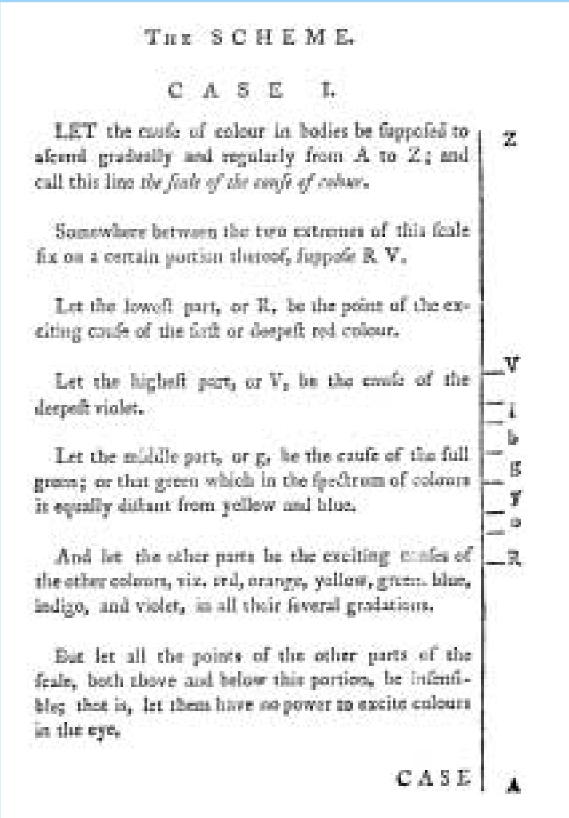
Figure 1.11 **Herschel's representation of the spectral efficiencies of what he supposed were two kinds of ray. *R* corresponds to visible radiation and *S* to the heat-making rays.**

> answerable colours in the eye, those rays cannot be visible; that is, they cannot excite in us any sensation of colour.

Thus it was the concept of a tuned transducer that allowed Elliot to envisage the possibility of nonvisible radiation. There might be optical vibrations for which we have no answering resonators, as there may be acoustic vibrations that are too high or too low for us to hear. And down the side of one page, Elliot explicitly represents the visible spectrum extended in two directions, with only a limited space devoted to the seven Newtonian colors ROYGBIV (Figure 1.12). His diagram has had many successors.

Elliot also deserves credit as the father of spectroscopy, and he was the first to hint at the radiant spectrum of a black body and the concept of color temperature. He observed through a prism the spectrum of bodies as they were heated or allowed to cool. During cooling, for example, the peak of the band of radiation sinks downwards through from the blue to the red in the visible spectrum and out into the infra-red:

> As the body in the third experiment cooled, it was pleasant to observe how, by degrees, the violet first, and then the indigo, blue, and the other inferior colours, vanished in succession, as if the spectrum were contracting itself towards its inferior part; and how the centre of the range seemed gradually to move from orange to red, and at length beneath it, as it sunk into the insensible part below R in the scheme, the superior part following it, till the whole range was out of sight, vanishing with red . . .



THE SCHEME.

CASE I.

LET the cauſe of colour in bodies be ſuppoſed to aſcend gradually and regularly from A to Z; and call this line *the ſcale of the cauſe of colour*.

Somewhere between the two extremes of this ſcale fix on a certain portion thereof, *ſuppoſe* R V.

Let the loweſt part, or R, be the point of the exciting cauſe of the firſt or deepeſt red colour.

Let the higheſt part, or V, be the cauſe of the deepeſt violet.

Let the middle part, or g, be the cauſe of the full green; or that green which in the ſpectrum of colours is equally diſtant from yellow and blue.

And let the other parts be the exciting cauſes of the other colours, viz. red, orange, yellow, green, blue, indigo, and violet, in all their ſeveral gradations.

But let all the points of the other parts of the ſcale, both above and below this portion, be inſenſible; that is, let them have no power to excite colours in the eye.

CASE

Figure 1.12 **The first representation of a spectrum that includes the ultra-violet and infra-red as well as the visible region. From John Elliot's *Experiments and observations on light and colours* of 1786. Elliot published the monograph anonymously.**

1.5 COLOR CONSTANCY, COLOR CONTRAST, AND COLOR HARMONY

When a given object is viewed in different illuminants, its apparent color changes much less than might be expected from the change in the spectral composition of the light that it reflects to our eye. The latter – the spectral flux reaching the eye – depends on both (a) the spectral composition of the illumination and (b) the object's spectral reflectance, its disposition to reflect some wavelengths more than others. It is the second of these that is of biological importance to us in recognizing the objects of our world; and the visual system appears able to discover, and compensate for, the color of the illumination in order to recover the surface property of the object. This relative stability of our color perception is called 'color constancy' (Chapter 4).

Color constancy cannot be accounted for by a simple model of three receptors and three corresponding nerves that each evoke particular sensations in the sensorium. Modern textbooks sometimes attribute such a model to Young, and so it is instructive to note that he was fully aware of color constancy. In his *Lectures* he writes:

> when a room is illuminated either by the yellow light of a candle, or by the red light of a fire, a sheet of writing paper still appears to retain its whiteness; and if from the light of the candle we take away some of the abundant yellow light, and leave or substitute a portion actually white, the effect is

> nearly the same as if we took away the yellow light from white, and substituted the indigo which would be left: and we observe accordingly that in comparison with the light of a candle, the common daylight appears of a purplish hue.
>
> (Young, 1807)

In this compressed passage, Young not only describes color constancy, but also links it – as it has often been linked since – to the simultaneous contrast of color. An earlier passage from Young's *Syllabus* is equally telling:

> Other causes, probably connected with some general laws of sensation, produce the imaginary colours of shadows, which have been elegantly investigated and explained by Count Rumford. When a general colour prevails over the whole field of vision, excepting a part comparatively small, the apparent colour of that part is nearly the same as if the light falling on the whole field had been white, and the rays of the prevalent colour only had been intercepted at one particular part, the other rays being suffered to proceed.
>
> (Young, 1802b)

Young, however, was neither the first to observe color constancy nor the first to relate it to color contrast. The phenomenon itself was already described by the geometer Philippe De La Hire in 1694 in his monograph *Sur les diférens accidens de la Vuë*. We do not commonly realize, he says, that we see colors differently by daylight and by candlelight. For in a given illumination, we judge the array of colors as a whole (*l'on compare toutes les couleurs ensemble*). To appreciate the difference between objects illuminated by candlelight and those illuminated by daylight, what one must do is close the shutters of a room tightly during daylight hours and illuminate this room with candle light.

> . . . passing then into another place illuminated by sunlight, if one looks through the door of the room, the objects that are lit by candlelight will appear tinted reddish-yellow in comparison with those lit by the sun and seen concurrently. One cannot appreciate this when he is in the candle-lit chamber.
>
> (De La Hire, 1694/1730)

La Hire's monograph was published under the aegis of the Royal Academy of Sciences of Paris. A century later, the same Academy was to hear the most brilliant paper ever delivered on color constancy. The lecture was delivered in the spring of 1789, only weeks before the revolution began, and the author was another distinguished geometer, Gaspard Monge (Figure 1.13). It is a mark of the genius of this man that he held high office under administrations as diverse as the *ancien régime*, the *Comité de Salut Publique*, and the First Empire, owing no doubt to his skills as a military technologist.

To illustrate his lecture, Monge had hung a red cloth on the wall of a house opposite the west-facing windows of the meeting room of the Academy. He invited his fellow *académiciens* to view the red cloth through a red glass. The appearance of the cloth was counter-intuitive. Seen through a filter that transmitted predominantly red light, it might have been expected to continue to look a saturated red. But no, it looked pale, even whitish. The same was true when the assembled company inspected one of their fellows who happened that day to be wearing a red outfit. A yellow-tinted paper examined through a yellow glass looked absolutely white. Monge was aware that his illusion (we may call it the Paradox of Monge) was strongest when the scene was brightly lit and when there was an array of variously colored objects present in the scene, including objects that one knew to be naturally white. When all that was visible through the red glass was a red surface, the effect was abolished.

Monge related his illusion to a second phenomenon, that of colored shadows. In his day, colored shadows were already a familiar and antique phenomenon. They were briefly described, for example, in 1672 by Otto von

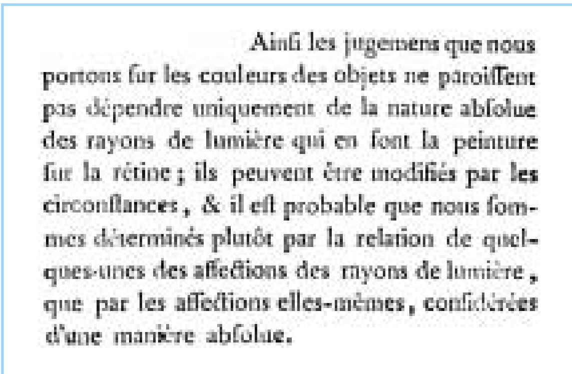

Ainſi les jugemens que nous portons ſur les couleurs des objets ne paroiſſent pas dépendre uniquement de la nature abſolue des rayons de lumière qui en font la peinture ſur la rétine; ils peuvent être modifiés par les circonſtances, & il eſt probable que nous ſommes déterminés plutôt par la relation de quelques-unes des affections des rayons de lumière, que par les affections elles-mêmes, conſidérées d'une manière abſolue.

Figure 1.13 **A critical passage from Gaspard Monge (1789), in which he insists on the relative nature of our color perception.**

Guericke of Magdeburg, the inventor of the vacuum pump. At the end of the eighteenth century, however, commentators were still uncertain as to whether they were perceptual phenomenon or had a physical basis. Von Guericke himself had supposed that they arose from the interaction of light and dark ('. . .*sicut gutta lactis & gutta atramenti ad invicem positae, in loco conjunctionis intermedio, coeruleum efficiunt colorem*'). Monge described how colored shadows can be seen in the morning of a fine day if one opens a window to allow diffuse skylight to enter a room and fall on a sheet of paper that is also illuminated by the light of a nearby candle. The shadow of a small object – where the paper is illuminated only by skylight – will look a rich blue. And yet if the candle is suddenly extinguished, the paper will look uniformly white, even though the region of the shadow has not physically changed. Very similar is an illusion communicated to Monge by Meusnier: If a room is illuminated by sunlight passing through a red curtain and if there is a small hole in the curtain that allows a beam of sunlight to fall on a sheet of white paper, then the patch of sunlight will not look white but rather will look 'a very beautiful green' (Monge, 1789).

