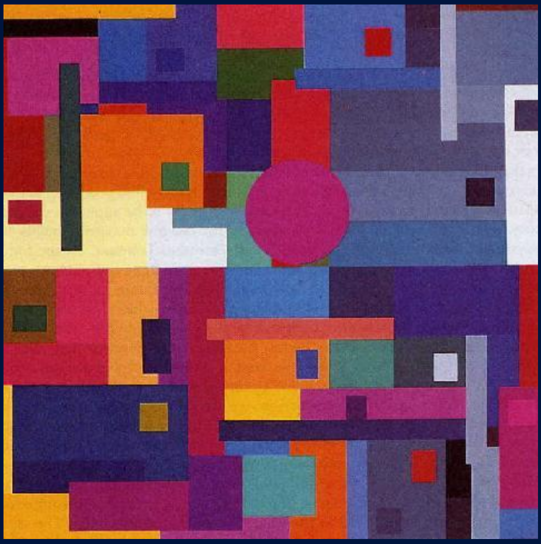
The Land Experiments in Colour Vision

Colour as a Physical, Phenomenological, and Synthetic Object



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The Land Experiments in Colour Vision

Colour as a Physical, Phenomenological, and Synthetic Object

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DECLARATION

I, Joseph Brown, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Joseph Brown ………………………………..

11/12/2022 …………………..

Joseph Brown

Date of signature

ABSTRACT

This thesis analyses the historical and intellectual context of Edwin Land's experiments in colour vision. I argue that the colour vision research program and *retinex* theory developed by Land and his colleagues provided a satisfying synthesis of two divergent schools in the history of colour science.

The first chapter of this thesis establishes the existence of the "physical" school of colour science. The defining feature of this school was the belief in the *colour atomism hypothesis*. This is the idea that the colour perceived at a point in the visual field is completely determined by the physical properties of the light rays entering the retina at that point. In other words, there is a one-to-one correspondence between the physical properties of light rays and colour sensation at a point in the visual field.

The second chapter establishes the existence of the "phenomenological" school of colour science. The defining feature of this school was the discovery of colour phenomena which could not be accounted for by the colour atomism hypothesis. Among these phenomena were "coloured shadows", "simultaneous colour contrast", and "colour constancy".

The third chapter shows how Land's colour vision research program and retinex theory reconciled these two schools. Land and his colleagues demonstrated that the colour atomism hypothesis is a special case, valid only for points of light. The colour phenomena studied by the "phenomenological" school could be predicted by a computational model – retinex theory – which accounted for colour as it is perceived over a wide visual field, rather than simply at single points. In this process, Land and colleagues built up a new understanding of colour vision as a practical utility evolved for the organism, designed to achieve colour constancy.

IMPACT STATEMENT

It is my hope that this thesis will be most beneficial as a bridge between disciplines.

Firstly, I hope that it will be a useful resource for practitioners of the visual arts. There is a long tradition in colour literature of pitting the work of Isaac Newton and Johann Wolfgang von Goethe against one another. Related to this is the idea that scientists have nothing to add to the artistic understanding of colour, and vice versa that artists have nothing to add to the scientific understanding of colour. I hope that this work can show that the reality of the history of colour science is more nuanced than is commonly believed, and show that the "physical" and "phenomenological" understanding of colour are not incommensurable.

Secondly, I hope that scientific practitioners, especially colour scientists and visual neuroscientists will benefit from an accessible and coherent framework for understanding the aspects of this thesis which impact their disciplines. For example, I have received positive feedback in this respect from a researcher who despite having dedicated much of their working life to colour vision, was unaware of some of the historical figures I have covered. The original translations included in this volume will also benefit historians of colour science who have different research interests than my own.

Thirdly, it is hoped that historians and sociologists of science will find this to be a useful case study. This is a rare example of "convergence" in the history of science, where the observations and established facts of two previously incommensurable sciences were united under one research program.

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PREFACE

For as long as I can remember I have been curious as to why there should be exactly "seven colours" in the rainbow and in the visual spectrum. Later, I think in my teenage years, I was bemused by the idea that two great intellects of their respective times – Newton and Goethe – could come up with such divergent theories of colour.

I had no intention of going into the history of science when I first went to university. When the time came to leave school I was curious about the brain and whether there was any hope in the programme of reducing mind to matter. I enrolled on a degree of Natural Sciences at UCL beginning in 2012. This was a broad programme and my original intention was to study neurobiology along with organic chemistry. In first year I picked an option in the history and philosophy of science. I'm glad I did. I decided to leave the joys of organic chemistry to my colleagues, and for the rest of my time there I studied neurobiology in combination with the history and philosophy of science. In 2015 I took the advanced course in visual neuroscience directed by Prof Andrew Stockman and Prof Stewart Shipp at UCL. This is when we were bowled over by first-hand replications of Edwin Land's experiments in colour vision … or at least I was. Under the supervision of Dr Chiara Ambrosio, I wrote my (history of and philosophy of science) undergraduate thesis on the use of cladistic models in phylogenetics and historical linguistics. Her support and enthusiasm for my project gave me belief in my ability to pursue the subject beyond undergraduate level. Unfinished business in the history of science and a desire to brush up on my French led me over to the Ecole Normale Supérieure and the LOPHISS programme, where the idea for this thesis crystallised under the supervision of Prof Justin E. H. Smith.

As part of this project, in the summer of 2018 I held a visiting fellowship at the Yale Center for British Art. This enabled me to make use of the Faber Birren Collection of Books on Color, and the YCBA's own extensive archives. Furthermore, I was able to use New Haven as a base to make trips up to the Polaroid Corporate Archives at Harvard Business School's Baker Library, and to meet John McCann, who was a long-time research collaborator and personal friend of Edwin Land, and former head of the Vision Research Laboratory at Polaroid.

I am grateful to Dr Jean-Baptiste Gouyon for his advice and helping me to procure resources at the BBC, and to Dr Tiago Mata for giving me the opportunity to present my work at the STS departmental seminar. Finally, I would like to thank Prof Andrew Gregory and Prof Jon Agar for helping to guide this project from its overambitious beginnings to the work I present here.

INTRODUCTION

This thesis provides the first historical account dedicated entirely to the intellectual context of Edwin Land's experiments in colour vision. Edwin Herbert Land (1909-1991) was an inventor, scientist, and founder of the Polaroid Corporation. Land is more commonly known for having developed the Polaroid instant camera and commercially viable polarizing light filters – innovations which have been given great attention by historians of technology[1,2,3] – but so far remarkably little academic historical attention has been given to his greatest contribution to natural science. I will establish the existence of two incommensurable schools in the history of colour science – the "physical" school and the "phenomenological" school – and argue that Land's contributions made the observations of these schools commensurable.

Land's experiments showed us that classical colour theory – according to which subjectively reported colours correspond to exact wavelengths of light – is only valid in certain controlled situations, for example when spots of light are observed in completely dark surroundings. He proved, quantitatively and qualitatively, that colour perception at any single point in the visual field is not exclusively determined by the pattern of wavelength reflectance at that point, but rather by the relative reflectance of that point compared with that of the entire surrounding visual field.

The "retinex" algorithm, subsequently developed by Land and colleagues at the Vision Research Laboratory at Polaroid, could explain why objects retain their colours despite being viewed under a wide range of lighting conditions – the phenomenon known as "colour constancy". It could also explain the long-known yet mysterious phenomena of coloured shadows and simultaneous colour contrast. The retinex algorithm facilitated the accurate prediction of colours perceived at any desired point in the visual field, given the input of surrounding-scene reflectance values. The retinex has been called "the first computational model of colour constancy to attract widespread attention".[4]

The starting point for my research was to look at textbooks on colour vision from the 1940s and 1950s, paying special attention to those which Land explicitly referenced in his papers. Land explicitly referenced:

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[1] McElheny, Victor K. (1998). *Insisting on the Impossible: The Life of Edwin Land, Inventor of Instant Photography*. (Perseus Books).

[2] Wensburg, Peter C. (1987). *Land's Polaroid. A Company and the Man Who Invented It.* (Houghton Mifflin Company, Boston).

[3] Fierstein, Ronald K. (2015). *A Triumph of Genius: Edwin Land, Polaroid, and the Kodak Patent War.* (American Bar Association).

[4] Shevell, Steven K. (ed.). (2003). *The Science of Color.* (Elsevier), p.185

- Edwin G. Boring's *Sensation and Perception in the History of Experimental Psychology* (New York: D. Appleton-Century Company. Inc., 1942)
- *The Science of Color*. Committee on Colorimetry, Optical Society of America. (New York: Thomas Y. Crowell, 1953).
- Ralph M. Evan's *An Introduction to Color* (New-York, John Wiley & Sons, 1948)

As I have mentioned, in Chapters One and Two I will establish the existence of the "physical" and "phenomenological" sciences of colour. Such a categorisation of the history of colour science is not entirely new. Land's principal source when looking at the history of his own discipline – Edwin G. Boring's *Sensation and Perception in the History of Experimental Psychology* (1942) – made this physical/phenomenological distinction explicit.[5] This work was a history of the investigation of colour phenomena as told by one of Land's preeminent scientific contemporaries. Boring made the distinction between investigators who were primarily interested in the "mechanisms" of colour perception, and those who were primarily interested in in the "phenomena and phenomenal experience" of colour.[6] Boring wrote that the latter – the "phenomenological tradition" – is "characterized by a belief in the value of the direct observation of experience and a mistrust of the mediation of physiological fact by elaborate experimentation … thus experimentalism finds itself opposed to phenomenology … the tempers of the two are opposite".[7]

> Where phenomenology is egoistic, asserting the validity of individual observation and insight, experimentalism is diffident, mistrusting individual observation and relying upon controls, procedures without knowledge, and the other techniques that have been devised to achieve assurance in the face of the unreliability of human observation. Nowhere is the changing balance between phenomenology and experimentalism better illustrated than in the history of visual sensation.[8]

Land also often cited other contemporary textbooks which characterised the history of colour science in a similar way.[9,10,11,12] In addition to this, as we shall see in Chapter Two, Land explicitly

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[5] Land cited Boring (1942) in:
- Land, E.H. (1959). "Experiments in Color Vision". *Scientific American,* Vol. 200, pp. 84-94, 96-99, May 1959.
- Land, E.H. (1962). "Colors Seen in a Flash of Light". *Proceedings of the National Academy of Sciences*, Vol. 48, pp. 1000-1008, June, 1962.

