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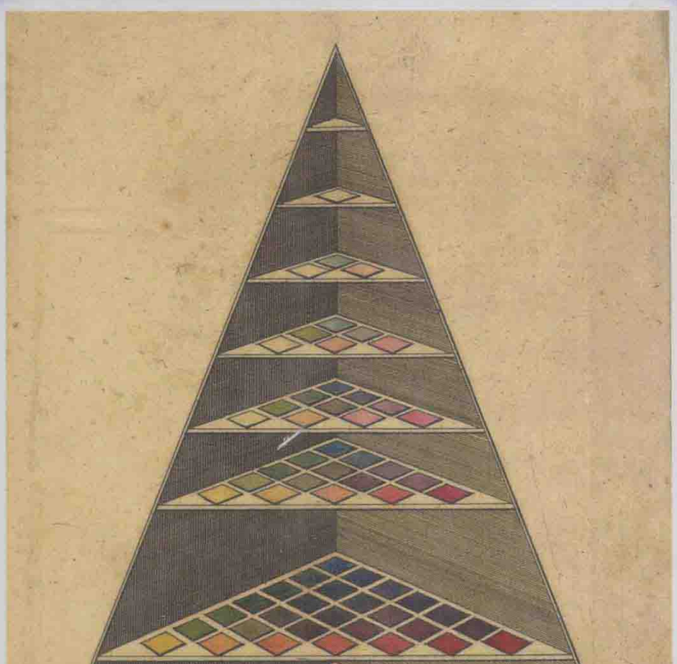
THE SCIENCE OF COLOR

Second Edition



EDITED BY

STEVEN K. SHEVELL

OSA®
Optical Society of America

The Science of Color

Second Edition

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Steven K. Shevell

Departments of Psychology and
Ophthalmology & Visual Science
University of Chicago

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Preface

This second edition of *The Science of Color* focuses on the principles and observations that are foundations of modern color science. Written for a general scientific audience, the book broadly covers essential topics in the interdisciplinary field of color, drawing from physics, physiology and psychology. The jacket of the original edition of the book described it as 'the definitive book on color, for scientists, artists, manufacturers and students'. This edition also aims for a broad audience.

The legendary original edition was published by the Optical Society of America in 1953 and sold until 1999 after eight printings. It was written by a committee of 23, with contributions from the Who's Who of color including Evans, Judd, MacAdam, Newhall and Nickerson. This new edition was written by a smaller group of distinguished experts. Among the 11 authors are eight OSA fellows, five past or present chairs of the OSA Color Technical Group, the two most recent editors for color at the *Journal of the Optical Society of America A*, and four recipients of the OSA's prestigious Tillyer Medal. The authors also reviewed related chapters to strengthen sustantive content. While the field of color has spread too broadly since 1953 to say the new edition is 'the definitive book on color', the topics in each chapter are covered by recognized authorities.

The book begins by tracing scientific thinking about color since the seventeenth century. This historical perspective provides an introduction to the fundamental questions in color science, by following advances as well as misconceptions over more than 300 years. The highly readable chapter is an excellent introduction to basic concepts drawn upon later.

Every chapter begins with a short outline that summarizes the organization and breadth of its material. The outlines are valuable guides to chapter structure, and worth scanning even by readers who may not care to go through a chapter from start to finish. The outlines are also useful navigation tools for finding material at the reader's preferred level of technical depth.

A book of modest length must selectively pare its coverage. The focus here is on principles and facts with enduring value for understanding color. No attempt was made to cover color engineering, color management, colorant formulation or applications of color science. These are very important and rapidly advancing fields but outside the scope of this volume.

The authors are grateful to two experts who reviewed the complete text: Dr Mark Fairchild (Munsell Color Science Laboratory, Rochester Institute of Technology) and Dr William Swanson (SUNY College of Optometry). Their time and expertise contributed significantly to the quality of the chapters. Thanks are due also to Alan Tourtlotte, associate publisher at the OSA, for his determination and patience from conception to completion.