To explain such illusions, and to explain the paradox of the red cloth, Monge suggested that our sensations of color do not depend simply on the physical light that reaches our eye from a given surface. Rather, we reinterpret this stimulus in terms of what we judge to be the illuminant falling on the scene: If we judge the illuminant to be reddish, then we shall perceive as greenish an object that physically delivers white light to the eye, since such an object is not delivering the excess of red light that a white surface ought to reflect in a reddish illuminant. Similarly, a red object in red illumination will look whitish to us because it delivers light of the same composition as the estimated illuminant.

In 1789, Thomas Young's Bakerian Lecture was more than a decade in the future, and Monge did not know what the physical variable was that distinguished the hues of the Newtonian spectrum, but he was clear that our perceptions of color in a complex scene do not depend *only* on that physical variable. In a passage that would be echoed two centuries later by Edwin Land, he wrote:

> So the judgements that we hold about the colors of objects seem not to depend uniquely on the absolute nature of the rays of light that paint the picture of the objects on the retina; our judgements can be changed by the surroundings, and it is probable that we are influenced more by the ratio of some of the properties of the light rays than by the properties themselves, considered in an absolute manner.

Monge is describing the process that today we should call 'color constancy,' the process that works largely unnoticed to allow us to judge the constant properties of surfaces in varying illuminants. Monge asked the question that has remained at the heart of studies of color constancy: How do we estimate the color of the illuminant in order to reinterpret the spectral stimulus reaching us from a given object? His answer reflects his primary interest in geometry. All surfaces reflect to our eye some light of the unmodified illuminant as well as light of the characteristic color of the object, the color that results from the object's absorption properties. At one extreme, a glossy object, like a stick of sealing wax, will exhibit highlights, regions of specular reflectance where the illuminant color predominates. Other regions of any object, whether glossy or not, will reflect varying proportions of illuminant and object colors, the proportions varying with the viewing angle and the indentations and protrusions of the surface. Here, Monge anticipates the theory of constancy advanced by Lee (1986): In a chromaticity diagram, the colors of each surface will lie along a line connecting the object color to the illuminant, and the illuminant chromaticity is defined by the intersection of such lines. Hurlbert (1998) has called this the 'chromaticity convergence' theory.

One of the first Americans to study color was Benjamin Thompson, Count Rumford. Writing to the Royal Society of London from Munich in April 1793, he described his experiments on colored shadows, experiments to which Thomas Young refers in the passage cited at the beginning of this section. He set up two matched Argand lamps (see section 1.2.3.1), 'well trimmed, and which were both made to burn with the greatest possible brilliancy.' The light they emitted was of the same color, for when they both illuminated a sheet of white paper and a small cylinder was interposed between the lamps and the paper, the two shadows of the cylinder were identical and colorless. Rumford mounted a blackened tube so that he could view in isolation the shadow cast by one of the two lamp beams. An assistant then introduced a yellow glass in front of this lamp. Observed through the tube, the shadow remained colorless, and indeed Count Rumford could not tell when the assistant passed the yellow glass in and out of the beam. Yet when he looked freely at the paper, the shadow was of a beautiful blue color, while the other was yellow. Here was uncontestable evidence that the cause of the colored shadows was not physical (Thompson, 1794). One other thing struck Rumford very forcibly in these experiments: Although the colors of the two shadows varied as the colors of the two illuminants were varied, there was always a perfect and very pleasing harmony between the colors of the paired shadows. Nowadays, we would note that the two colors are physical complementaries with respect to the light falling on the surrounding white paper: Each of the two shadows lacks part of the total illumination of the scene, and the missing part is present in the fellow shadow.

1.6 COLOR DEFICIENCY

1.6.1 INHERITED COLOR DEFICIENCY

We have seen that the normal human observer requires only three variables in a color-matching experiment (section 1.2). The common forms of inherited color deficiency are defined in terms of how they depart from standard color-matching behavior: ‘Dichromats’ can match all colors by mixing two primary lights, whereas ‘anomalous trichromats’ resemble normals in requiring three primaries in a color match but differ from the normal in the matches that they make. These inherited forms of color blindness are surprisingly frequent, affecting 8% of male Caucasian populations.

Yet the historical recognition of color deficiency came very late. This may reflect the imprecision of our common coinage of color words, and also the fact that the color blind seldom regret what they never have enjoyed, even reaching adulthood before an occupational test brings recognition. Robert Boyle, in his ‘Uncommon Observations about Vitiated Sight’ of 1688, described a ‘Mathematician, Eminent for his skill in Opticks and therefore a very competent Relator of *Phaenomena*.’ This subject made excellent use of his eyes in astronomical observations, but confused colors that appeared quite dissimilar to other men. Frustratingly Boyle does not tell us the particular colors that his subject confounded, but we may speculate on the identity of this mathematician and optician. Could we relate Boyle’s brief description to Newton’s remark that ‘my own eyes are not very critical in distinguishing colours’ (Newton, 1675/1757)?

Further cases of color deficiency were described with increasing detail in the English and French literature of the 1770s. Joseph Huddart (1777) gave an account of the shoemaker Harris, from a Quaker family of Maryport in Cumberland. Harris had good discrimination of form but poor color discrimination, a defect that he shared with his brother, a sea captain. Huddart writes of Harris:

> He observed also that, when young, other children could discern cherries on a tree by some pretended difference of colour, though he could only distinguish them from the leaves by their difference of size and shape. He observed also, that by means of this difference of colour they could see the cherries at a greater distance than he could, though he could see other objects at as great a distance as they; that is, where the sight was not assisted by the colour. Large objects he could see as well as other persons; and even the smaller ones if they were not enveloped in other things, as in the case of cherries among the leaves.

This is a telling passage, for it reveals the conditions under which we need color vision in the natural world. When a stationary target object is embedded in a background that varies randomly in form and lightness, it is visible only to an observer who can distinguish colors – that is, an observer who can discriminate surfaces by differences in their spectral reflectances (Mollon, 1989). As we shall see, the natural task of finding fruit in foliage was later to find its analogue in artificial tests for color deficiency (see section 1.7.4).

As the second half of the eighteenth century progressed, a wider public became aware that not everyone's perceptions of color were the same. In 1760 Oliver Goldsmith, who may himself have been color deficient, wrote of the inappropriateness of recommending the contemplation of paintings 'to one who had lost the power of distinguishing colors' (MacLennan, 1975). And by the 1780s color blindness was well enough known to be remarked on at the English court. Fanny Burney recounts in her journal an uncomfortable conversation with George III:

> He still, however, kept me in talk, and still upon music. 'To me,' said he, 'it appears quite as strange to meet with people who have no ear for music and cannot distinguish one air from another, as to meet with people who are dumb . . . There are people who have no eye for difference of colour. The Duke of Marlborough actually cannot tell scarlet from green!' He then told me an anecdote of his mistaking one of those colors for another, which was very laughable, but I do not remember it clearly enough to write it. How unfortunate for true virtuosi that such an eye should possess objects worthy of the most discerning – the treasures of Blenheim!'
>
> (Barrett, 1904)

So the existence of color deficiency was already well established when in 1794 the young John Dalton gave an account of his own dichromacy to the Manchester Literary and Philosophical Society. But Dalton's account was more analytic than anything that had gone before, and his later fame as a chemist meant that 'daltonism' became the term for color deficiency in many languages, including French, Spanish, and Russian. For him, the solar spectrum had two main divisions, which he called 'blue' and 'yellow.' 'My yellow,' he wrote, 'comprehends the red, orange, yellow and green of others' (Dalton, 1798). The red of sealing wax and the green of the outer face of a laurel leaf looked much the same to him, but scarlet and pink – which share a common quality for the normal observer – were quite different colors for Dalton, falling on opposite sides of neutral. In daylight the pink flowers of clover (*Trifolium pratense*) and of the red campion (*Lychnis dioica*) resembled the light blue of sky. What first prompted him to investigate his own vision was his observation that the flowers of the cranesbill, *Pelargonium zonale* (Figure 1.14), looked sky-blue by daylight but yellowish by candlelight (Lonsdale, 1874). Of his immediate acquaintances, only his own brother experienced this striking change. On further enquiry, however, he discovered that his defect of color perception was not so very rare: in one class of 25 pupils, he found two who agreed with him. He never, however, 'heard of one female subject to this peculiarity,' so giving the first indication that color deficiency is a sex-linked characteristic. We now know that it affects fewer than half of one percent of women.

John Dalton himself thought that his defect arose from a blue-colored medium within his eye. Since there was nothing odd to be seen by external observation of the anterior parts of his eye, he thought that it was likely be his vitreous humor that was blue, absorbing disproportionately the red and orange parts of the spectrum. To allow a test of this hypothesis, he directed that his eyes should be examined on his death.

Figure 1.14 **The pink geranium or cranesbill, *Pelargonium zonale*. To John Dalton and his brother, the flower looked sky-blue by daylight but yellowish by candlelight. (Copyright: Department of Experimental Psychology, University of Cambridge, reproduced with permission.)**

He died aged 78 on 27 July 1844, and on the following day an autopsy was done by his medical attendant, Joseph Ransome. Ransome collected the humors of one eye into watch glasses and found them to be 'perfectly pellucid', the lens itself exhibiting the yellowness expected in someone of Dalton's age. He shrewdly left the second eye almost intact, slicing off the posterior pole and noting that scarlet and green objects were not distorted in color when seen through the eye (Wilson, 1845; Henry, 1854).

In fact, as we have seen (section 1.2.3.1), the correct explanation of most forms of inherited dichromacy had already been advanced by George Palmer (Voigt, 1781), when Dalton was only 15 years old. Palmer's suggestion was taken up in 1807 by Thomas Young. Listing Dalton's paper in the bibliography of his *Lectures on Natural Philosophy*, he remarks: 'He [Dalton] thinks it probable that the vitreous humour is of deep blue tinge: but this has never been observed by anatomists, and it is much more simple to suppose the absence or paralysis of those fibres of the retina, which are calculated to perceive red.'

Many distinguished commentators (e.g. Abney, 1913; Wright, 1967) have followed Young in assuming that it was the long-wavelength receptor that Dalton lacked. It is instructive to consider why this view was so persistent. First, in an often-cited phrase, Dalton described the red end of the solar spectrum as 'little more than a shade or defect of light.' Second, he saw no redness in pinks and crimsons, matching them to blues.

Let us take the two observations in turn. In the type of color blindness called 'protanopia,' where the long-wavelength cone is absent, a prominent sign is the foreshortening of the red end of the spectrum. In fact, the physicists Sir David Brewster and Sir John Herschel both questioned Dalton directly and both reported that he did not see the spectrum as foreshortened at long wavelengths (Brewster, 1842; Henry, 1854). In fact, even a deuteranope – someone lacking the middle-wave pigment – might speak of the long-wave end of the spectrum as dim, for the long-wave pigment in fact peaks in the yellow-green, and for a dichromat the long-wave end of the spectrum does not offer the *Farbenglut*, the extra brightness of saturated colors, that enhances the red end of the spectrum for the normal observer (Kohlrausch, 1923).