[6] Boring, E.G. (1942). *Sensation and Perception in the History of Experimental Psychology* (New York: D. Appleton-Century Company. Inc., 1942), p.4

[7] *Ibid.* p.116-117

[8] *Ibid.* p.117

[9] Crowell, T.Y. (1953). *The Science of Color*. Committee on Colorimetry, Optical Society of America. (New York: Thomas Y. Crowell, 1953)

[10] Land cited Crowell (1953) in:
- Land, E.H. (1962). "Colors Seen in a Flash of Light". *Proceedings of the National Academy of Sciences*, Vol. 48, pp. 1000-1008, June, 1962.

[11] Evans, R.M. (1948). *An Introduction to Color*. New-York, John Wiley & Sons, 1948

[12] Land cited Evans (1948) in:
- Land, E.H. and McCann, John J. (1971). "Lightness and Retinex Theory". *Journal of the Optical Society of America,* Vol. 61, No.1, pp.1-11, January 1971.

acknowledged the existence of the phenomenological tradition. Furthermore, in Chapter Three we shall see how Land pitted his findings against the Newtonian "physical" school's assumption that "Colours in the Object are nothing but a disposition to reflect this or that sort of Rays more copiously than the rest".[13]

This distinction is also present in more recent historical commentary on the subject, for example in Turner (1994):

> By the 1930s American scientists acknowledged that the study of "color" was badly polarized between "physicalist" and "psychological" approaches (Jones 1953; Optical Society of America 1966).[14]

Although it is true that the history of colour science has often been oversimplified and characterised as a sort of incommensurable schism between the "Newtonians" and the "Goethians" [15,16], I will argue that there is fundamental sense in dividing the history of colour science into the "physical" and "phenomenological" schools. As we shall see, my argument relies on one feature that divided these schools – the *colour atomism hypothesis*.

In the process of researching this thesis I came across important treatises that had not yet been translated into English. Attached to this thesis are the author's translations of:

- Comte de Buffon's "Observations on accidental colours, and on coloured shadows" (1774)
- Guillaume Le Gentil's "On the colours that red and yellow-painted objects assume when they are viewed through red or yellow-tinted glasses" (1791)
- Georg Wilhelm Muncke's "On subjective colours and coloured shadows" (1820)

Coloured diagrams are used extensively throughout this thesis. In order to benefit the most from these, I advise the reader to view them in the electronic pdf form, as some of the effects may be lost in a printed version due to the variable hues of the ink pigments.

- McCann, J.J, Land, E.H, and Tatnall, S.M. (1970). "A Technique for Comparing Human Visual Responses with a Mathematical Model for Lightness". *American Journal of Optometry and Archives of American Academy of Optometry,* Vol. 47, No.11, pp.845-855, Nov. 1970.
- Land, E.H. (1974). "Smitty Stevens' Test of Retinex Theory". *Sensation and Measurement*, Papers in Honor of S.S. Stevens, edited by Howard R. Moskowitz, Bertram Scharf, and Joseph C. Stevens, D. Reidel Publishing Company, Boston, 1974, pp.363-368.

[13] Newton, I. (1952) [1704]. *Opticks, Or a Treatise on the Reflections, Refractions, Inflections & Colours of Light.* Based on the fourth edistion London, 1730. (Dover 1952), Book I Part II p.109

[14] Turner, R. S. (1994) *In the Eye's Mind : Vision and the Helmholtz-Hering Controversy* (Princeton University Press), p.264

[15] As Shapiro (1990) put it, "the vast literature inspired by Goethe's attack on Newton's theory of color nearly two centuries ago has been excessively partisan and largely a continuation of the original polemics."

[16] *See* Sepper, Dennis. (1988). *Goethe contra Newton: Polemics and the project for a new science of color* (Cambridge University Press)

CHAPTER ONE

The Physical Science
of Colour

By convention there is colour, by convention sweetness and bitterness, but in reality there are atoms and space.

Democritus (c. 460 BCE–c. 400 BCE) Fragment 125

INTRODUCTION: THE COLOUR ATOMISM HYPOTHESIS

Throughout the history of the physical science of colour, models of light have undergone numerous changes, most obviously of all with the transition from a corpuscular model to a wave model. Models of the perception of colour have changed from Newton's "vibrating" nerves, to the three "particles" of the trichromatic theory, to "rods" and "cones". Yet throughout this time one model has persisted. This is the idea that the colour perceived at a point in the visual field is completely determined by the physical properties of the light rays entering the retina at that point. In other words, there is a one-to-one correspondence between the physical properties of light rays and colour sensation at a point. This is I will call the *colour atomism hypothesis*.

The following proposition from Isaac Newton's *Optical Lectures* is characteristic of this school of thought:

> Corporum naturalium colores e genere radiorum derivantur, quos maxime reflectunt.
>
> ("The colours of natural bodies are derived from the type of rays which they reflect to the highest degree.") [17]

Davies (2012) has used the term *reflectance physicalism* to describe the view that:

1. Colours are surface spectral reflectance properties.
2. Colours are not in any sense ontologically dependant on the visual responses or representational capacities of perceiving subjects.
3. Colours are *type identical with* physical properties.[18]

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[17] Newton, Isaac. (1729). *Academia Cantabrigiensi. Matheseeos olim Professoris Lucasiani. Lectiones Opticæ.* (Royal Society, 1729). (Prop V, Sect. I Lucis Coloribus), p.215

[18] Davies, W. (2012). Essays on the perception, representation, and categorisation of colour [PhD thesis]. Oxford University, UK, pp.68-69

There are some subtle differences between this and the colour atomism hypothesis. In relation to the three parts of Davies' definition of reflectance physicalism:

1. The colour atomism hypothesis is the idea that the colour perceived *at a point* is completely determined by the surface spectral reflectance properties at that point. Colours are determined point by point – pixel by pixel – and colours in the surround have no influence over the determination of colour at a point. Adapting Davies' definition, we can define the colour atomism hypothesis as the view that "colour at a point is determined by spectral reflectance properties AND colours in the surround have no influence over the determination of colour at that point".
2. The colour atomism hypothesis does not exclude theories, such as the trichromatic theory, which maintain that colour is dependent on the visual responses of the perceiving subject. As we shall see in this chapter, supporters of the trichromatic theory posited the existence of three kinds of "particles" in the retina which respond to different parts of the visual spectrum. What is important is that colour is determined point by point. It is not important whether the physical process that "causes" this is located in the light rays themselves or in a visual response at a point on the retina.
3. The colour atomism hypothesis does not claim that colours are type identical with physical properties. It only claims that colours at a point are completely *determined by* physical properties at a point.

For Descartes, the physical input which determined colour was "globules" with differing rotational speeds, caused by a "modification" of light. For Newton and the "separationist" school, the corpuscles making up white light already had their colour inducing properties, with no need for modification. In the Young-Helmholtz-Maxwell trichromatic model, waves with different frequencies/wavelengths caused differing responses in the three sorts of "particles" at a point on the retina. This chapter will demonstrate that despite these changes in the models of light, the fundamental colour atomism hypothesis remained unchanged.

MODIFICATIONISM AND CARTESIAN COLOUR

MODIFICATIONISM AND SEPARATIONISM: AN INTRODUCTION

Historians of science have traditionally identified two doctrines of colour theory among the early investigators of colour; "modificationism" and "separationism". [19, 20, 21, 22, 23] As we shall see, supporters of the modificationist doctrine regarded colour as arising from the physical *modification* of pure light. For the modificationists, white was the primary original colour of light. For example, in Descartes' model, otherwise "pure" white light globules were modified and made coloured when they started to spin when white light passed through a modifiying medium such as a glass prism. The colour a human observer would then perceive depended upon the speed of rotation of these globules.

On the other hand, supporters of the separationist doctrine saw colour as arising when pure white light was *separated* out into its natural constituent parts by a separating medium such as a glass prism. In the separationist view, white light is already composed of different sorts of "coloured" rays before it encounters the separating medium. These rays are not modified by the prism in any way – the prism simply exposes what was already there by separating out the rays based on their refrangibility.

THE RAINBOW

A good example of modification theory in practice is the evolution of the understanding of the rainbow. In Book III of his *Meteorology*, Aristotle gave a geometric explanation of the rainbow, arguing that the rainbow only appears when there is a certain angle subtended between the sun, the observer, and the cloud opposite him. For Aristotle the colours of the rainbow were caused by the interaction of this (darker) cloud with the light incident upon it.[24] This explanation could account for why the rainbow was curved, why the rainbow disappeared when the sun reached its zenith, and why the rainbow moved as the observer moved.

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[19] Nakajima, H. (1983). "Two kinds of modification theory of light: Some new observations on the Newton-Hooke controversy of 1672 concerning the nature of light". *Annals of Science* (Volume 41, 1984 – Issue 3), pp 261-278.