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Steven K. Shevell
Chicago

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The Origins of Modern Color Science

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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
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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

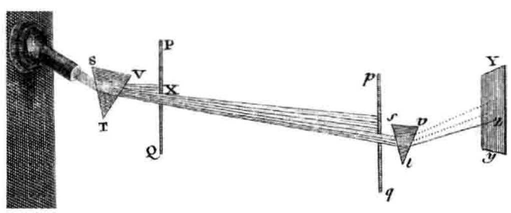


Figure 1.1 **An eighteenth-century representation of Newton's *Experimentum crucis*. As the left-hand prism is rotated around its long axis, the beam selected by the two diaphragms is constant in its angle of incidence at the second prism. Yet the beam is refracted to different degrees at the second 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

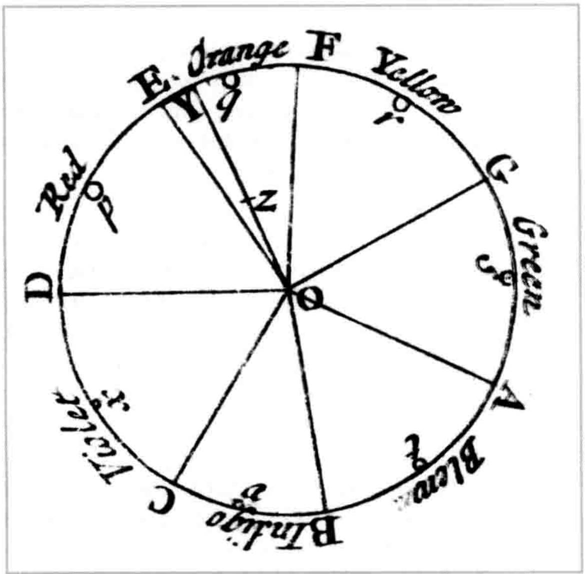


Figure 1.2 Newton's color circle, introduced in his *Opticks* of 1704.

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.

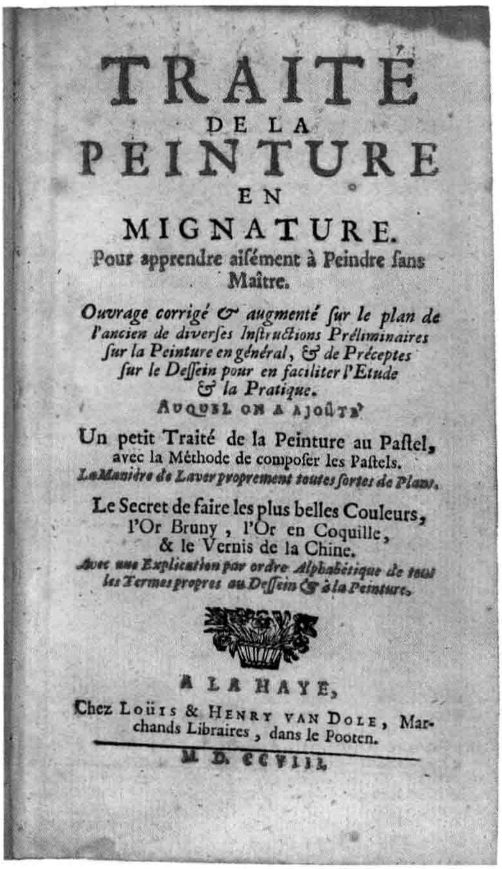
1.2 THE TRICHROMACY OF COLOR MIXTURE

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.

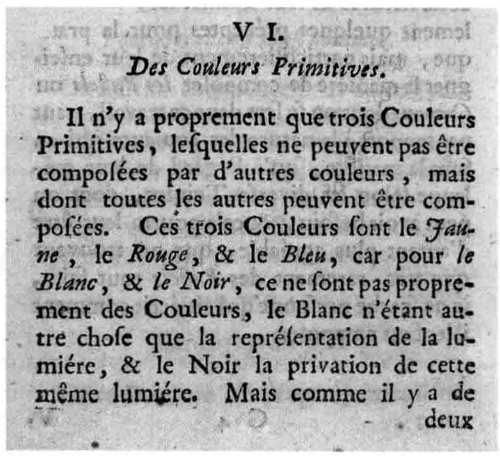
Ouvrage corrigé & augmenté ſur le plan de l'ancien de diverſes Inſtructions Préliminaires ſur la Peinture en général, & de Préceptes ſur le Deſſein pour en faciliter l'Etude & la Pratique.

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 Alphabétique de tous les Termes propres au Deſſein & à la Peinture.

A LA HAYE,
Chez LOÜIS & HENRY VAN DOLE, Marchands Libraires, dans le Pooten.
M. D. CCVIII.