But what of the absence of redness in Dalton's experience of surfaces that the normal would call pink or scarlet? Does that mean he lacked long-wavelength cones? The trichromatic theory has historically often been combined with a primitive form of Mueller's Doctrine of Specific Nerve Energies: There are three receptors and three corresponding nerves, and centrally the nerves secrete red, yellow, and blue sensations or red, green, and blue sensations. It took a very long time for color science fully to free itself from this notion, and to this day generations of undergraduates are misled by lecturers and textbooks that speak of 'red,' 'green,' and 'blue' cones. Dalton helpfully specified several crimson and pink flowers that appeared blue to him. I have measured these flowers spectroradiometrically and have plotted their chromaticities in Figure 1.15. The two straight lines passing through the chromaticity of the daylight illuminant represent sets of chromaticities that match daylight for protanopes and deuteranopes respectively. Chromaticities that lie above the line will have the hue quality that the dichromat associates with long wavelengths, and chromaticities that lie below the line will have the quality that the dichromat associates with short wavelengths. For both types of dichromat the several pink and crimson flowers lie below the line and should have the same hue quality as blue sky. So Dalton's failure to see redness in these flowers is no basis for placing him in one category of dichromat or the other.

Shriveled fragments of Dalton's eye, preserved only in air, survive to this day in the possession of the Manchester Literary and Philosophical Society (Brockbank, 1944). In the 1990s the Society gave permission for small samples to be examined using the polymerase chain reaction, which allows the amplification of short stretches of DNA defined by primer sequences specific to particular genes. This exercise in molecular biography yielded only copies of the gene that encodes the long-wave photopigment of the retina and never the gene that encodes the middle-wave photopigment (Hunt *et al.*, 1995; Mollon *et al.*, 1997). So Dalton appears to have been a deuteranope, and not the protanope lacking 'red' cones, as so often supposed.

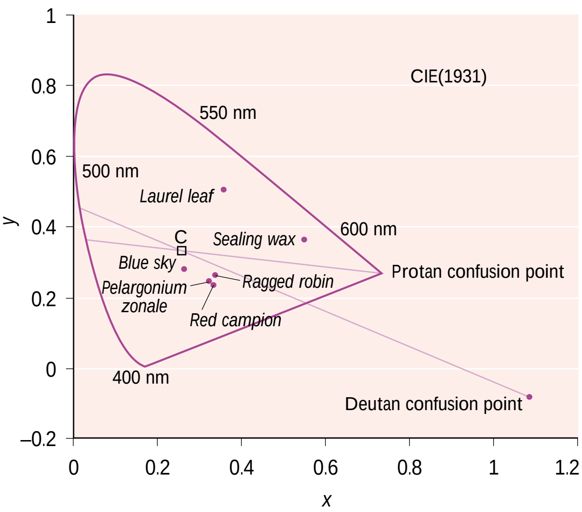


Figure 1.15 **The CIE (1931) chromaticity diagram (see section 1.7.1 and Chapter 3). Plotted in the diagram are several flowers that looked blue to Dalton: the cranesbill (*Pelargonium zonale*), red campion (*Lychnis dioica*) and ragged robin (*Lychnis floscuculi*). Also plotted are sealing wax and the upper side of a laurel leaf, which Dalton judged to be very similar in color. The open square in the center of the diagram represents Illuminant C, a standard approximation to daylight. Passing through this point are two lines, one (a 'protan confusion line') representing the set of chromaticities that would be confused with white by a dichromat who lacks the long-wave cones, and the other (a 'deutan confusion line') representing the set of chromaticities that would be confused with white by a dichromat who lacks the middle-wave cones. For both kinds of dichromat, the pink flowers lie on the blue side of the neutral line, whereas sealing wax will have the opposite quality. Dalton (1798) himself wrote '*Red* and *scarlet* form a genus with me totally different from pink'.**

1.6.2 ACQUIRED DEFICIENCIES OF COLOR PERCEPTION

Color discrimination can deteriorate during a person's lifetime, owing to ocular diseases (such as glaucoma), or to systemic conditions that affect the eye and optic pathways (such as diabetes and multiple sclerosis), or to strokes, cerebral inflammations, and head injuries. What one loses, one notices and regrets. So it might be expected that acquired deficiencies would have been recorded historically before the inherited deficiencies.

Certainly, a self-report of altered color vision occurs as early as 1671 in the *Traité de Physique* of Jacques Rohault (Figure 1.16). Since it leads him to suspect the existence of congenital color anomalies, the passage is worth translating in full:

> Yet I would venture to insist that just as it often happens that the same food tastes quite different to two different people, similarly it can be that two men have very different sensations when looking at the same object in the same way; and I am the more convinced of this because I have an experience of it that is wholly personal to me: For it happening once that my right eye was weakened and injured, by looking for more than twelve hours through a telescope at the contest of two armies, which was going on a league away; I now find my vision so affected that when I look at yellow objects with my right eye, they do not appear to me as they used to do, nor as they now appear when I observe them with the left. And what is remarkable is that I do not notice the same variation in all colors but only in some, as for example in green, which appears to come close to blue when I observe it with the right eye. This experience of mine makes me believe that there are perhaps some men who are born with, and retain all their life, the disposition that I currently have in one of my eyes, and that there perhaps are others who have the disposition that I enjoy in the other: However, it is impossible for them or anyone else to be aware of this, because each is accustomed to call the sensation that a certain object produces in him by the name that is already in use; but which, being common to everyone's different sensations, is nonetheless ambiguous.

Rohault's textbook was widely circulated in several editions, and so it may not be coincidence that the following decade brought a flurry of case reports – of varying sophistication. Stephan Blankaart, in a Dutch collection of medical reports, briefly described a woman who, after suffering a miscarriage, 'saw objects as black' but later recovered (Blankaart, 1680). In 1684 'the great and experienced Oculist' Dawbenry Turbervile wrote from Salisbury to the Royal Society: 'A Maid, two or three and twenty years old, came to me from *Banbury*, who could see very well, but no colour beside *Black* and *White*' (Turbervile, 1684). But Turbervile then spoils his already slight report by adopting an emissive theory of vision: 'She had such Scintillations by night (with the appearances of Bulls, Bears Etc.) as terrified her

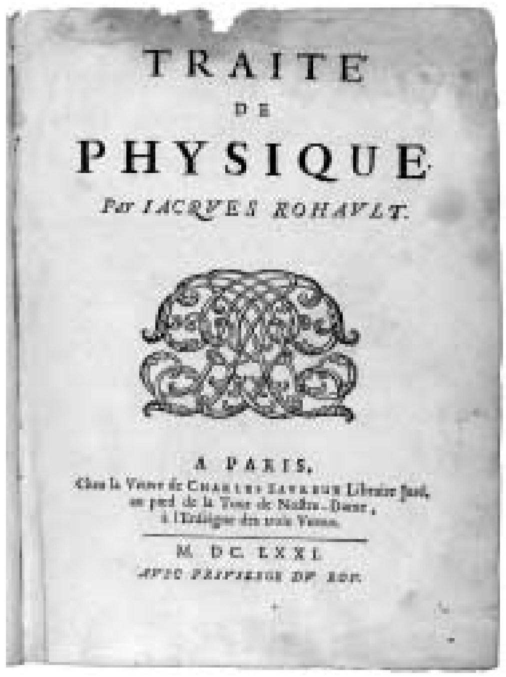


Figure 1.16 The treatise of physics of Jacques Rohault (1671), in which he describes an acquired disturbance of his own color vision.

very much; she could see to read sometimes in the great darkness for almost a quarter of an hour.' He is implying that the 'Scintillations' – the subjective sensations of light that now would be called 'phosphenes' – corresponded to actual light. This misinterpretation of phosphenes lingered until the nineteenth century and was one of the factors that prompted the young Johannes Mueller to develop his 'Doctrine of Specific Nerve Energies.'

Whatever we make of Turbervile's Maid from Banbury, we can only admire Robert Boyle's account of a suspiciously similar case, published in his *Vitiated Sight* of 1688. The subject was a gentlewoman 'about 18 or twenty years old' when Boyle had examined her. After an unidentified illness treated with blisters, she had lost her sight entirely. Slowly light sensation and then form vision returned, but color perception remained impaired. Like the Maid from Banbury 'she is not unfrequently troubled with flashes of Lightning, that seem to issue out like Flames about the External Angle of her Eye, which often make her start, and put her into Frights and Melancholy Thoughts' (Boyle, 1688). With materials that came to hand, Boyle established that she could read and had good acuity, but was unable to identify reds, greens or blues. He adds – in a passage both poetic and insightful – 'when she had a mind to gather Violets, tho' she kneel'd in that Place where they grew, she was not able to distinguish them by the Colour from the neighbouring Grass, but only by the Shape, or by feeling them.' Banbury is but 25 km from Boyle's home in Oxford; and Boyle, always troubled by poor eyesight, himself consulted Turbervile. Almost certainly, Boyle and Tubervile describe the same case, but Boyle's is much the better account.

1.7 THE GOLDEN AGE (1850–1931)

Our survey has shown that many of the concepts of modern color science were in place by the middle of the nineteenth century. The following decades saw a golden era, when colorimetry emerged as a quantitative science and when color perception held a more prominent place in scientific discussion and in public debate than it has held before or since.

1.7.1 COLOR MIXTURE

When Hermann Helmholtz published his first papers on color in 1852, he was already celebrated for his essay on the conservation of force, his measurements of the speed of neural conduction, and his invention of the ophthalmoscope. Born in Potsdam in 1821, he had become professor at Königsberg in 1849. One of his first contributions to color science was to clarify the distinction between the subtractive mixture of pigments and the additive mixture of colored lights (Helmholtz, 1852). He conceived of a pigment as a series of semi-transparent layers of particles acting as filters to light that is reflected from the underlying layers. Consider a mixture of yellow and blue pigments. A bright yellow pigment will reflect red, yellow, and green light, whereas a blue pigment will reflect green, blue, and violet. Some light, Helmholtz suggested, will be reflected by particles at the surface, and this component will include a large range of wavelengths and will be close to white in its composition. Light that is reflected from deeper layers, however, will be subject to absorption by both blue and yellow particles; and so the light that is returned to the eye will be dominated by wavelengths that are not absorbed by either component – in this case, wavelengths from the green region of the spectrum.