[20] Shapiro, Alan E. (1980). "The Evolving Structure of Newton's Theory of White Light and Color". *Isis* (Vol. 71, No. 2 Jun. 1980), pp. 211-235

[21] Shapiro, Alan E. (1994). "Artists' Colors and Newton's Colors". *Isis* (Vol. 85, No. 4, Dec. 1994), pp. 600-630

[22] Westfall, Richard S. (1962). "The Development of Newton's Theory of Color ». *Isis* (Vol. 53, No. 3 Sep. 1962), pp. 339-358

[23] Zemplén, Gábor Á. (2005). *The History of Vision, Colour, & Light Theories: Introductions, Texts, Problems*. (Bern Studies in the History and Philosophy of Science)

[24] Meteorologica - Works of Aristotle translated into English: Meteorologica. By E. W. Webster. I vol. Oxford: Clarendon Press, 1923

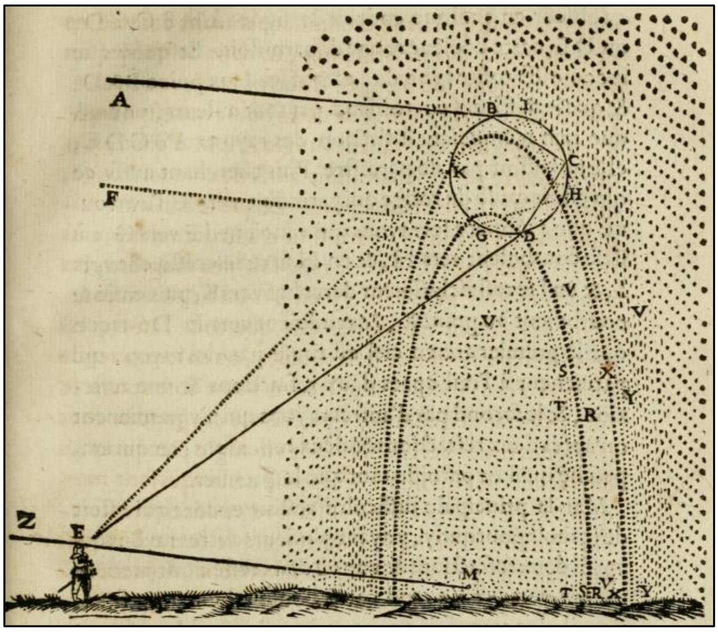

Figure 1: Schematic diagram of a rainbow, taken from Descartes' *Météores*, Discours VIII (page 251)

The fact that a man-made "spectrum" [25] could be produced using glass had been known since the time of Seneca (d. AD 65). The English friar Roger Bacon (1214-1292) noticed that spraying mouthfuls of water produced the same spectrum as was exhibited in the colours of the rainbow. Kamāl al-Dīn al-Fārisī (1267-1319)[26], Theodoric von Freiberg (1250-1310)[27], Johannes Kepler (1571-1630)[28] and René Descartes (1596-1650)[29] all carried out experiments with large spherical glass vessels filled with water to simulate a water droplet. The same conclusion was reached by all – the primary arc of the rainbow is caused by a ray of light which undergoes two refractions (entering and exiting the droplet) and one total internal reflection, and the secondary arc is caused by a ray of light which undergoes two refractions and *two* total internal reflections. Each of these practitioners gave more precise measurements than the last for the exact angle of the arcs, Descartes measuring 41° 17' for the primary arc and 51° 37' for the secondary arc.[30]

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[25] A term coined by Newton in his *Opticks*. From Latin *spectrum* ("appearance, image, apparition"), from *speciō* ("look at, view")

[26] *Kitab Tanqih al-Manaẓir* (*The Revision of the Optics*)

[27] *De iride et radialibus impressionibus* (*On the Rainbow and the impressions created by irradiance*, c. 1304-1311)

[28] *Ad vitellionem paralipomena* (1604)

[29] *Les Météores*, Discours VIII

[30] Descartes R. (2009) [1637]. *Les Météores* – p.357

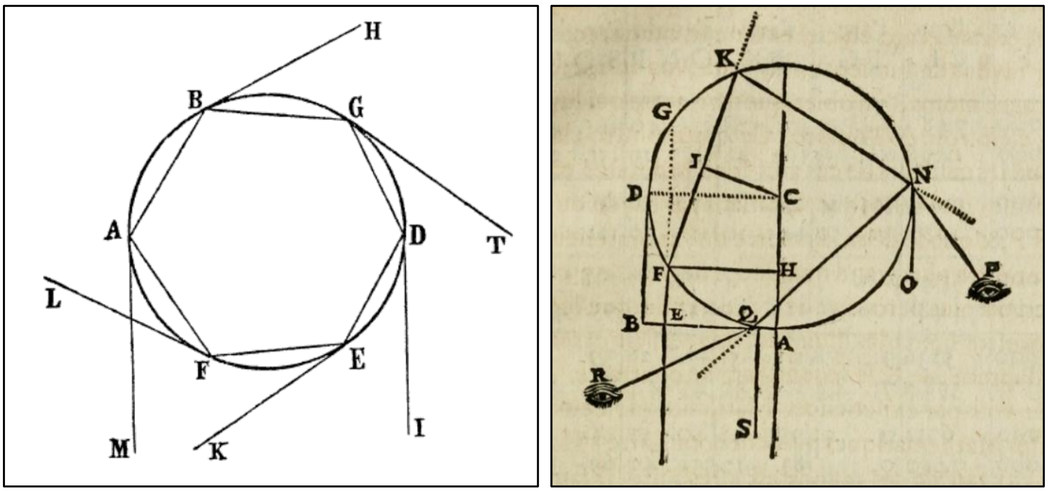

Figure 2: The Keplerian theory of internal reflection/refraction in the rainbow (left) compared with that of Descartes (right). MA (left image) and EF (right image) are the rays that enter the droplet from the sun, GP and NP are the rays that make up the primary rainbow arc, and EK and QR are those that make up the secondary rainbow arc. (Johannes Kepler, Joannis Kepleri Astronomi Opera Omnia, vol. 2, p. 70, ed. Christian Frisch [Heyden & Zimmer, Frankfurt am Main and Erlangen, 1859] and Descartes *Météores* p.263.)

What is important for our purpose is to understand that these practitioners all saw the colours arising from a *modification* of the "pure" light that entered the water droplet. However, as a number of historians have made clear, not all of these practitioners held exactly the same kind of modification theory.[31, 32]

MODIFICATIONISM CHEZ DESCARTES

Hideto Nakajima and Alan E. Shapiro have identified two kinds of modification theory; an "Aristotelian" one in which darkness has a role in creating colour; and a "Cartesian" one in which there is a mechanical modification of the properties of light, with no reference to subjective colour.[33]

Anaximenes of Miletus (c. 586 – c. 526 BC) had proposed that the colours of the rainbow were engendered when light from the sun met the darkness of a cloud. Aristotle built on this idea and generalised it for all colours. In the *Meteorologica* Aristotle proposed that colours are generated as

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[31] Nakajima, H. (1984). *Op cit*

[32] Shapiro, Alan E. (1994). *Op cit*

[33] Nakajima, H. (1984). *Op cit*

"pure" white light is modified by passing through or being reflected from a dark medium.[34] Aristotle also equated the "strength" of a colour with its purity and brilliance. Thus, the "strongest" colour of the spectrum – red – was considered to be the closest to white, and the least "modified". As the light is modified more and more by the darkness, it will become green, then violet, and finally black. Thus, he concluded that all colours were on a continuum between the poles of black and white.[35] Aristotle's form of modificationism persisted into the era of medieval optics. For example, Robert Grosseteste (c. 1175-1253) described coloured light as *lumen admixtum cum diaphono* ("light mixed with a transparent medium").[36]

Now we turn to Descartes' "mechanical" modificationism. In the Cartesian mechanical universe, light sensations had to be caused by physical *impressions* on the eye. Descartes used the analogy of a blind man with a walking stick to illustrate this:

> I would invite the reader to think of the light that we see emanatating from bodies we call "luminous" as nothing other than a certain kind of motion, or as a kind of very strong and lively action which travels towards our eyes through the medium of air and other transparent media, in the same way that movement or resistance of bodies are perceived by the hand of a blind man through the medium of his walking stick. [37]

Descartes also constructed a model for how the impression of light was to be transmitted, founded upon his theory of matter. In his *Principia Philosophiæ* (1644) Descartes set out what he believed were three kinds of "substance" in the universe – *res cogitans* (mind), *res extensa* (matter), and God. For Descartes, light would have to be transmitted by the *res extensa* in some way.

Between 1629 and 1633 Descartes wrote *Traité du monde et de la lumière* (often referred to in English as "The World"). It was finally published much later in 1664 due to Descartes' cautiousness following the trial and house arrest of Galileo, as it contained an affirmation of a heliocentric view of the cosmos.[38] In this work, following Aristotle, Descartes maintained that there was no such thing as a vacuum in nature (the old doctrine of *horror vacui*). Thus, he reasoned, for motion to be possible, other matter must take the place of the matter which has moved – much like a grand cosmic game of musical chairs. This motion was necessarily circular, and he therefore concluded that the universe must be full of vortices. Vortices were most famously used by Descartes to explain gravitation and fluid dynamics among other phenomena. Descartes also believed that the

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[34] *Meteorolgica,* Bk. Iii, 4.

[35] *De sensu*, Chap. iii

[36] *De iride seu de iride et speculo; Die Philosophischen Werke,* ed. Ludwig Baur, (*Beiträge zur Geschichte der Philosophie des Mittelalters*, 9, Münster i. W., 1912), p. 77

[37] Descartes R. (2009) [1637]. *OEuvres complètes (III) : Discours de la Méthode suivi de La Dioptrique, Les Météores, La Géométrie* (dir. Jean-Marie Beyssade et Denis Kambouchner) – (Paris : Gallimard) – p.150. My translation.

[38] Reasons for his decision not to release were discussed in letters to Marin Mersenne (1599-1648). See *Gaukroger, Stephen (2004). Descartes an intellectual biography (Repr., paperback ed.). Oxford: Oxford University Press*

theory of vortices could be used to hypothesise the different forms/shapes of matter in the universe:

> Even if we were to suppose that there were at the beginning all sorts of shapes and that they had for the most part many angles and many sides, like the pieces that fly off from a stone when it is broken, it is certain that afterward, in moving and hurtling themselves against one another, they little by little had to break the small points of their angles and dull the square edges of their sides, until they had almost all been rendered round, just as grains of sand and pebbles do when they roll with the water of a river.[39]

Thus, there were three shapes of matter (*res extensa*) in the Cartesian universe: spheres; the shavings ("raclure") of those spheres; and matter too bulky to be shaped into a sphere. Light came into the first category.