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)

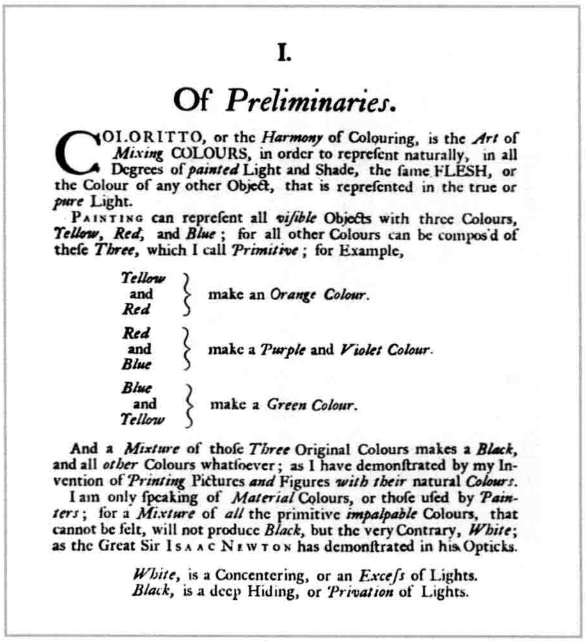
1.2.1 TRICHROMACY AND THE DEVELOPMENT OF THREE-COLOR REPRODUCTION

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 reprefent naturally, in all Degrees of *painted* Light and Shade, the fame FLESH, or the Colour of any other Object, that is reprefented in the true or *pure* Light.

PAINTING can reprefent all *vifible* Objects with three Colours, *Yellow*, *Red*, and *Blue*; for all other Colours can be compos'd of thefe *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 thofe *Three* Original Colours makes a *Black*, and all *other* Colours whatfoever; as I have demonftrated by my Invention of *Printing* Pictures *and* Figures *with their* natural *Colours*.

I am only fpeaking of *Material* Colours, or thofe ufed 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 demonftrated in his Opticks.

White, is a Concentering, or an *Excefs* 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

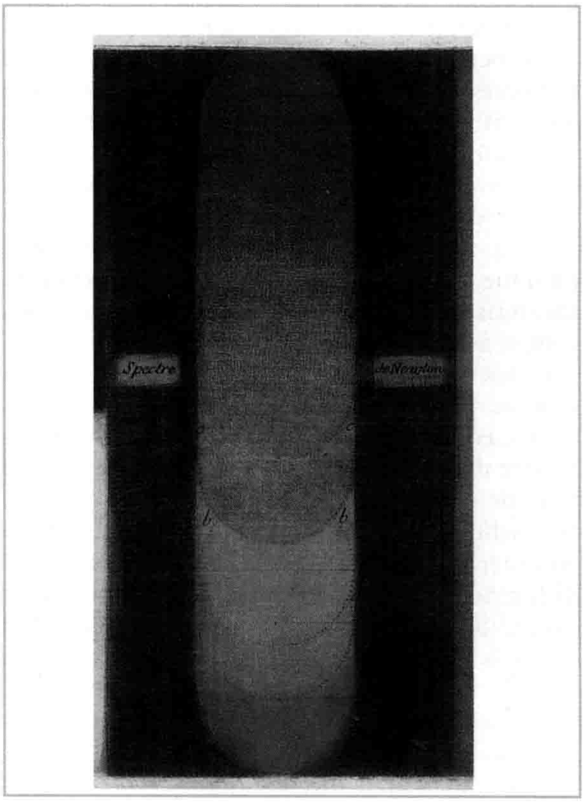


Figure 1.5 The first representation of Newton's spectrum to be printed in color. From the *Observations sur l'Histoire Naturelle* of Gautier D'Agoty, 1752.

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.

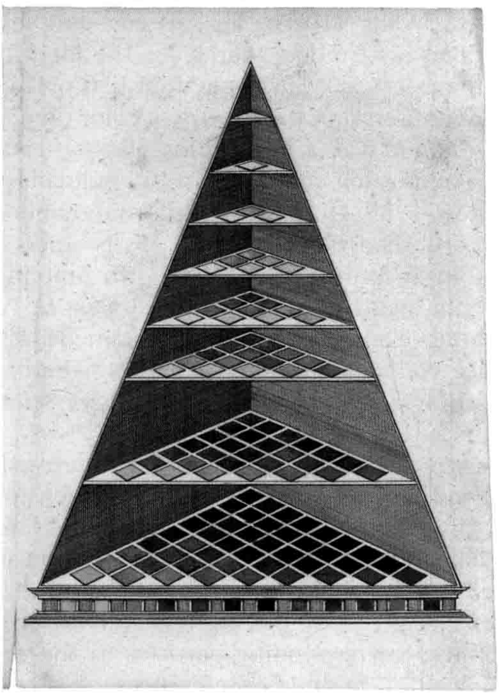


Figure 1.6 **The *Farbenpyramide* of J.H. Lambert (1772). Reproduced with permission of J.D. Mollon.**

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).