Helmholtz offered a striking illustration of the difference between additive and subtractive mixture. He painted the center of a disk with a mixture of yellow and blue pigment, but in the outer part of the disk he painted separate sectors with the same individual component pigments. When the disk was spun, the center looked dark green, as painterly tradition required, but the circumference looked lighter and grayish. In the former case, the perceived color depends on residual rays that are reflected after the physical mixture of pigments. In the latter case, the two broadband components are effectively combined at the retina, owing to the temporal integration of successive stimuli within the visual system.

It is reassuring, however, and instructive, to see a genius err. And so we can note that Helmholtz's 1852 paper contains an empirical error and a conceptual error. He reports his results for the additive mixture of spectral, narrow-band, colors. He formed two prismatic spectra that overlay each other at 90°, so that all combinations of monochromatic lights were present in the array; and he then viewed small regions of the array in isolation. His empirical error was to conclude that there was only one pair of spectral colors, yellow and indigo-blue, that were complementaries in that they would mix additively to form a pure white; from other combinations, the best that he could achieve was a pale flesh color or a pale green – a report that recalls Newton's phrase 'some faint anonymous Colour.' The failure of Helmholtz to identify more than one pair of complementaries may merely reflect difficulty in isolating the appropriate small regions of the array. But his conceptual error in the 1852 paper is instructive. By mixing red and a mid-green, he was unable to match a monochromatic yellow in saturation. This result is correct and the reason for it is that a mid-green light stimulates all three cones, whereas a monochromatic yellow stimulates only the long- and middle-wave cones. Helmholtz was led, however, explicitly to reject what he understood to be Young's trichromatic theory. If yellow is the color seen when red and green sensations are concurrently excited, he argued, then exactly the same color should be produced by the simultaneous action of red and green rays. Because green is a phenomenologically simple hue, he does not entertain the possibility that monochromatic green light excites more than one class of fiber.

The failure of Helmholtz to find more than one pair of complementaries drew a response from the mathematician Hermann Grassmann. Grassmann (1853) began with the assumption that color experience is three-dimensional, being fully described by the attributes of hue, brightness, and saturation. These three attributes of sensation correspond, he suggested, to the three physical variables of wavelength (or frequency), intensity (or amount of light), and purity (the ratio of white to monochromatic white in a mixture). By assuming from the start that vision was three-dimensional and by adding the assumption that phenomenological experience never changed discontinuously as one of the physical variables was changed, Grassmann was able to show that each point on the color circle ought to have a complementary. Helmholtz now adopted a better method of mixing spectral lights and found that the range of wavelengths between red and greenish-yellow had complementaries in the range between greenish-blue and violet (Helmholtz, 1855; Figure 1.17). A range of greens, however, do not have complementaries that lie within the spectrum: Their complementaries are purples, i.e. mixtures of lights drawn from the red and violet ends of the spectrum. Moreover, complementary lights of equal brightness do not necessarily mix to yield white: The ratio needed in the mixture may be very unequal. For example, in the mixture of yellow-green and violet that matches white, the violet component will be of much lower brightness than the yellow-green component. If the center-of-gravity principle for mixing is to be preserved and if the weightings of the component lights are to be in terms of subjective luminosity, then a chromaticity diagram like that of Figure 1.18 is required. The range of purples is represented by a straight line connecting the two ends of the locus of spectral colors.

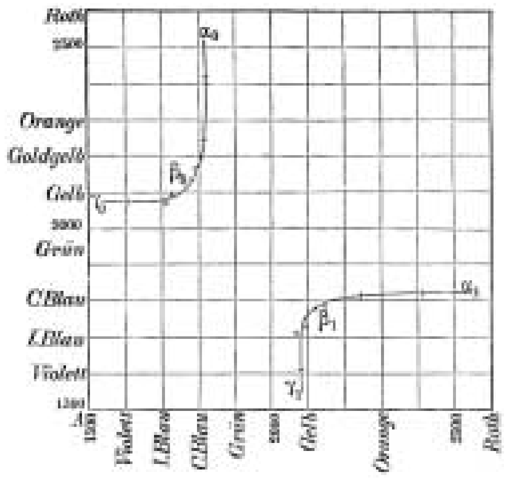


Figure 1.17 **Helmholtz's graph of the wavelengths that are complementaries, i.e., the wavelengths that will form white when mixed in a suitable ratio.**

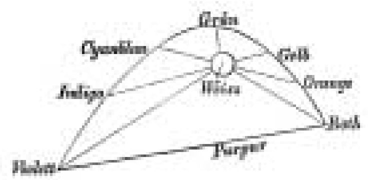


Figure 1.18 **The first chromaticity diagram to have a modern form, prepared by Helmholtz on the basis of his measurements of complementaries.**

In the same year, 1855, the 24-year-old James Clerk Maxwell took Young's theory several steps further (Maxwell, 1855a, 1855b). He made his experiments on additive mixture by means of a spinning top that carried superposed disks (Figure 1.19). The disks, cut from colored papers, were slit along a radius, so that Clerk Maxwell could expose a chosen amount of a given color by slipping one disk over another. He used two sets of disks, one set of twice the diameter of the other. The inner disks were typically formed by white and black and, when spun, they exhibited a gray corresponding to how much of each paper was exposed. In the outer ring, he typically used sectors of three different colors. Clerk Maxwell experimentally adjusted the proportions of the three colors of the outer ring until, being spun, they gave a gray that was equivalent to the gray

Figure 1.19 **The color-mixing top of James Clerk Maxwell. The instrument survived in the collection of the Cavendish Laboratory, Cambridge. This photograph was taken in 1982. (Copyright: Department of Experimental Psychology, Cambridge University, reproduced with permission.)**

seen in the inner area. Once the match was achieved, Clerk Maxwell used the perimeter scale to read off the space occupied by each paper in hundredths of a full circle. Suppose the outer colors were vermilion (V), ultramarine (U), and emerald green (EG), and the center papers snow white (SW) and black (Bk). Then he would write an equation of the following form:

$$.37\ \mathrm{V} + .27\ \mathrm{U} + .36\ \mathrm{EG} = .28\ \mathrm{SW} + .72\ \mathrm{Bk}$$

Suppose that we take the three outer colors as our standard colors. By replacing one of the outer colors by some test color, Clerk Maxwell could obtain a series of equations that contained two of the standard colors and the test color. Then, by bringing the test color to the left-hand side of the equation, and bringing the three standard colors to the right, he could represent the test color as the center of gravity of three masses, whose weights are taken as the number of degrees of each of the standard colors.

By 1860 Clerk Maxwell had constructed a device that allowed him to match daylight with mixtures of three monochromatic lights (Maxwell, 1860). This allowed him to express the spectrum in terms of three primaries and to plot against wavelength the amounts of the three primaries required to match any given wavelength (Figure 1.20). The latter curves are the forerunners of later 'color matching

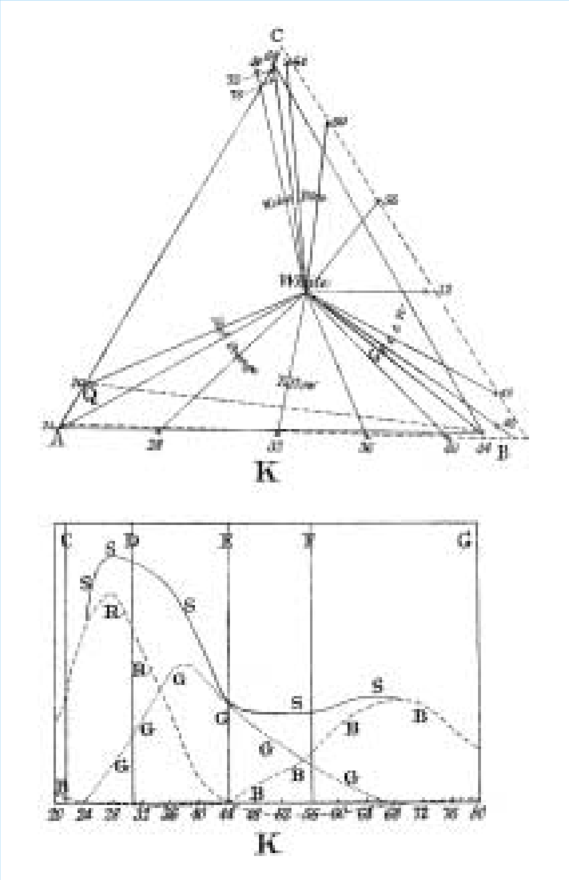


Figure 1.20 **The first empirical color-matching functions. The data shown are for Clerk Maxwell's wife, Katherine. The lower plot represents the proportions of the red, green and blue primaries needed to match a given wavelength. The spectrum runs from red on the left to violet on the right. The upper plot is a chromaticity diagram based on the same color-matching data. The locus of the spectral colors is expressed in terms of the proportions of the three primaries used in the experiment.**

functions.' In the same paper, Clerk Maxwell noted that the matches he made with central vision did not hold when he observed them indirectly. This discrepancy, and also the discrepancy between his central matches and those of his wife, he attributed to the yellow spot of the central retina, which selectively absorbs light in the wavelength range 430–90 nm.

Fresh determinations of the color matching functions were made in the 1920s by Guild, using a filter instrument, and by Wright, using monochromatic stimuli. When the two sets of results were expressed in terms of a common set of primaries, they were found to agree extremely well, and they were taken as the basis for a standard chromaticity diagram adopted by the Commission Internationale d'Éclairage (CIE) in 1931. This CIE system has remained the principal means of specifying colors for trade and commerce (Chapter 3). W.D. Wright has left us a personal account of its origins, in an Appendix to Kaiser and Boynton (1996).