Descartes' preferred instrument for demonstrating his theory of colour was the glass prism (see Figure 3). He observed the spectrum produced, as others had before him, and explained what he saw with his mechanical model of light. In this Cartesian particulate world, the spherical "globules" which constituted light caused variable colour perceptions according to their variable speed of rotation. Red, the colour with the most "vivacity and brilliance" ("vivacité et de l'éclat")[40] corresponded with the globules which rotated the fastest, and blue with those with the weakest tendency to rotate. Globules which rotated at the same speed as their forward velocity would appear to be white to the observer.[41]

As we have seen, this relationship between a certain speed of rotation and a certain colour took its inspiration from a traditional conceptualisation (of Aristotelian origins) which associated potency with the colour red and weakness with the colour blue.[42] For our purposes however, it is only necessary to understand that Descartes viewed colour as a consequence of a perturbation of these light "globules". Cartesian colour was engendered by the interaction of the prism and the white light globules – matter acting on matter. Most crucially of all for our purposes, Descartes was the first to suggest that there is a one-to-one correspondence between light rays with particular physical properties, and the colours they engender.

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[39] Descartes, René. (1979) [1664]. *Le Monde, ou Traite de la lumiere*. Translation and introduction by Michael Sean Mahoney. New York: Abaris Books, 1979. (French and English text on facing pages), Chapter 8

[40] Descartes R. 2009 [1637]. *Les Météores* – p.334

[41] For a full treatment see Westfall (1962)

[42] A point well made in Blay, M. 2009. « Présentation des Météores » dans *Œuvres complètes (III) : Discours de la Méthode suivi de La Dioptrique, Les Météores, La Géométrie* (dir. Jean-Marie Beyssade et Denis Kambouchner) – (Paris : Gallimard) – p.277.

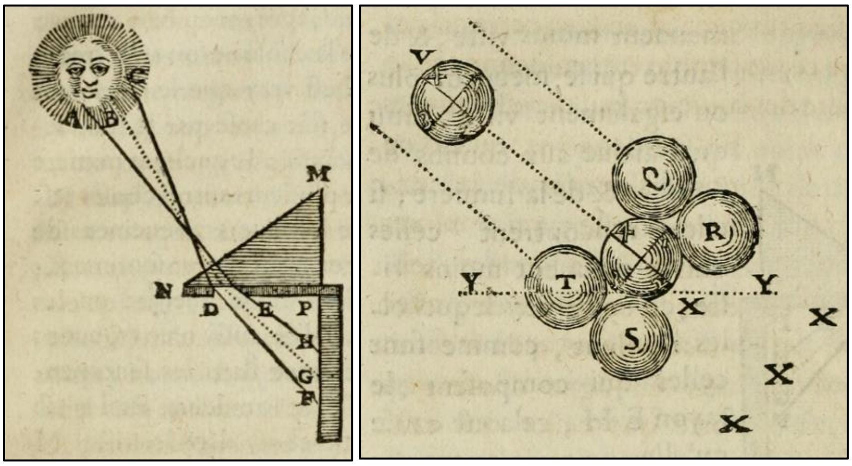

Figure 3: (**a**) A "zoomed out" view of the prism experiment according to Descartes; (**b**) The globules (the "second element" of matter) which form the surface of the prism (QRST) cause the subsequent rotation of the light globule (V) (Discours VIII, pages 258 and 229)

DESCARTES CONTRA ARISTOTLE

There is another point on which Descartes' modificationism differed with the Aristotelian tradition. This was a disagreement on the epistemological status of colour sensations as bearers of information about the "real world". The Aristotelians had distinguished between the "real"/"true" colours that are inherent in objects, and "apparent" colours that are due to reflection.

In Part I of his *Principles of Philosophy*, Descartes wrote:

> We must pay special attention to this: when pain and colour and their like are regarded merely as sensations or thoughts, they are vividly and clearly perceived; but when they are considered as real things existing outside our mind, we haven't the faintest idea of what sort of things they are. If someone says 'I see red in that cherry' or 'I feel pain in my wrist', all he is saying, really, is that he sees or feels something there of which he is wholly ignorant—which amounts to saying that he doesn't know what he is seeing or feeling! [43]

In other words, for Descartes, the true cause of the colour of the red cherry is not the subjective sensation of red, but rather "real things existing outside of our mind" which are not directly accessible to the observer. The following passage reveals how little Descartes thought of the significance of colour sensations as bearers of information about the physical world:

> Of course, we don't really know what it is that we're calling a colour; and we can't make any sense of the idea of something in the objects *resembling* our sensation. But we ride rough-shod over this fact; and there's another fact that encourages us in our error: There are plenty of features—size, shape and number etc.—that actually *are* or at least *could be*

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[43] Descartes, R. (2017). [1644]. *Principles of Philosophy. Part 1.* (Early Modern Texts. Trans: Jonathan Bennett). §68

> present in objects in the same way that we sense or understand them; and we vividly perceive this to be the case. That makes it easy for us to fall into the error of judging that so-called 'colour' in objects is exactly like the colour that we're aware of through our senses, wrongly thinking we have a brightly open perception of something that we don't perceive at all.[44]

This can be sharply contrasted with the received Aristotelian doctrine that colours reflected "real qualities".[45] Descartes' aim was to remove this "distinction that philosophers make when they say that there are [colours] that are real, and others that are false or apparent. Since all their true nature is revealed in their appearance, it seems to me to be a contradiction to say that they are false and yet they appear".[46] It did not matter if a coloured ray originated from a reflection or directly from an object itself. For Descartes the colour that was to be perceived in the sensorium was completely determined by the mechanical properties of the light – "real things existing outside of our mind" – and nothing else.

This is an important point which would be picked up by Newton, despite his dismantling of all the other aspects of Descartes' modificationist theory of colour. Both were "dualists" in that they were keen to demarcate colour sensations from the physical rays that caused them, treating them as if they existed in separate metaphysical realms.[47] Newton made this clear in his *Opticks* (1704) when he emphasised that only God was able to see the "things in themselves":

> The Organs of Sense are not for enabling the Soul to perceive the Species of Things in its Sensorium, but only for conveying them thither; and God has no need of such Organs, he being every where present to the Things themselves.[48]

I will discuss this further in relation to Newton in "Newton's Dualism" below.

MODIFICATIONISM AFTER DESCARTES

Descartes' "spinning globuli" mechanical model of light and colour was not taken seriously by investigators from the following generation. However, those who sought to replace this theory did so within the "modificationist" way of thinking.

For example, Francesco Maria Grimaldi (1618-1663) pictured light as a substantial fluid, and colour sensations as coming about through vibrations in the fluid. He performed experiments to prove that reflection, refraction and diffraction (which he is best known for observing) produce colours

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[44] Descartes, R. (2017). [1644]. *Op cit.* §70

[45] Westfall (1962). *Op cit.* p.339

[46] Dioptrique, VI, p.335. My translation.

[47] This is arguably the origin of the physical/phenomenological distinction.

[48] Newton, Isaac. (1952) [1704]. *Opticks, Or a Treatise on the Reflections, Refractions, Inflections & Colours of Light.* Based on the fourth edition. (Dover 1952), p.403

through a modification of light. He emphasised what he saw as the link between "intensity" and colour, remarking of the spectrum from a prism: "the colour red appears in that place where the light is more intense or dense, blue in that where the light is more diffuse and extended; nor can it be doubted that red is more lucid and cheerful than blue …" [49]

Robert Boyle (1627-1691) wrote in his *Experimental History of Colours* that "beams of light, modified by the bodies whence they are sent (reflected or refracted) to the eye, produce there that kind of sensation men commonly call colour".[50] Boyle rejected Descartes "spinning globuli" model, but nevertheless contended in his *Experimental History of Colours* that colours could be explained with "intelligible and mechanical principles" [51], that "unimaginably subtile corpuscles … make up the beams of light" [52], and that colour phenomena are not caused "by airy qualities, but by real, though extremely minute bodies".[53] Boyle did not, however, proffer a rival model of his own, preferring to wait for more evidence so that "a solid theory may be safely built" [54]: "whether I think this modification of the light to be performed by mixing it with shades, or by varying the proportion of the progress and rotation of the Cartesian *Globuli Cælestes*, or by some other way, which I am not now to mention, I pretend not here to declare".[55]

SEPARATIONISM AND NEWTONIAN COLOUR

NEWTON'S DOUBLE MOTIVE

Newton was taught by his Cambridge tutor Isaac Barrow (1630-1677) that colour is:

> practically nothing else but light impinging on rather larger bodies that it meets, retaining to some extent the stable position of their parts, and, according to the differing shape, disposition or texture of the particles of which they consist, diverted or bouncing off in some way or other; with the result of course that the light had fallen on these bodies comes out such as it does, whether in its motion, or its power of action, or simply in its quantity (I mean in regard to its rarity or density and the copiousness or scantiness of its rays), and according to the distinction of its type produces different appearances, which we denote by the various colour-names.[56]

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[49] Grimaldi, F.M. (1665). *Physico-methesis de lumine, coloribus, et iride* (Bononiae, 1665), pp. 254-62. Translated in Westfall 1962, p.345

[50] Boyle, R. [1664] (1772). *Experiments and Considerations Touching Colours; The Works of the Honourable Robert Boyle,* ed. Thomas Birch, new ed. 6 vols. (London, 1772), p.696

[51] *Ibid.,* p.695

[52] *Ibid.,* p.689

[53] *Ibid.,* p.746

[54] *Ibid.*, p.695

[55] *Ibid.,* p.695

[56] Barrow, I. (1987). *Isaac Barrow's Optical Lectures (Lectiones XVIII)*, The Worshipful Company of Spectacle Makers, London. Trans. Fay, H. C.

In the early 1660s, Newton would begin to question this accepted doctrine of modificationism. Newton's optical system was born out of two principle concerns; one more theoretical, and one more practical:

1. The demolition of Descartes' modificationism and the "overthrow the received doctrine of colors which the tradition, tracing its descent back some two thousand years, had delivered to him." [57]
2. To understand the limitations of refracting (glass lens-based) telescopes.