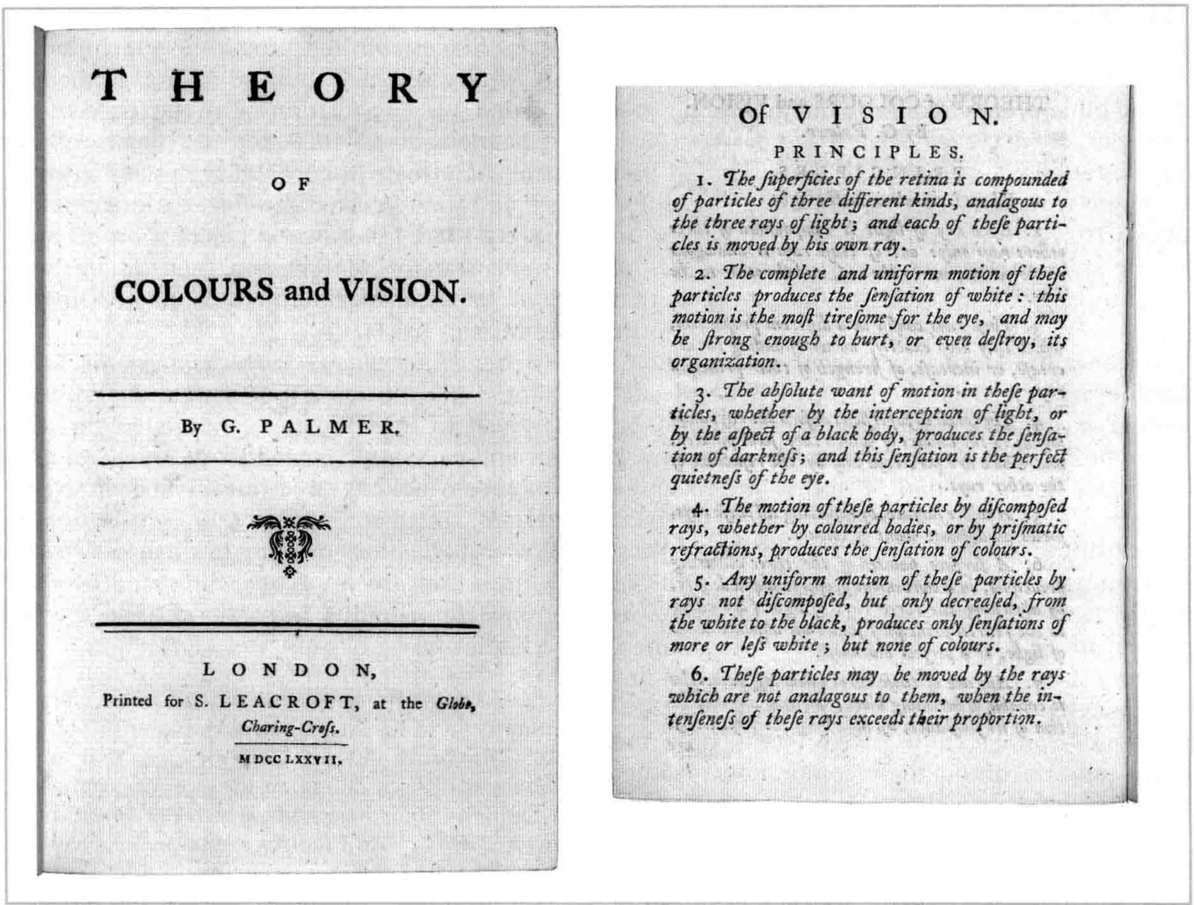
In the *Essai de Psychologie* of Charles Bonnet (1755) we find the idea of retinal resonators combined with a conventionally Newtonian account of light. Bonnet, however, supposed that for every degree of refrangibility there must be a resonator, just as – he suggested – the ear contains many different 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, analagous 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 aſpect 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 analagous 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,