1.7.2 THE SPECTRAL SENSITIVITIES OF THE RECEPTORS

We have seen that a chromaticity diagram allows any light to be specified in terms of three arbitrary primary lights: All that we need to know is the relative amount of each primary that is required to match the test light. It is then straightforward to re-express the chromaticity of the test light in terms of a new set of primary lights, since we know how much of each of the old primaries is required to match each of the new primaries. But somewhere in the diagram there should be a set of three points that have a special status: These would be the lights – if they existed – that stimulated only one individual class of Young's receptors. Clerk Maxwell in 1855 was firm in saying that such lights do not exist in the real world. He draws a version of Newton's color circle within a larger triangle and writes:

> Though the homogeneous rays of the prismatic spectrum are absolutely pure in themselves, yet they do not give rise to the 'pure sensations' of which we are speaking. Every ray of the spectrum gives rise to all three sensations, though in different proportions; hence the position of the colours of the spectrum is not at the boundary of the triangle, but in some curve CRYGBV considerably within the triangle . . . All natural colours must be within this curve, and all ordinary pigments do in fact lie very much within it.
>
> (Maxwell, 1855b)

Clerk Maxwell himself proposed how it might be possible experimentally to establish the positions of the individual receptors in a chromaticity diagram – and thus to express each wavelength of the spectrum in terms of the relative excitation it produces in the three receptors. It is necessary to assume that the color blind retain two of the normal receptors and lack a third. In 1855 Clerk

Maxwell was aware of only one class of color blind subjects, those he thought to lack the long-wave receptor. Using his technique of spinning disks, he showed that these dichromatic subjects needed only four colors (including black) in their equations (Maxwell, 1855a). With the red, green, and blue standard colors of Figure 1.21, for example, a dichromat generated the equation

$$.19G + .05B + .76\ Bk = 1.00\ R,$$

that is, a full red was equivalent to a dark blue-green mixture. Along the line Redβ (see Figure 1.21), the subject can match all chromaticities merely by varying the amount of black in the mixture: In other words, provided we equate the different chromaticities in lightness, he cannot discriminate among them. Such a line would today be called a 'dichromatic confusion line.' To distinguish chromaticities on this line, the normal must be using the receptor that the dichromat lacks. All that varies along the line is the degree of excitation of the receptor that is missing in the color blind. If we establish a second confusion line (e.g. $\gamma\delta$ in the diagram), then the point D, where Redβ and $\gamma\delta$ intersect, gives the position in the chromaticity diagram of the missing receptor. Physical lights can then be re-expressed in terms of the relative excitations of the three receptors.

This approach, which Clerk Maxwell proposed in 1855, has remained a prominent psychophysical method for estimating the spectral sensitivities of the retinal receptors. Arthur König (Figure 1.22), a colleague of Helmholtz, obtained color-matching functions for normals, protanopes and deuteranopes, and derived the sensitivities shown in Figure 1.23 (König and Dieterici, 1892). Notice that the peak of König's long-wave receptor lies in the yellow region of the spectrum. Twentieth-century color-matching functions allowed fresh estimates of the receptor sensitivities (e.g. Nuberg and Yustova, 1955; Wyszecki and Stiles, 1967). An important advance came from precise measurements of the confusion lines of tritanopes, those rare dichromats who lack the short-wave receptor (Wright, 1952). However, even amongst those who favored a trichromatic theory, receptor sensitivities derived by Clerk Maxwell's method did not secure universal acceptance until late in the twentieth century. Convergent evidence came from the work of W.S. Stiles, who measured thresholds for monochromatic increments on monochromatic fields. By varying systematically either the wavelength of the test flash or that of the adapting field, he was able to show that the sensitivity of an individual cone channel is primarily determined by

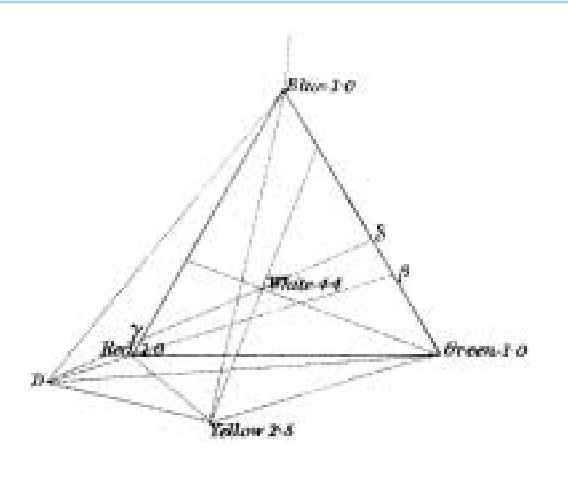


Figure 1.21 **Clerk Maxwell's diagram showing how the position in the chromaticity diagram of one of the retinal receptors can be estimated from the confusions made by a dichromat.**

Figure 1.22 **Arthur König (1856–1901), a protégé of Helmholtz. König suffered from a progressive and painful deformity of the spine.**

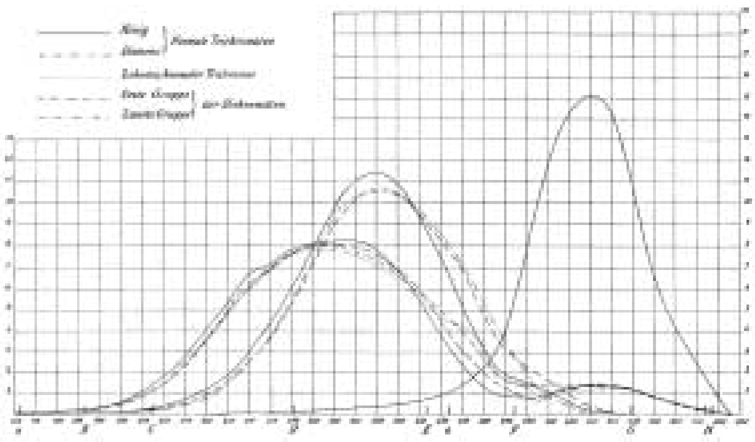


Figure 1.23 **The first realistic estimates of the sensitivities of the retinal receptors. The spectrum is plotted with long wavelengths to the left. The solid and dashed curves show the estimates of the receptors of normal observers. (From König and Dieterici, 1892.)**

the photons absorbed by that channel alone; and thus he was able to estimate the spectral sensitivities of the cones, estimates that resembled those obtained by Clerk Maxwell's method (Stiles, 1939). Objective measurements of the cone pigments were later obtained by the method of reflection densitometry (Rushton, 1965) and by direct microspectrophotometric and electrophysiological measurements of single cones.

1.7.3 ANOMALOUS TRICHROMACY

Clerk Maxwell died of cancer in 1879, when still only forty-eight. His successor in the Cavendish chair of physics at Cambridge was Baron Rayleigh, who took the post only because the agricultural depression had temporarily spoiled his plans of maintaining a large private laboratory on his family estate at Terling Place (Strutt, 1924). In 1881, Lord Rayleigh described how he had discovered that three of his wife's brothers – including Arthur Balfour, later British Prime Minister and author of the 'Balfour Declaration' – differed from him in matching monochromatic yellow light with a mixture of red and green. The mixture set by Rayleigh himself looked 'almost as red as red sealing wax' to his brothers-in-law, who set a match with only half as much red in it. A fourth brother was normal, as were the three sisters. Others in Rayleigh's circle, including J.J. Thompson (his successor as Cavendish Professor), similarly required a much smaller ratio of red to green in the match than did the normal observer, while two further observers required *more* red in the match, in the ratio 2.6 to 1 relative to the normal. Yet several of these deviant observers had fine discrimination in the red–green range and could not be conventionally described as color blind (Rayleigh, 1881).

The class of observers identified by Rayleigh were soon being called 'anomalous trichromats'(König and Dieterici, 1886). Rayleigh himself suggested that they were very common, and we now know that they constitute some 6% of the male population. However, the distinguished Dutch ophthalmologist Donders showed that the anomalous observers with good discrimination (such as the Balfour brothers) were relatively uncommon, and that an anomalous match was more often associated with reduced discrimination of color (Donders, 1884). He also obtained 'Rayleigh equations' for a population of over 50 normal observers and noted the large variation in their individual matches.

Donders standardized the wavelengths used for the Rayleigh equation: The red and green components of the mixture were provided by the lithium line at 670 nm and the thallium line at 535 nm, and this mixture was to be matched to the orange light of the sodium line at 589 nm. Remarkably, Donders' red and orange wavelengths have been retained to this day as standards for the Rayleigh equation (e.g. German standard DIN 6160). The green component was later moved to the mercury line at 546 nm, since this gives a mixture that is closer to the orange in saturation.

1.7.4 TESTS FOR COLOR DEFICIENCY

There is never any end to the invention of new color tests, but nearly all the main principles emerged in the period 1870–1930. The introduction of tests for mass screening was prompted by the use of color signaling on the rapidly expanding railroads (Wilson, 1855; Jennings, 1896). At Lagerlunda in Sweden, in the early hours of 15 November 1875, nine people died when two express trains collided on a single-line track (Nettleship, 1913). The engineer of the late-running northbound express apparently did not recognize a red light waved by the stationmaster at Bankeberg station, for he slowed and then restarted forwards without the stationmaster's order. A lineman ran with a red lamp after the train, but a carriage oiler, in the front van, is said to have called out to the engineer that he saw the 'line-clear' signal. Two or three minutes later, as it steamed up the incline to the bridge over the Lagerlund river, the train met the southbound express (Figure 1.24). The engineer and the oiler of the northbound train were among the dead, but Professor F. Holmgren of Upsala raised the possibility that one or other had been color blind. He campaigned for the screening of all railway employees. The superintendent of the Upsala–Gefle line provided Holmgren with a private rail car and he proceeded down the line, halting at each station and gatekeeper's house to test every employee. Some 4.8% of the personnel, including a stationmaster and an engineer, were found to be color-deficient (Holmgren, 1877).

Holmgren sought a test that did not require the naming of colors, since the daltonian's use of color terms will often disguise an inability to discriminate. Instead, Holmgren required the sorting of colored wools: 'it is necessary to leave to the activity of the hands the task of revealing the nature of sensation.' The examiner places on the table a sample skein, green for the first test and purple for the second. Nearby, is a jumbled pile of skeins of varying color and lightness. The subject is asked to pick from the pile the skeins that have the same hue. Daltonians quickly reveal themselves by picking from the pile not only the skeins that a normal would pick, but also 'confusion colors' characteristic of this form of deficiency.

Concurrently, in Germany, Stilling introduced the first 'pseudoisochromatic plates,' which pres-

Figure 1.24 **The fatal consequence of color blindness? The scene after the Lagerlunda collision of November 1875. (Reproduced by permission of Sveriges Järnvägsmuseum.)**

ent a target digit or letter of one color embedded in a background of another color. Initially, an attempt was made to print solid figures of one chromaticity on an equally light background of a second chromaticity, the chromaticities being ones confused by the color blind. It was quickly found, however, that it was impossible to print figure and ground in such a way as to eliminate all edge artifacts. Moreover, a figure and ground that were equally light for one daltonian were not necessarily so for another. Stilling solved these problems by two ingenious manoeuvres (Stilling, 1877). First, he broke the target and the field into many small patches, each with its own contour; and secondly, instead of attempting to equate the lightness of target and field, he varied the lightness of the individual patches (Figure 1.25). So neither edge artifacts nor luminance differences could be used as cues to discriminate the target from the background. The target can be detected only by color discrimination, and the task resembles the natural task that challenges the color blind, that of finding fruit amongst dappled foliage.