As we have seen in the previous section, before the acceptance of Newton's "separationist" model of light, it had been widely believed since antiquity that white light was elemental, and that colour resulted from a "modification" of this pure white light. Part of Newton's project was to wrest control of God's creation out of the hands of the dogmatic, rationalist, catholic, and French Descartes. Famously, Newton was successful in putting forward a convincing argument that white light is *not* pure, but rather a composition of differentially refrangible rays. In the process of doing so, he provided natural philosophy with the archetypal example of an *experimentum crucis* [58] to resolve a philosophical debate.

Newton's *practical* concern was to prove by experiment that lens-based astronomy was inherently limited. Chromatic aberration had been the main hindrance to the production of telescopes (and microscopes) with greater magnifying power. In the hind-sighted terms of Newtonian optics, we now call these "refracting telescopes". His aim was to prove that the apparent "spectrum" – a term coined by Newton himself – was the inevitable result of the interaction of light with convex lenses of this type. If white light was a heterogenous mixture of differently refrangible rays, then there could be no refractive surface which could bring all the rays together to focus at a single point, and thus the project of building a perfect refracting telescope could never be achieved. Newton's *reflecting* telescope was intended as a solution to this problem. Interestingly, Newton's innovation was motivated by a false assumption. This was proven around half a century later when the English optician John Dollond (1706-1761) developed the achromatic doublet lens. This was a simple adaptation of the convex lens which acted to cancel out the effects of chromatic aberration.

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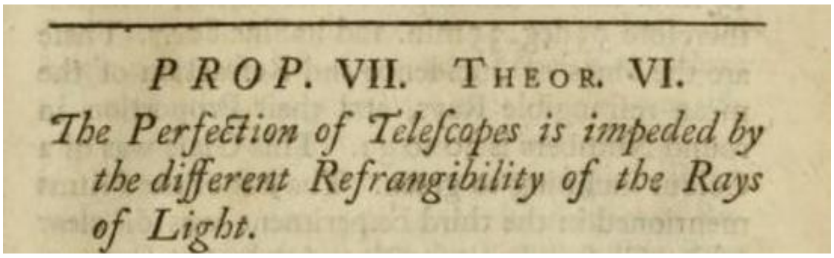
[57] Westfall (1962), *Op cit.* p.339

[58] This phrase was coined by Robert Hooke in his *Micrographia*, a variant on Francis Bacon's phrase "instantia crucis" from the *Novum Organum*.



PROP. VII. THEOR. VI.

The Perfection of Teleſcopes is impeded by the different Refrangibility of the Rays of Light.

Figure 4: Opticks Book 1 p.71.[59] Book 1 Part 1 establishes basic properties of light and colour, and how this can be applied to make better telescopes. Part 2 refutes Cartesian "modificationist" ideas, and explores colour mixing

THE MODIFICATIONIST NEWTON

We can see from Newton's early notebooks from his days as an undergraduate at Trinity College Cambridge that he read Descartes' *Dioptrique*, and Boyle's *Experimental History of Colours*.[60] In the notebook which contains his *Quaestiones quaedam philosophicae* (in which he made entries between 1661-1665), Newton revealed that he was seeking to explain colour phenomena in a mechanical fashion (first para below), and that he, at this early stage, still believed that colours arose as a result of the modification of white light:

> That darke colours seeme further of y^{n} light ones may be from hence y^{t} the beames loose little of theire force in reflecting from a white body because they are powerfully resisted thereby but a darke body by reason of y^{e} loosenes of its parts give some admission to y^{e} light & reflects it but weakly & so y^{e} reflection from whitenes will be sooner at y^{e} eye, or else because ye whit sends beams wth more force to y^{e} eye & givs it a feircer knock.
>
> Coulors [sic] arise either from shaddows intermixed wth light, or stronger as weaker reflection, or parts of y^{e} body mixed wth carried away by light.[61]

At this early stage Newton seemed to have believed that these differently coloured "rays" of light (which come into existence through a modification of white light) travelled at different speeds, thus explaining why they would be refracted at different angles as they pass through a prism:

> Hence rednes yellownes &c are made in bodys by stoping y^{e} slowly moved rays wthout much hindering of y^{e} motion of y^{e} swifter rays. & blew greene & purple by diminishing y^{e} motion of y^{e} swifter rays & not of ye slower. Or in some bodys all these colours may arise by diminishing ye motion of all ye rays in greater or lesse geometricall proportion, for y^{n} there will be lesse difference in theire motions y^{n} otherwise.

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[59] Newton, I. (1730) [1704]. *Opticks, Or a Treatise on the Reflections, Refractions, Inflections & Colours of Light* (London : Printed for William Innys at the West-End of St. Paul's)

[60] Newton, I. (1661-1665). Trinity College Notebook (MS Add.3996), Cambridge University Library.

[61] *Ibid.* "Quaestiones quaedam philosophicae", p. 69

THE SEPARATIONIST NEWTON

Simon Schaffer has suggested that before their rise to philosophical fame glass prisms were used in chandeliers or as toys.[62] As we have seen, Descartes made use of them in his *Dioptrique*. Boyle described the prism as "the usefullest Instrument Men have yet imploy'd about the Contemplation of Colours, (and perhaps that of Others too)".[63] Newton recorded that he obtained his prisms at Stourbridge Fair in Cambridge in August 1665 and performed his first experiments back at Woolsthorpe Manor after he was forced to leave Cambridge later that year because of the Great Plague.[64]

Newton first came to scientific fame because of his work in optics. He first presented his new ideas in his inaugural lectures as Lucasian Professor between 1670 and 1672.[65] Then he sent a paper to the Royal Society in February 1672, the "New Theory about Light and Colours", which contained the main experiments and conclusions that would later be formally laid out in his *Opticks* of 1704.[66,67] This paper was published in the *Philosophical Transactions of the Royal Society* without pomp and circumstance, alongside various submissions from other authors including "An Essay to the Advancement of Musick" and "A Description of the East-Indian Coasts, Malabar, Coromandel, Ceylon". Thomas Kuhn noted that this was the "first major contribution to science made through a technical journal, the medium that rapidly became the standard mode of communication among scientists." [68] It is here that Newton first described his experimentum crucis[69] involving the two prisms: one which separated white light into its constituent colours; the other which further refracted these constituent colours to different heights on the wall, without changing their colour.

> The gradual removal of these suspicions at length led me to the *experimentum crucis*, which was this; I took two boards, and placed one of them close behind the prism at the window,

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[62] Schaffer, S. (1989). "Glass Works" in *The Uses of Experiment: Studies in the Natural Sciences* (David Gooding, Trevor Pinch, Simon Schaffer – Cambridge University Press, 18 May 1989) p.73

[63] Boyle, R. [1664] (1772). *Experiments and Considerations Touching Colours; The Works of the Honourable Robert Boyle,* ed. Thomas Birch, new ed. 6 vols. (London, 1772), p.696

[64] Westfall, Richard S. (1980). *Never at Rest: a Biography of Isaac Newton*. Cambridge: Cambridge University Press.

[65] Newton, I. (1973) [1670-72]. The Unpublished First Version of Isaac Newton's Cambridge Lectures on Optics 1670-1672: A Facsimile of the Autograph, now Cambridge University Library MS. Add. 4002, with an introduction by D. T. Whiteside (Cambridge: Cambridge University Library, 1973)

[66] Newton, I. (1672). 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

[67] Fara, P. (2015). *Newton shows the light: a commentary on Newton (1672) 'A letter … containing his new theory about light and colours…'* 373. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences

[68] Kuhn, T.S. (1978). *Newton's Optical Papers* in I.B. Cohen ed. *Isaac Newton's Papers & letters on natural philosophy and related documents* – Harvard University Press. p.27

[69] As Schaffer points out in *Glass Works* (1989) this term "was not used in his notebooks, drafts, or lectures before 1672, nor did it appear in the *Opticks* in 1704. Nevertheless, the label remained current among Newton's readers and disciples." (p.69)

> so that the light might pass through a small hole made in it for the purpose and fall on the other board, which I placed at about 12 feet distance, having first made a small hole in it also, for some of that incident light to pass through. Then I placed another prism behind this second board so that the light, targeted through both the boards, might pass through that also, and be again refracted before it arrived at the wall. This done, I took the first prism in my hand, and turned it to and fro slowly about its axis, so much as to make the several parts of the image cast on the second board successively pass through the hole in it, that I might observe to what places on the wall the second prism would refract them. And I saw by the variation of those places that the light tending to that end of the image towards which the refraction of the first prism was made did in the second prism suffer a refraction considerably greater than the light tending to the other end. And so the true cause of the length of that image was detected to be no other than that light consists of rays differently refrangible, which, without any respect to a difference in their incidence, were, according to their degrees of refrangibility, transmitted towards divers parts of the wall.[70]

In the "New Theory" paper, Newton made it clear that he believed that there was a one-to-one correspondence between colour and degree of refrangibility. The first two (of thirteen) propositions of his "Doctrine" read as follows:

> 1. As the Rays of light differ in degrees of Refrangibility, so they also differ in their disposition to exhibit this or that particular colour. Colours are not Qualifications of Light, derived from Refractions, or Reflections of natural Bodies (as 'tis generally believed,) but Original and connate properties, which in divers Rays are divers. Some Rays are disposed to exhibit a red colour and no other; some a yellow and no other, some a green and no other, and so of the rest. Nor are there only Rays proper and particular to the more eminent colours, but even to all their intermediate gradations.
>
> 2. To the same degree of Refrangibility ever belongs the same colour, and to the same colour ever belongs the same degree of Refrangibility. The least Refrangible Rays are all disposed to exhibit a Red colour, and contrarily those Rays, which are disposed to exhibit a Red colour, are all the least refrangible: So the most refrangible Rays are all disposed to exhibit a deep Violet Colour, and contrarily those which are apt to exhibit such a violet colour, are all the most Refrangible. And so to all the intermediate colours in a continued series belong intermediate degrees of refrangibility. And this Analogy 'twixt colours, and refrangibility, is very precise and strict; the Rays always either exactly agreeing in both, or proportionally disagreeing in both.[71]

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[70] Newton, I. (1672). *Op cit.*

[71] *Ibid.*

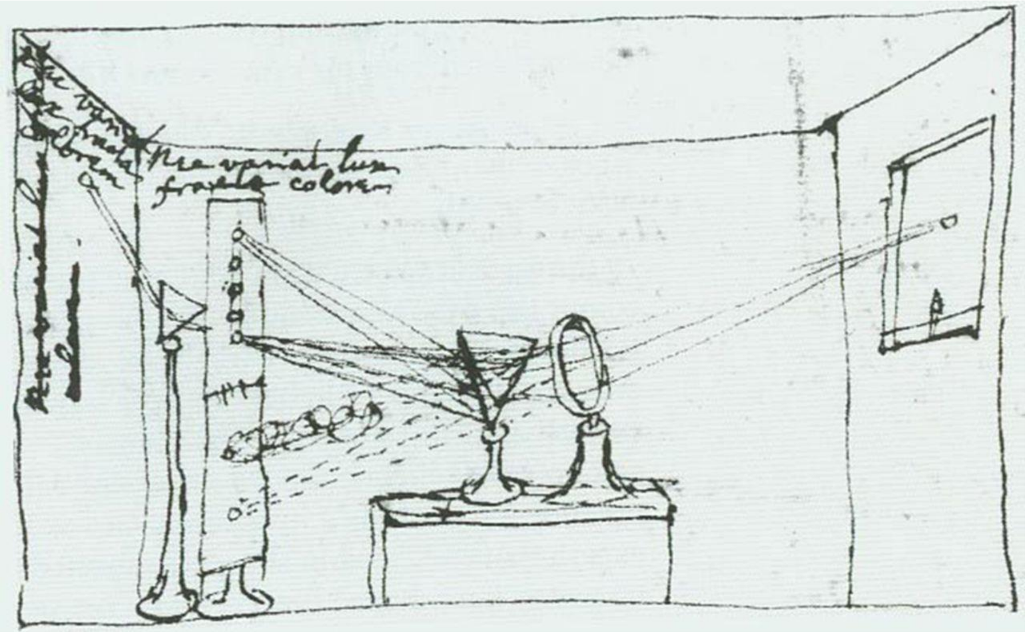

Figure 5: Newton's sketch of his experimentum crucis.[72]

He emphasised this one-to-one correspondence further by demonstrating the "immutability" of these separated colours – the fact that when a certain ray is separated off, all attempts to split it up into further colours with another prism fail:

> 3. The species of colour, and degree of Refrangibility proper to any particular sort of Rays, is not mutable by Refraction, nor by Reflection from natural bodies, nor by any other cause, that I could yet observe. When any one sort of Rays hath been well parted from those of other kinds, it hath afterwards obstinately retained its colour, notwithstanding my utmost endeavours to change it. I have refracted it with Prismes, and reflected it with Bodies, which in Day-light were of other colours; I have intercepted it with the coloured film of Air interceding two compressed plates of glass; transmitted it through coloured Mediums, and through Mediums irradiated with other sorts of Rays, and diversly terminated it; and yet could never produce any new colour out of it. It would by contracting or dilating become more brisk, or faint, and by the loss of many Rays, in some cases very obscure and dark; but I could never see it changed *in specie*.[73]

Further, in a 1673 letter to Christiaan Huygens, Newton could not have made himself clearer in his belief that an exact colour perception corresponded to a ray of light with an exact refractive property:

> 1. The Sun's light consist of rays differing by indefinite degrees of refrangibility.

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[72] Newton's *Correspondence I, p. 107. (MS 361 vol. 2 fol, 45.)*

[73] Newton, I. (1672). *Op cit.*

> 2. Rays wch differ in refrangibility, when parted from one another do proportionally differ in the colours wch they exhibit. These two Propositions are matter of fact.
>
> 3. There are as many simple or homogeneal colours as degrees of refrangibility. For to every degree of refrangibility belongs a different colour by Prop: 2. And that colour is simple...
>
> 4. Whiteness in all respects like that of the Sun's immediate light & of all ye usuall obects of our senses cannot be compounded of two simple colours alone...
>
> 5. Whiteness in all respects like that of the Sun's immediate light cannot be compounded of simple Colours, without an indefinite variety of them.[74]

Since from Newton's purely physical perspective, there were an infinite number of degrees of refrangibility, so there were an infinite number of "primary"/"simple" colours. It is commonly taught that Newton believed there were only seven colours, but this is misleading.[75] This confusion has arisen because later in the *Opticks* Newton constructed a colour circle which divided the circle into seven identifiable colour names, which he associated with the diatonic musical scale. This will be discussed further below.

In a later letter, Newton further emphasised the point that the only property that mattered when it came to determining the colour of a particular ray was its property of refrangibility, a property which was *innate* to the ray, and not subject to modification:

> That in any Hypothesis whence ye rays may be supposed to have any originall diversities, whether as to size or figure or motion or force or quality or any thing els imaginable wch may suffice to difference those rays in colour b& refrangibility, there is no need to seek for other causes of these effects then those original diversities. This rule being laid down, I argue thus. In any Hypothesis whatever, light as it comes from ye Sun must be supposed either homogeneal or heterogeneal. If ye last, then is that Hypothesis comprehended in this general rule & so cannot be against me: if the first then must refractions have a power to modify light so as to change it's colorifick qualification & refrangibility; wch is against experience.[76]

In the *Opticks* a further experiment was reported, in which Newton attempted a further proof that the coloured rays in no way modified the others when they were recombined to produce white. In this experiment Newton placed a moving wheel with a comb attached to intercept the converging rays, so that different colours were blocked in succession. As the wheel was turned, a succession of colours flickered on the screen, but as he increased the speed, he noticed:

> But if I so much accelerated the Motion, that the Colours by reason of their quick Succession could not be distinguished from one another, the Appearance of the single

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[74] Turnbull, H.W. (ed.) (1959). Newton to Oldenburg, 23 June 1673; *Correspendence, I,* 293.

[75] David Hargreave studied this mistaken idea as it was widely propagated in the 18th century in "Thomas Young's Theory of Color Vision: Its Roots, Development, and Acceptance by the British Scientific Community" (Ph. D. Dissertation, Univer- sity of Wisconsin, 1973. University Microfilms order No. 73-27, 103), pp. 60-74, 477-495

[76] Turnbull, H.W. (ed.) (1959). Newton to Oldenburg, 15 February 1675/6; *Correspondence, I,* 419-20

> Colours ceased. There was no red, no yellow, no green, no blue, nor purple to be seen any longer, but from a Confusion of them all there arose one uniform white Colour.[77]

With this experiment Newton added further to his disproof of modificationism. He had also made an additional discovery – that of the persistence of human vision. This is the idea that a visual impression does not cease the instant that the ray causing it has ceased to enter the eye. This is the property of human vision that allows cinema, for example, to be possible.

> If Impressions follow one another slowly, so that they may be severally perceived, there is made a distinct Sensation of all the Colours one after another in a continual Succession. But if the Impressions follow one another so quickly, that they cannot be severally perceived, there ariseth out of them all one common Sensation, which is neither of this Colour alone nor of that alone, but hath it self indifferently to 'em all, and this is a Sensation of Whiteness. By the Quickness of the successions, the Impressions of the several Colours are confounded in the Sensorium, and out of that Confusion ariseth a mix'd Sensation.[78]

In CE 165 Ptolemy had described a similar experiment in his *Optics*, except in his case it was a potter's wheel with colours. Furthermore, as we shall see, James Clerk Maxwell performed a similar – although more quantitative – experiment with his coloured spinning top.

NEWTON'S DUALISM

As shown in the last section, Newton strongly believed in the idea of one-to-one correspondence between rays with particular properties (in his case refrangibility), and the colour they induce in the eye of the perceiving subject. However, this does not mean that Newton believed that the rays were "coloured" in and of themselves. As I mentioned above in "Descartes Contra Aristotle", Newton was keen to make the philosophical distinction between colour-inducing rays and colour sensations themselves, and he made this clear in Book 1 of the *Opticks* :

> The homogeneal Light and Rays which appear red, or rather make Objects appear so, I call Rubirifick or Red-making; those which make Objects appear yellow, green, blue, and violet, I call Yellow-making, Green-making, Blue-making, Violet-making, and so of the rest. And if at any time I speak of Light and Rays as coloured or endued with Colours, I would be understood to speak not philosophically and properly, but grosly, and according to such Conceptions as vulgar People in seeing all these Experiments would be apt to frame. For the Rays to speak properly are not coloured. In them there is nothing else than a certain Power and Disposition to stir up a Sensation of this or that Colour.[79]

Newton then proceeded to make an analogy with sound – a musical string's frequency is to a particular pitch, as a light ray is to a particular colour:

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[77] Newton, I. (1952) [1704]. *Opticks.* Book I Part II p.140

[78] *Ibid.* p.141

[79] *Ibid.* Book I pp.108-9

> For as Sound in a Bell or musical String, or other sounding Body, is nothing but a trembling Motion, and in the Air nothing but that Motion propagated from the Object, and in the Sensorium 'tis a Sense of that Motion under the Form of Sound; so Colours in the Object are nothing but a disposition to reflect this or that sort of Rays more copiously than the rest; in the Rays they are nothing but their Dispositions to propagate this or that Motion into the Sensorium, and in the Sensorium they are Sensations of those Motions under the Forms of Colours.[80]

Newton continued his analogy with sound and speculated that a particular "bigness of vibration" propagated by a ray would then fall on the retina and cause a corresponding "bigness of vibration" in the optic nerves leading to the brain, which would then excite the sensation of a particular colour:

> *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.* 13. Do not several sorts of Rays make Vibrations of several bignesses, which according to their bignesses excite Sensations of several Colours, much after the manner that the Vibrations of the Air, according to their several bignesses excite Sensations of several Sounds? And particularly do not the most refrangible Rays excite the shortest Vibrations for making a Sensation of deep violet, the least refrangible the largest for making a Sensation of deep red, and the several intermediate sorts of Rays, Vibrations of several intermediate bignesses to make Sensations of the several intermediate Colours.[81]

With this reference to "Bigness of Vibrations" it would be tempting to conclude that this passage contains the first expression of the wave theory of light. In addition, in a later passage Newton made a water-wave analogy to describe the propogation of light from a point:

> *Qu.* 17. If a Stone be thrown into stagnating Water, the Waves excited thereby continue some time to arise in the place where the Stone fell into the Water, and are propagated from thence in concentrick Circles upon the Surface if the Water to great distances. And the Vibrations or Tremors excited in the Air by percussion, continue a little time to move from the place of percussion in concentrick Spheres to great distances. And in like manner, when a Ray of Light falls upon the Surface of any pellucid Body, and is there refracted or reflected, may not Waves of Vibrations, or Tremors, be thereby excited in the refracting or reflecting Medium at the point of Incidence, and continue to arise there, and be propagated from thence as long as they continue to arise and be propagated …[82]

To make such a conclusion would only be in historical hindsight however. Although Christiaan Huygens (1629-1695) was contemporaneously treating light as if it were a (longitudinal) wave, it is only with the work of Thomas Young (1773-1829) that the wavelength/frequency of light became the defining contemporary model of light.

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[80] *Ibid.* Book I p.109

[81] *Ibid.* Book III p.320

[82] *Ibid.* Book III p.322

In fact, Newton rather tended towards a "corpuscular" view of light, in which light was composed of small particles of matter, in contrast to his contemporaries Huygens and Robert Hooke (1635-1703), who advocated for the wave view. This "corpuscular" model of light had been held, as we have seen, by Boyle and Descartes. However, contrary to what is now commonly taught about "Newton's corpuscular theory", it is clear on closer examination that for Newton this model of light was simply a thought experiment on the periphery to his main results. As he clearly stated in a robust reply letter (from 1672) to criticisms from Robert Hooke, the corpuscular model was a mere suggestion, nothing more:

> 'Tis true, that from my Theory I argue the *Corporeity* of Light; but I do it without any absolute positiveness, as the word *perhaps* intimates; and make it at most but a very plausible *consequence* of the Doctrine, and not a fundamental *Supposition*, nor so much as any part of it; which was wholly comprehended in the precedent Propositions. And I somewhat wonder, how the *Objector* could imagine, that, when I had asserted the Theory with the greatest rigour, I should be so forgetful as afterwards to assert the fundamental supposition it self with no more than a *perhaps*. Had I intended any such *Hypothesis*, I should somewhere have explain'd it.[83]

This is in line with Newton's famous declaration from the *Principia Mathematica*; "hypotheses non fingo". This said, Newton still felt that the corpuscular view was the best theory that was then available to explain such phenomena as "Reflection and Refraction, the production of Heat by the Sun-beams, the Emission of Light from burning putrifying, or other substances, whose parts are vehemently agitated, the *Phænomena* of thin transparent Plates and Bubles, and of all Natural bodies, the Manner of Vision, and the Difference of Colors, as also their Harmony and Discord", although he added that he would leave this to other practitioners "who may think it worth their endeavor to apply this *Hypothesis* to the solution of *phænomena"*. [84]

NEWTON'S COLOUR CIRCLE

In another letter, Robert Hooke criticised Newton's early contention (from the "New Theory" of 1672) that colours could only be produced by rays of a particular degree of refrangibility. He pointed out that it was quite possible to make green light from combinations of another two, for example yellow and blue. In a reply letter to Hooke, Newton emphasised the difference between compound colours, which could be further decomposed by a prism, and immutable uncompounded "original" colours, which couldn't:

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[83] Newton, I. (1672). Mr Isaac Newtons Answer to some Considerations [of Robert Hooke] upon his doctrine of Light and Colors. *Philosophical Transactions of the Royal Society*, No. 88 (18 November 1672), p. 5086

[84] *Ibid.* p.5087

> But supposing that all colours might according to this experiment be produced out of two by mixture, yet it follows not that those two are the onely originall colours; and that for a double reason: First, because those two are not themselves original colours, but compounded of others … and then, because though those two were original, and all others might be compounded of them, yet it follows not that they cannot be otherwise produced. For I said, that they had a double origin, the same colours to sense being in some cases compounded, and in other cases uncompounded …[85]

Still, Newton admitted here that the same psychological sensation of colour can be produced either through one "original" uncompounded ray, or through a mixture (compound) of two or more "original" rays. For example, the same sensation of green could be produced by an "original" green ray, or by a combination of "yellow" and "blue" rays. Therefore, Newton was forced to admit that the doctrine of one-to-one correspondence between colour and refrangibility only held for "original" uncompounded rays.

In "The New Theory" Newton also made it clear that white is not a "simple" colour like all the spectral colours, but rather a result of a compound of *all* these colours:

> 7. But the most surprising, and wonderful composition was that of *Whiteness*. 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, mixed in a due proportion.[86]

Newton later changed this opinion[87] after a query from Huygens in 1673 showed that a combination of all the spectral colours was not the only way of producing white. Huygens wrote:

> As for the composition of White made by all the Colors together, it may possibly be, that Yellow and Blew might also be sufficient for that: Which is worth while to try; and it may be done by the Experiment, which Mr. Newton proposeth, by receiving against a wall of a darkn'd room the Colours of the Prisme, and to cast their reflected light upon white paper. Here you must hinder the Colors of the extremities, viz. the Red and Purple, from striking against the wall, and leave only the intermediate Colors, yellow, green and blew, to see, whether the light of these alone would not make the paper appear white, as well as when they all give light. I even doubt, whether the lightest place of the yellow color may not all alone produce that effect, and I mean to try it at the first conveniency.... Mean time you may see, that if these Experiments do succeed, it can no more be said, that all the Colors are necessary to compound White, and 'tis very probable, that all the rest are nothing but degrees of Yellow and Blew, more or less charged.[88]

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[85] Isaac Newton to Henry Oldenburg, Feb. 6, 1671/72, *The Correspondence of Isaac Newton*, ed. H. W. Turnbull (Cambridge: Cambridge University Press, 1959), Vol. I, p.180

[86] Newton, I. (1672). *Op cit.*

[87] This process is discussed thoroughly in Shapiro (1980).

[88] Cohen, I. Bernard (ed.) *Isaac Newton's Papers and Letters on Natural Philosophy* (Cambridge: Harvard University Press, 1958), pp. 136-137

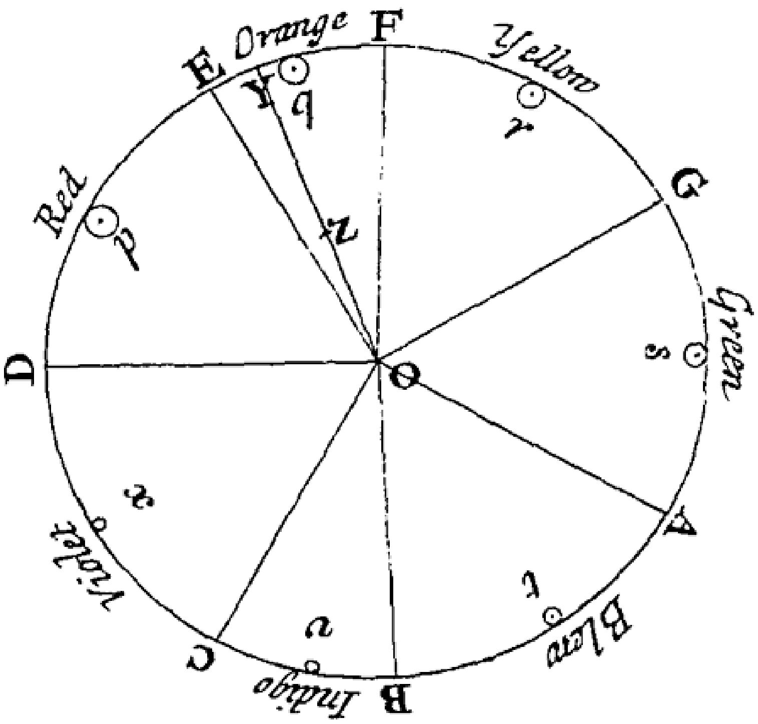

Figure 6: Figure 11 from Newton's *Opticks*. "With the Center O and Radius OD describe a circle ADF, and distinguish its Circumference into seven Parts DE, EF, FG, GA, AB, BC, CD, proportional to the seven Musical Tones or Intervals of the eights Sounds, *Sol, la, fa, sol, la, mi, fa, sol*, contained in an eight, that is, proportional to the Number $\frac{1}{9}, \frac{1}{16}, \frac{1}{10}, \frac{1}{9}, \frac{1}{16}, \frac{1}{16}, \frac{1}{9}$ …" [89]

Newton then conceded (as we can see from his colour wheel in the *Opticks*) that a "sensible" white can be produced from two colours – that is, a perception of white in our senses.[90] Newton did not however concede that this "white" was physically equivalent to white sunlight, which he maintained was necessarily composed of all the colours of the spectrum.

In addition to this, during the 17th century there was a growing awareness that painters could make a wide gamut of hues from a combination of just three pigments – yellow, red, and blue. In the 1660s Newton had himself read and made notes on the theory of dying: "All ye materialls (wch of themselves doe colour) are Red yellow & blew, from wch (wth fundamentall white) ariseth yt greate variety wee see in dyed stuffs".[91] This begged the question of Newton's early formulation of his optical theory from 1672 – how could artists create "any" colour from only two or three primaries, where Newton held that there were an infinite number of primaries? Also, how could white light be produced from three, or perhaps only two colours? Newton addressed these questions in the

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[89] Newton, I. (1952) [1704]. *Op cit.* p.154

[90] However see below – he did not think that such a method could produce a *perfect*, pure white.