Stilling's pseudoisochromatic plates are all of the 'disappearing' type, so called because the target becomes invisible for a particular type of color-deficient observer. A clever later variant was the 'transformation plate', where the normal and the color-deficient give alternative readings. This is achieved by linking the elements of the array by one neural signal for the normal and by a different one for the daltonian: For example, on an orange background, the normal might link bluish-green elements with yellow-green elements, whereas, for the daltonian, the more salient linkage might be between the bluish-green elements and plum-colored ones, or between elements of similar lightness. Early examples of transformation plates dating from 1916 are seen in the test of Podestà, who was *Marine-Generaloberarzt* of the Germany Navy. This test has passed into the graveyard that accommodates many forgotten color tests, but it is the most baroque set of plates ever produced, and it is particularly clever because some of the alternative readings are also antonyms (Figure 1.26). The following year, the Japanese ophthalmologist Ishihara published the first edition of a set of plates that included disappearing and transformation plates, as well as plates in which the daltonian sees a digit that is masked for the normal by random color variation (Ishihara, 1917). Despite many rivals, the pseudoisochromatic plates of Ishihara became – and remain today – the dominant instrument for routine screening of color vision. They readily detect dichromats and all but a tiny minority of anomalous trichromats. In part, this sensitivity is achieved not by testing color discrimination but by pitting one perceptual organization against a second.

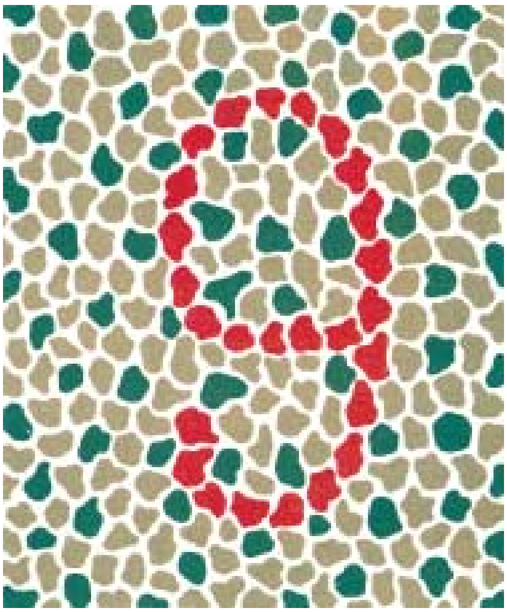


Figure 1.25 **An example of a pseudoisochromatic test for color deficiency. (From Stilling, 1877.)**

Whereas the Ishihara plates are used for screening, the *classification* of color deficiency depends on another instrument introduced early in the twentieth century: the anomaloscope of Nagel (1907). This optical device is essentially a reverse spectroscope: Lights from three slits pass through a prism, and an ocular lens focuses them on the subject's pupil. In the standard model, the slits isolate the wavelengths chosen by Donders for the Rayleigh equation (see section 1.7.3). The subject sees a field subtending 2 degrees: One half-field is illuminated by orange light and the second by the red-green mixture. One control varies the ratio of red to green light in the mixture, and a second adjusts the luminance of the orange light. Dichromats

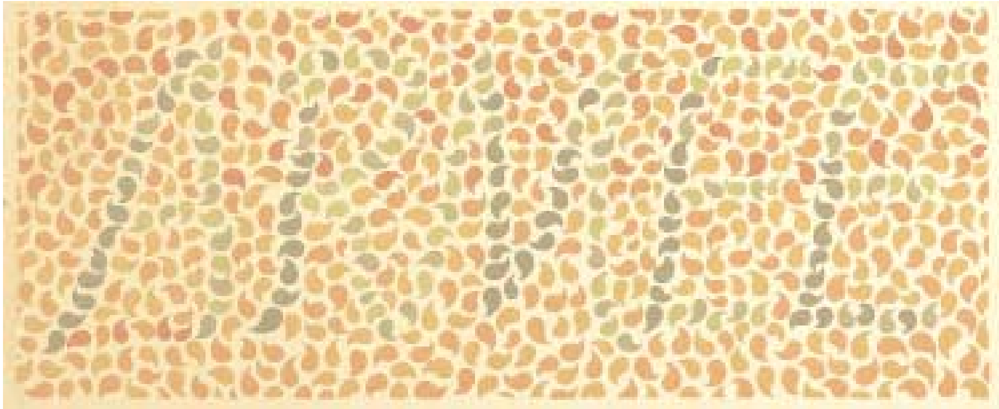


Figure 1.26 **A transformation plate from the test of Podestà (1916). The normal reads 'Armee' but the dichromat reads the antonym, 'Zivil'.**

reveal themselves by matching the orange field with any mixture of red and green, and protanopes and deuteranopes can be distinguished by the amounts of orange lights they require to match different red-green mixtures. Anomalous trichromats are classified by their Rayleigh equations as 'protanomalous' (requiring excess red) or 'deuteranomalous' (requiring excess green). Their power of discrimination (and that of those with normal equations) can be gauged by the *range* of matches that they accept.

An insight into the early days of color testing can be had by reading the entertaining history of Mr Trattles, a British seaman who was denied his First Mate's certificate after earlier passing the Holmgren test (Boltz, 1952). His case was discussed in both Houses of Parliament, and Winston Churchill, then President of the Board of Trade, defended Holmgren's test (Hansard, 1909). On the basis of spectral luminosity measurements at Imperial College, the physicist William Abney declared Trattles a protanope. Trattles finally secured his certificate after he had been taken down the Thames one winter's night on a steamer and had successfully identified navigation lights in the presence of witnesses. He was probably protanomalous, but there is no record that he was ever tested with Nagel's new invention. The Trattles case well illustrates the intense public interest in color perception in the period before the First World War.

1.7.5 COLOR AND EVOLUTION

The Origin of Species was published in 1859, and in the following decades, Darwinism spread to all branches of biology. The father of visual ecology is undoubtedly a Canadian, Grant Allen, later infamous for his feminist novel *The Woman Who Did*. In 1879 he argued systematically that color perception in animals had co-evolved with color signals in plants. His own summary cannot be bettered:

> Insects produce flowers. Flowers produce the colour-sense in insects. The colour-sense produces a taste for colour. The taste for colour produces butterflies and brilliant beetles. Birds and mammals produce fruits. Fruits produce a taste for colour in birds and mammals. The taste for colour produces the external hues of humming-birds, parrots, and monkeys. Man's frugivorous ancestry produces in him a similar taste; and that taste produces the various final results of the chromatic arts.
>
> (Allen, 1879)

Donders (1883) explicitly suggested that human trichromacy evolved from an earlier dichromatic state and had appeared first in females. The basis of the evolution was the successive differentiation of a visual molecule. The American psychologist Christine Ladd-Franklin (Figure 1.27) made evolution central to her own theory of color perception. She proposed:

Figure 1.27 **Christine Ladd-Franklin (1847–1930). A graduate of Vassar, Ladd-Franklin studied vision in Göttingen and Berlin, and developed an evolutionary account of color perception (Copyright: Vassar College Library, reproduced with permission).**

> that the substance which in its primitive condition excites the sensation of grey becomes in the first place differentiated into two substances, the exciters of yellow and blue respectively, and that at a later stage of development the exciter of the sensation of yellow becomes again separated into two substances which produce respectively the sensations of red and green.
>
> (Ladd-Franklin, 1892)

Mrs Ladd-Franklin's chemistry is of its time, and she assumes too close a link between her receptor molecules and sensations. But her *sequence* anticipates the modern view of the evolution of primate photopigments: Molecular genetics suggest that the long- and middle-wave pigments became differentiated relatively recently in primate evolution, whereas the common ancestor of these molecules diverged from the short-wave pigment at a much earlier, pre-mammalian stage (Nathans *et al.*, 1986).

1.8 NERVES AND SENSATIONS

The work of Helmholtz, Clerk Maxwell and König did not secure universal acceptance of a three-receptor theory. A prominent opponent was the physiologist Ewald Hering, who took his start from color sensations. There are four hues in our experience – red, green, yellow, and blue – that look phenomenologically simple, whereas other hues, such as orange or purple, look to us mixed in quality. We can see the redness and the blueness in a purple, whereas we cannot mentally dissect a pure red or a pure blue. Moreover, the simple hues are organized into two antagonistic pairs (*Gegenfarben*): red and green, and yellow and blue. The qualities of a given pair are ones that do not normally occur together. Hering proposed that each pair of *Gegenfarben* was associated with the dissimilation or assimilation of a specific visual substance in the eye or visual system (Hering, 1878).

For much of its history, the trichromatic theory had the disadvantage of being tied to a simple Müllerian doctrine in which there were three types of visual nerve corresponding to the three receptors. Granted, as early as 1869 J.J. Chisholm, a physician from Charleston, South Carolina, suggested that 'there are special nerve fibres, for the recognition of special colours, independent of those used in the clear definition of objects'(Chisholm, 1869). And the same suspicion was expressed by Thomas Laycock (1869), who wrote: 'the optic nerve may subserve to at least three differentiations – namely, form, colour, and as a nerve of touch simply'. Only in the twentieth century, however, did the idea emerge that some nerve fibers might be excited by one type of photoreceptor and inhibited by others (Adams, 1923). A nerve that signaled the ratio of quantum catches in different classes of cone would be directly signaling chromaticity, rather than signaling the absolute level of quantum catch in one class of photoreceptors. The cones themselves are color blind (section 1.2), responding with a signal of the same sign to a broad spectral band; but a nerve that responds to the ratio of cone excitations does represent chromaticity as such.

In the 1960s, by micro-electrode recording from the lateral geniculate nucleus (LGN) of the primate visual system, neurons were revealed that did draw inputs of opposite sign from different classes of cone (De Valois *et al*., 1967). Such cells gave an excitatory response to one part of the spectrum and an inhibitory response to another part. Moreover, the cells appeared to fall into four classes, on the basis of (a) whether their excitatory response was at short wavelengths or at long and (b) where in the spectrum the excitatory response crossed over to inhibition. Many commentators were ready to identify these spectrally antagonistic cells with the yellow–blue and red–green opponent processes of Hering. Brindley (1970) was one of very few skeptics. In textbooks it became a commonplace to say that that theory of Helmholtz held at the level of receptors while the theory of Hering applied at a post-receptoral level. In fact, there turned out to be little correspondence between: (a) the directions in color space that uniquely stimulate individual types of chromatically antagonistic cells in the primate LGN, and (b) the red–green and blue–yellow axes of phenomenological color space (Derrington *et al*., 1984).

In surveying the history of color science, we have seen that confusion arose when information from one domain was used to constrain models in a different domain. The properties of our subjective color space still remain to taunt us today. We do not know the status that should be given to the phenomenological observations of Hering and we do not know how to incorporate them into a complete account of color science.

FURTHER READING

The following works are recommended:

Crone, R.A. (1999) *A History of Color*. Dordrecht: Kluwer Academic.

Gage, J. A. (1993) *Colour and Culture*. London: Thames and Hudson.

MacAdam, D. (1970) *Sources of Color Science*. Cambridge, MA: MIT Press.

Turner, R.S. (1994) *In the Eye's Mind: Vision and the Helmholtz–Hering Controversy*. Princeton, NJ: Princeton University Press.

The following analytic bibliographies are valuable:

Bell, J. (1926) *Colour-blindness. Eugenics Laboratory Memoirs, XXIII*. Cambridge: Cambridge University Press.

Helmholtz, H. von (1896) *Handbuch der Physiologischen Optik*, 2nd edn. Hamburg: Voss.

Plateau, J. (1877) Bibliographie analytique des principaux phénomènes subjectifs de la vision. *Mémoires de l'Académie royale des sciences, des lettres et des beaux-arts de Belgique*, volume 42.

Sutcliffe, J.H. (1932) *British Optical Association Library and Museum Catalogue*. London: BOA.

A chronological bibliography of color is maintained by the Grupo Argentino del Color at the web site: http://www.fadu.uba.ar/sicyt/color/bib.htm

REFERENCES

Abney, W. (1913) *Researches in Colour Vision and the Trichromatic Theory*. London: Longmans, Green Co.

Adams, E.Q. (1923) A theory of color vision. *Psychological Review*, 30, 56–76.

Allen, G. (1879) *The Colour-Sense: Its Origin and Development*. London: Trübner & Co.

Anonymous (1708) *Traité de la peinture en mignature*. La Haye (The Hague): van Dole.

Anonymous (1786) *Experiments and observations on light and colours: to which is prefixed the analogy between heat and motion*. London: J. Johnson.

Anonymous (1787) *A Narrative of the Life and Death of John Elliot M.D. containing an account of the rise, progress, and catastrophe of his unhappy passion for Miss Mary Boydell; a review of his writings. Together with an Apology, written by himself*. London: Ridgway.

Ayama, M., Nakatsue, T., and Kaiser, P.K. (1987) Constant hue loci of unique and binary balanced hues at 10, 100, and 100 Td. *Journal of the Optical Society of America A*, 4, 1136–44.

Barrett, C. (ed.) (1904) *Diary and Letters of Madame D'Arblay*. London: Macmillan.

Blankaart, S. (1680) *Collectanea Medico-Physica oft Hollands Jaar-Register Der Genes- en Natuur-kundige Aanmerkingen van gantsch Europa*. Amsterdam: Johan ten Hoorn.

Boltz, C.L. (1952) *A Statue to Mr. Trattles*. London: Butterworths.

Bonnet, C. (1755) *Essai de psychologie; ou considérations sur les opérations de l'âme, sur l'habitude et sur l'education*. London.

Bouma, P.J. (1947) *Physical Aspects of Colour*. Eindhoven: Philips.

Boyle, R. (1688) *Some Uncommon Observations about Vitiated Sight*. London: J. Taylor.

Brewster, D. (1842) *Letters on Natural Magic, addressed to Sir Walter Scott, Bart*. London: J. Murray.

Brindley, G. S. (1970) *Physiology of the Retina and Visual Pathway*. London: Arnold.

Brockbank, E.M. (1944) *John Dalton*. Manchester: Manchester University Press.

Castel, L. (1740) *L'Optique des couleurs*. Paris: Briasson.

Chisholm, J.J. (1869) Colour blindness, an effect of neuritis. *Ophthalmic Hospital Reports*, pp. 214–15.

Cunningham, P. (ed.) (1857) *The Letters of Horace Walpole, Earl of Orford*. London: Richard Bentley.

Dalton, J. (1798) Extraordinary facts relating to the vision of colours. *Memoirs of the Literary and Philosophical Society of Manchester*, 5, 28–43.

De La Hire, P. (1694) Dissertation sur les différens accidens de la vuë. *Mémoires de l'Académie Royale des Sciences*, 9, 530–634.

De Valois, R.L., Abramov, I., and Jacobs, G.H. (1967) Analysis of response patterns of LGN cells. *Journal of the Optical Society of America*, 56, 966–77.

Derrington, A.M., Krauskopf, J., and Lennie, P. (1984) Chromatic mechanisms in lateral geniculate nucleus of macaque. *Journal of Physiology (London)*, 357, 241–65.

Donders, F.C. (1883) *Nog eens: de kleurstelsels, naar aanleiding van Hering's kritiek*. Utrecht: G. Metzelaar.

Donders, F.C. (1884) Equations de couleurs spectrales simples et de leurs mélanges binaires, dans les systèmes normal (polychromatique) et anormaux (dichromatiques). *Archives Néerlandaises des sciences exactes et naturelles*, 19, 303–46.

Dossie, R. (1758) *The Handmaid to the Arts*. London: J. Nourse.

Elliot, J. (1780) *Philosophical Observations on the Senses of Vision and Hearing*. London: J. Murray.

Elliot, J. (1786) *Elements of the Branches of Natural Philosophy Connected with Medicine*. London: J. Johnson.

Forbes, E.G. (1970) Tobias Mayer's theory of colour-mixing and its application to artistic reproductions. *Annals of Science*, 26, 95–114.

Forbes, E.G. (1971) *Tobias Mayer's Opera Inedita*. London: Macmillan.

Gamauf, G. (1811) *Lichtenberg über Luft und Licht nach seinen Vorlesungen herausgegeben. Erinnerungen aus Lichtenbergs Vorlesungen über Erxlebens Anfangsgründe der Naturlehre*. Vienna and Trieste: Geistinger.

Gautier D'Agoty, J.F. (1752) *Observations sur l'Histoire Naturelle, sur la Physique et sur la Peinture, avec des Planches imprimées en couleur*. Paris: Delaguette.

Gautier D'Agoty, J.F. (1775) *Exposition anatomique des organes des sens, jointe a la névrologie entiere du corps humain et conjecture sur l'électricité animale*. Paris: Demonville.

Grassmann, H.G. (1853) Zur Theorie der Farbenmischung. *Annalen der Physik*, 89, 69–84.

Guericke, O. v. (1672) *Experimenta Nova (ut vocantur) Madeburgica de Vacuo Spatio*. Amstelodami: Janssonium.

Gurney, H. (1831) *Memoir of the Life of Thomas Young, M.D., F.R.S.* London: John and Arthur Arch.

Guyot, G.-G. (1769) *Nouvelles récréations physiques et mathématiques*. Paris: Gueffier.

Hall, A.R. (1992) *Isaac Newton*. Oxford: Blackwell.

Hansard (1909) *The Parliamentary Debates of the United Kingdom*. London: HMSO.

Helmholtz, H. (1852) Über die Theorie der zusammengesetzten Farben. *Annalen der Physik*, 87, 45–66.

Helmholtz, H. (1855) Über die Zusammensetzung von Spectralfarben. *Annalen der Physik*, 94, 1–28.

Henry, W.C. (1854) *Memoirs of the life and scientific researches of John Dalton*. London: Cavendish Society.

Hering, E. (1878) *Zur Lehre vom Lichtsinne. Sechs Mittheilungen an die Kaiserliche Akademie der Wissenschaften in Wien*. Vienna: Carl Gerold's Sohn.

Herschel, W. (1800a) Investigation of the Powers of the prismatic Colours to heat and illuminate Objects; with remarks that prove the different Refrangibility of radiant Heat. To which is added, an Inquiry into the Method of viewing the Sun advantageously with Telescopes of large Apertures and high magnifying Powers. *Philosophical Transactions of the Royal Society*, 90, 255–83.

Herschel, W. (1800b) Experiments on the Refrangibility of the Invisible Rays of the Sun. *Philosophical Transactions of the Royal Society*, 90, 284–92.

Heyer, T. (1864) *Ami Argand*. Geneva: Gruaz.

Hodgson, E. (1787) *The Trial of Doctor John Elliot, for Feloniously Shooting at Miss Mary Boydell*. London: Hodgson.

Holmgren, F. (1877) *Color-blindness in its Relation to Accidents by Rail and Sea*. Washington: Smithsonian Institute.

Huddart, J. (1777) An account of Persons who could not distinguish Colours. *Philosophical Transactions of the Royal Society*, 67, 260–5.

Hunt, D.M., Dulai, K.S., Bowmaker, J.K., and Mollon, J.D. (1995) The chemistry of John Dalton's color blindness. *Science*, 267, 984–8.

Hurlbert, A.C. (1998) Computational models of colour constancy. In V. Walsh and J. Kulikowski (eds), *Perceptual Constancy: Why Things Look as They Do.* Cambridge: Cambridge University Press.

Hutton, J. (1794) *A Dissertation upon the Philosophy of Light, Heat and Fire*. Edinburgh.

Huygens, C. (1673) An Extract of a Letter Lately Written by an Ingenious Person from Paris, Containing Some Considerations upon Mr. Newtons Doctrine of Colors, as Also upon the Effects of the Different Refractions of the Rays in Telescopical Glasses. *Philosophical Transactions of the Royal Society*, 8, 6086–7.

Ishihara, S. (1917) *Series of Plates Designed as Tests for Colour-blindness*. Tokyo.

Jennings, J.E. (1896) *Color-Vision and Color-Blindness. A Practical Manual for Railroad Surgeons*. Philadelphia: F.A. Davis.

Kaiser, P.K. and Boynton, R.M. (1996) *Human Color Vision*. Washington, DC: Optical Society of America.

Kohlrausch, A. (1923) Theoretisches und Praktisches zur heterochromen Photometrie. *Pflügers Arch. Gesamte Physiol. Menschen Tiere*, 200, 216–19.

König, A. and Dieterici, C. (1886) Die Grundempfindgungen und ihre Intensitätsvertheilung im Spectrum. *Sitzungsberichte Preuss. Akad. Wissenschaften, Berlin*, pp. 805–29.

König, A. and Dieterici, C. (1892) Die Grundempfindungen in normalen und anomalen Farbensystemen und ihre Intensitätsverteilung im Spektrum. *Zeitschrift für Psychologie*, 4, 241–347.

Ladd-Franklin, C. (1892) A new theory of light sensation. *International Congress of Psychology, 2nd Congress*. London, Kraus Reprint, 1974.

Lambert, J.H. (1770) Mémoire sur la Partie Photométrique de l'Art du Peintre. *Histoire de L'Académie Royale des Sciences et Belles-Lettres. Année MDCCLXVIII*, 24, 80–108.

Lambert, J.H. (1772) *Beschreibung einer mit dem Calauschen Waschse ausgemalten Farbenpyramide, wo die Mischung jeder Farbe aus Weiss und drey Grundfarben angeordnet, dargelegt und derselben Berechnung und vielfacher Gebrauch angewiesen wird durch J. H. Lambert.* Berlin: Hande and Spener.

Laycock, T. (1869) *Mind and Brain*. New York: Appleton.

Lee, B.B. (2001) Colour science in Göttingen in the 18th Century. *Color Research and Application*, 26, S25–S31.

Lee, H.-C. (1986) Method for computing the scene-illuminant chromaticity from specular highlights. *Journal of Optical Society of America, A3*, 1694–9.

Leicester, H.M. (1970) *Mikhail Vasil'evich Lomonosov on the Corpuscular Theory*. Cambridge, MA: Harvard University Press.

Lilien, O.M. (1985) *Jacob Christoph Le Blon*. Stuttgart: Anton Hiersemann.

Lomonosov, M.V. (1757) *Oratio de origine lucis*. Petropoli: Typis Academiae Scientiarum.

Lonsdale, H. (1874) *The Worthies of Cumberland. Volume 5. John Dalton*. London: Routledge.

MacLennan, M. (1975) *The Secret of Oliver Goldsmith*. New York: Vantage Press.

Marat, J.P. (1780) *Découvertes de M. Marat sur la Lumière; Constatées par une suite d'Expériences nouvelles*. Paris: Jombert.

Mason, W. (1958) Father Castel and his color clavecin. *Journal of Aesthetics and Art Criticism*, 17, 103–16.

Maxwell, J.C. (1855a) Experiments on Colour, as perceived by the Eye, with remarks on Colour-blindness. *Transactions of the Royal Society of Edinburgh*, 21, 275–98.

Maxwell, J.C. (1855b) On the theory of colours in relation to colour-blindness. *Researches on colour-blindness*. G. Wilson, pp. 153–9.

Maxwell, J.C. (1860) On the theory of the compound colours and the relations of the colours in the spectrum. *Philosophical Transactions of the Royal Society*, 150, 57–84.

Maxwell, J.C. (1871) On colour vision. *Proceedings of the Royal Institution of London*, pp. 260–71.

Mayer, T. (1775) *Opera Inedita*. Göttingen: J.C. Dieterich.

Mollon, J. D. (1985) L'Auteur énigmatique de la théorie trichromatique. *Actes du 5eme Congrès*. Paris, Association Internationale de la Couleur.

Mollon, J.D. (1987) John Elliot MD (1747–87). *Nature*, 329, 19–20.

Mollon, J.D. (1989) 'Tho' she kneel'd in that Place where they grew …'. *Journal of Experimental Biology*, 146, 21–38.

Mollon, J.D. (1992) Signac's secret. *Nature*, 358, 379–80.

Mollon, J.D. (1993) George Palmer. *The Dictionary of National Biography* (ed. C. S. Nicholls). Oxford: Oxford University Press, pp. 509–10.

Mollon, J.D. (1997) '..aus dreyerley Arten von Membranen oder Molekülen': George Palmer's legacy. *Colour Vision Deficiencies XIII* (ed. C.R. Cavonius). Dordrecht: Kluwer.

Mollon, J.D. (2002) The origins of the concept of interference. *Philosophical Transactions of the Royal Society A*, 360, 1–13.

Mollon, J.D. (in press) John Elliot (1747–87). *New Dictionary of National Biography* (ed. H.C.G. Matthew). Oxford: Oxford University Press.

Mollon, J.D., Dulai, K.S., and Hunt, D.M. (1997) Dalton's colour blindness: an essay in molecular biography. *John Dalton's Colour Vision Legacy* (eds C. Dickinson, I. Murray and D. Carden). London: Taylor and Francis, pp. 15–33.

Monge, G. (1789) Mémoire sur quelques phénomènes de la vision. *Annales de Chimie*, 3, 131–47.

Mortimer, C. (1731) An Account of Mr. James-Christopher Le Blon's Principles of Printing, in Imitation of Painting and of Weaving Tapestry, in the same manner as Brocades. *Philosophical Transactions of the Royal Society*, 37, 101–7.

Müller, J. (1840) *Handbuch der Physiologie des Menschen*. Coblenz: H. Ischer.

Nagel, W.A. (1907) Zwei Apparate für die Augenärzliche Funktionsprüfung. Adaptometer und kleines Spektralphotometer (Anomaloskop). *Zeitschrift für Augenheilkunde*, 17, 201–22.

Nathans, J., Thomas, D., and Hogness, D.S. (1986) Molecular genetics of human color vision: The genes encoding blue, green, and red pigments. *Science*, 232, 193–202.

Nettleship, E. (1913) *On Cases of Accident to Shipping and on Railways due to Defects of Sight*. London: Adlard and Son.

Newton, I. (1671) A Letter of Mr. Isaac Newton, Professor of the Mathematicks in the University of Cambridge; Containing His New Theory about Light and Colors: Sent by the Author to the Publisher from Cambridge, Febr. 6. 1671/72; In Order to be Communicated to the R. Society. *Philosophical Transactions of the Royal Society*, 6, 3075–87.

Newton, I. (1675/1757) Newton's second paper on color and light, read at the Royal Society in 1675/6. *History of the Royal Society of London*. T. Birch. London, Millar, vol. 3, pp. 247–305.

Newton, I. (1688) *Philosophiae Naturalis Principia Mathematica*. London: Joseph Streater.

Newton, I. (1730) *Opticks, or a Treatise of the Reflections, Refractions, Inflections & Colours of Light*. London: Wm. Innys.

Nuberg, N.D. and Yustova, E.N. (1955) Issledovanie cvetovogo zrenija dikhromatov. *Trudy Gosudarstvennogo Opticheskogo Instituta*, 24, 33–93.

Palmer, G. (1777a) *Théorie des couleurs et de la Vision*. Paris: Prault.

Palmer, G. (1777b) *Theory of colours and vision*. London: S. Leacroft.

Palmer, G. (1785) *Lettre sur les moyens de produire, la nuit, une lumière pareille à celle du jour*. Paris: 'Chez l'Auteur, rue Meslé, No. 18'.

Palmer, G. (1786) *Théorie de la Lumière, applicable aux arts, et principalement à la peinture*. Paris: Hardouin et Gattey.

Parrot, G.F. (1791) *Traité contenant la manière de changer notre lumière artificielle de toute espèce en une lumière semblable à celle du jour.* Strasbourg: J.G. Treuttel.

Partington, J.R. and McKie, D. (1941) Sir John Eliot, Bart. (1736–86), and John Elliot (1747–87). *Annals of Science*, 6, 262–7.

Peacock, G. (1855) *Life of Thomas Young MD, FRS*. London: John Murray.

Podestà, H. (1916) *Wandtafeln zur Prüfung des Farbensinnes und Erkennung der Farbensinnstörungen*. Hamburg: Friederischsen.

Rayleigh, L. (1881) Experiments on colour. *Nature*, 25, 64–6.

Rimington, A.W. (1912) *Colour-music. The Art of Mobile Colour*. London: Hutchinson.

Rood, O.N. (1879) *Modern Chromatics with Applications to Art and Industry*. London: Kegan Paul.

Rushton, W.A.H. (1965) Chemical basis of colour vision and colour blindness. *Nature*, 206, 1087–91.

Schrøder, M. (1969) *The Argand Burner*. Odense: Odense University Press.

Shapiro, A.E. (1980) The evolving structure of Newton's theory of white light and color. *Isis*, 71, 211–35.

Shapiro, A.E. (1993) *Fits, Passions and Paroxysms*. Cambridge: CUP.

Stiles, W.S. (1939) The directional sensitivity of the retina and the spectral sensitivities of the rods and cones. *Proceedings of the Royal Society B 127*, pp. 64–105.

Stilling, J. (1877) *Die Prüfung des Farbensinnes beim Eisenbahn- und Marine-personal*. Cassel: Theodor Fischer.

Strutt, R.J. (1924) *John William Strutt: Third Baron Rayleigh*. London: Edward Arnold.

Thompson, B. (1794) An Account of some Experiments upon coloured Shadows. By Lieutenant-General Sir Benjamin Thomson, Count of Rumford, F.R.S. In a Letter to Sir Joseph Banks, Bart. P.R.S. *Philosophical Transactions of the Royal Society*, 84, 107–18.

Turbervile, D. (1684) Two Letters from the great, and experienced Oculist, Dr. Turbervile of Salisbury, to Mr. William Musgrave S.P.S. of Oxon, containing several remarkable cases in Physick, relating chiefly to the Eyes. *Philosophical Transactions of the Royal Society*, 14, 736–7.

Voigt, J.H. (1781) Des herrn Giros von Gentilly Muthmassungen über die Gesichtsfehler bey Untersuchung der Farben. *Magazin für das Neueste aus der Physik und Naturgeschichte (Gotha)*, 1, 57–61.

Walls, G.L. (1956) The G. Palmer Story. *Journal of the History of Medicine*, 11, 66–96.

Weale, R.A. (1957) Trichromatic ideas in the seventeenth and eighteenth centuries. *Nature*, 179, 648–51.

Wilson, G. (1845) The life and discoveries of Dalton. *British Quarterly Review*, 1, 157–98.

Wilson, G. (1855) *Researches on colour-blindness, with a supplement on the danger attending the present system of railway and marine coloured signals.* Edinburgh: Sutherland & Knox.

Wood, A. (1954) *Thomas Young, Natural Philosopher 1773–1829*. Cambridge: Cambridge University Press.

Wright, W.D. (1952) The characteristics of tritanopia. *Journal of the Optical Society of America*, 42, 509–21.

Wright, W.D. (1967) *The Rays are not Coloured*. London: Hilger.

Wünsch, C. E. (1792) *Versuch und Beobachtungen über die Farben des Lichts*. Leipzig: Breitkopf.

Wyszecki, G. and Stiles, W.S. (1967) *Color Science*. New York: Wiley.

Young, T. (1800) Outlines of experiments and inquiries respecting sound and light. *Philosophical Transactions of the Royal Society*, 90, 106–50.

Young, T. (1802a) The Bakerian Lecture. On the Theory of Light and Colours. *Philosophical Transactions of the Royal Society of London*, 92, 12–48.

Young, T. (1802b) *A syllabus of a course of lectures on natural and experimental philosophy*. London: Royal Institution.

Young, T. (1804) *Reply to the animadversions of the Edinburgh reviewers on some papers published in the Philosophical Transactions*. London: Longman & Co.

Young, T. (1807) *A course of lectures on natural philosophy and the mechanical arts*. London: J. Johnson.

Young, T. (1817) Chromatics. *Supplement to the Encyclopaedia Britannica*, 3**,** 141–63.