[91] Newton, I. Cambridge University Library (CUL), Add. MS 3958, fol. 7v.

Opticks (published 1704). It is widely held among historians that Newton delayed publication of the *Opticks* until the death of his fiercest critic Robert Hooke in 1703.

Aristotle had arranged the colours on a musical scale, according to the proportions of light (λευκὸν) and dark (μελαν) contained in each colour.[92] Newton arranged his in proportion to the space they occupied on the spectrum, from red to violet, and then imposed a diatonic musical scale on top of this (see Figure 6). It is possible that he had been particularly attracted to a spectrum of seven colours because it suggested that God's creation was consistent: the musical diatonic scale also had seven intervals; alchemists counted seven elemental metals; there were seven planets known to astronomers. From Newton's notebooks we know he was an admirer of Kepler's 1619 treatise *Harmonices Mundi* ("The Harmony of the World"), in which the connection of these phenemona was argued. Newton also seemed to believe that the colours could produce harmonies in the same way that certain musical intervals did:

> *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.[93]

This idea that some colours are "agreeable" when "view'd together" is not so far from the discussion of complementary colours that would expand in the following two centuries.

Newton was not *so* dogmatic about the seven-colour spectrum based on the diatonic musical scale. In the "Optical Lectures" of 1671-72, he admitted that the colours could be defined "somewhat differently", and that he simply preferred the musical analogy "because it perhaps involves something about the harmonies of colors (such as painters well know, but which I myself have not yet sufficiently studied) perhaps analogous to the concordance of sounds".[94] He had initially divided the spectrum up into five colours before settling on this seemingly more harmonious division.[95]

Newton then explained how colour mixing operated using this circle. If a chord is drawn across the circle between two particular colours, then a compound of those two is produced which approximates the colour at the middle of the chord. If there are more than two colours, then it is the centre of gravity of those colours that will determine the colour. For example, as shown in

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[92] Aristotle, De sensu, 439b23-28, 439b34, 442a27, in Aristotle, De sensu and de memoria, trans. G. R. T. Ross (Cambridge: Cambridge Univ. Press, 1906), pp. 57, 59, 69.

[93] Newton, I. (1952) [1704]. *Opticks*. p.345

[94] Shapiro, A. (1984) (ed.) *The Optical Papers of Isaac Newton. vol. 1: The Optical Lectures (1670-72)* 3 vols (Cambridge, 1984) pp. 545-547

[95] *Ibid.* pp. 51, 87

Figure 6, the colour at "Z" can be produced either from a mixture of pure spectral orange and white, or a mixture of red and yellow and some white. If a line is drawn between opposite colours of the circle, then a "white" is produced:

> Also if only two of the primary Colours which in the circle are opposite to one another be mixed in equal proportion, the point Z shall fall upon the center O, and yet the Colour compounded of those 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 of 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.[96]

This description satisfied the criticisms of Hooke and Huygens we discussed earlier, and the experience of painters. However, it is interesting that Newton could only arrive at an "off white" when two opposing colours in the circle were mixed.[97] In hindsight, it could be argued that this is because Newton's colour wheel omits the non-spectral colour magenta and is thus non-symmetrical in terms of complementary opposing colours.[98] It is interesting that Newton *did* observe the non-spectral colour magenta, when he mixed the red and violet extremes of his spectrum and described it thus:

> … in general the compounded violet is more bright and more fiery than the uncompounded.[99]

What he saw here is what later practitioners would call "magenta", although he still called it violet because he could not conceive that spectral colours would be able to produce another that is not part of the spectrum.[100]

For the reasons given above, this section of the *Opticks* (Book I, Part II) can be seen as the first ever "scientific" colorimetric text.[101] Newton's colour wheel is certainly the first example of a barycentric colour mixing model.

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[96] Newton, I. (1952) [1704]. p.156

[97] In the mid-nineteenth century Hermann von Helmholtz discovered that the "greens" of the visual spectrum have no spectral complementary colour. Only the non-spectral colour magenta could be mixed with green to create "white".

[98] This will be elaborated on further in Chapter Two where I will discuss the evolution of more accurate "phenomenological" colour wheels. Newton's colour wheel is derived from the spectrum *only*, and not from experiments in subjective human colour vision as the others would be.

[99] Newton, I. (1952) [1704]. p.156

[100] The colour term "magenta" appears to have originated in the mid-19th century, when the name of the fuchsine dye was changed in 1859 to commemorate the victory of the French and Sardinian armies at the Battle of Magenta.

[101] That is, written by a natural philosopher rather than an "artist".

THE TRICHROMATIC THEORY

The acceptance of the trichromatic theory of colour marks the point at which colour came to be regarded as a construct starting inside the eye rather than a simple reading of physical world. This change was not simply a result of the work of the three commonly named practitoners – Young, Helmholtz, and Maxwell – whose names are often attached to the theory. Although, as we shall see, these figures were crucial to the *scientification* of the trichromatic theory.

In his description of the rainbow in the *Meteorologica*, Aristotle declared that there are three colours – red, green, and violet – which "are almost the only colours which painters cannot manufacture".[102] As I touched on in the last section, in the 17th century there was growing awareness among painters and artists that a wide gamut of hues could be made from a combination of just three ("red", "yellow" and "blue"). Then, as we have seen, Newton's colour wheel exhibited some degree of trichromacy, but fell short of formalising and naming it. In the 18th century Jacob Christoph LeBlon (1667-1741) invented the mezzotint method of colour printing, and insisted that there were only three primaries. LeBlon's method is the first example of subtractive colour printing, which remains the basis for printing technology to this day.[103]

Throughout the eighteenth century the three artists' primaries were often displayed diagrammatically on a colour triangle, with the primaries at the vertices, and every point on the triangle represented a colour that could be made from the combination of these primaries. A typical example is Tobias Mayer's colour triangle dating from 1775, shown in Figure 7. These colour triangles were soon complemented with colour solids, which relied on the three primary colour principle but also exhibited variations in brightness, like that of J. H. Lambert (1772), shown in Figure 8.

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[102] Aristotle. Complete Works of Aristotle, Volume 1: The Revised Oxford Translation. Princeton University Press, 1 Sep 2014. Book III, p.600

[103] LeBlon used blue, red, and yellow. Today we use cyan, magenta, and yellow to achieve a wider gamut.

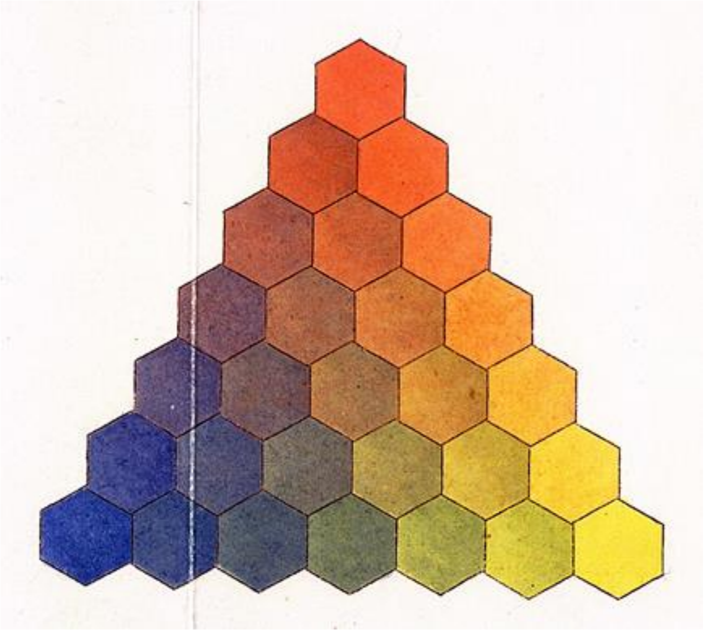

Figure 7: Tobias Mayer's colour triangle.[104]

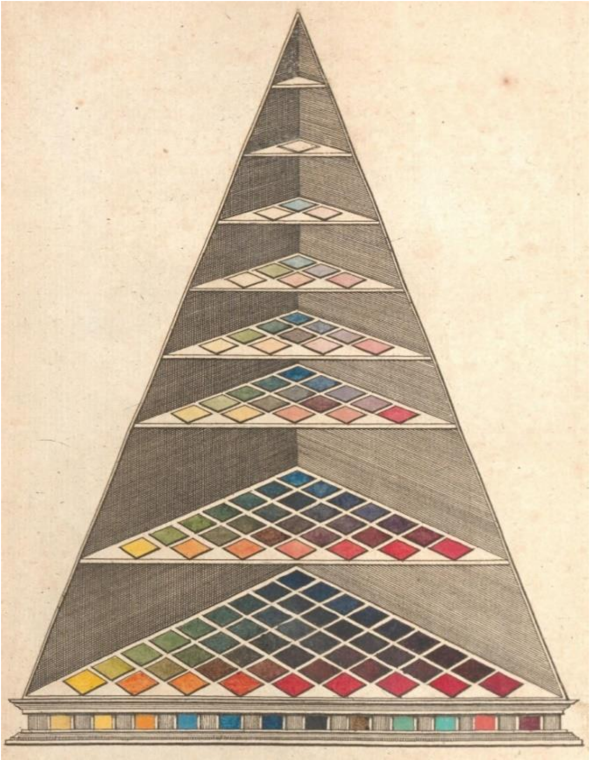

Figure 8: J. H. Lambert's colour pyramid. This is the first known example of a three-dimensional colour model.[105]

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[104] Georg Christoph Lichtenberg - Tobiae Mayeri. . . Opera inedita: Vol. I. Commentationes Societati Regiae scientiarvm oblatas, qvae integrae svpersvnt, cvm tabvla selenographica complecten. Trans. and ed. Georg Christoph Lichtenberg. Göttingen, 1775, plate III., reproduced in *The Creation of Color in Eighteenth-Century Europe*

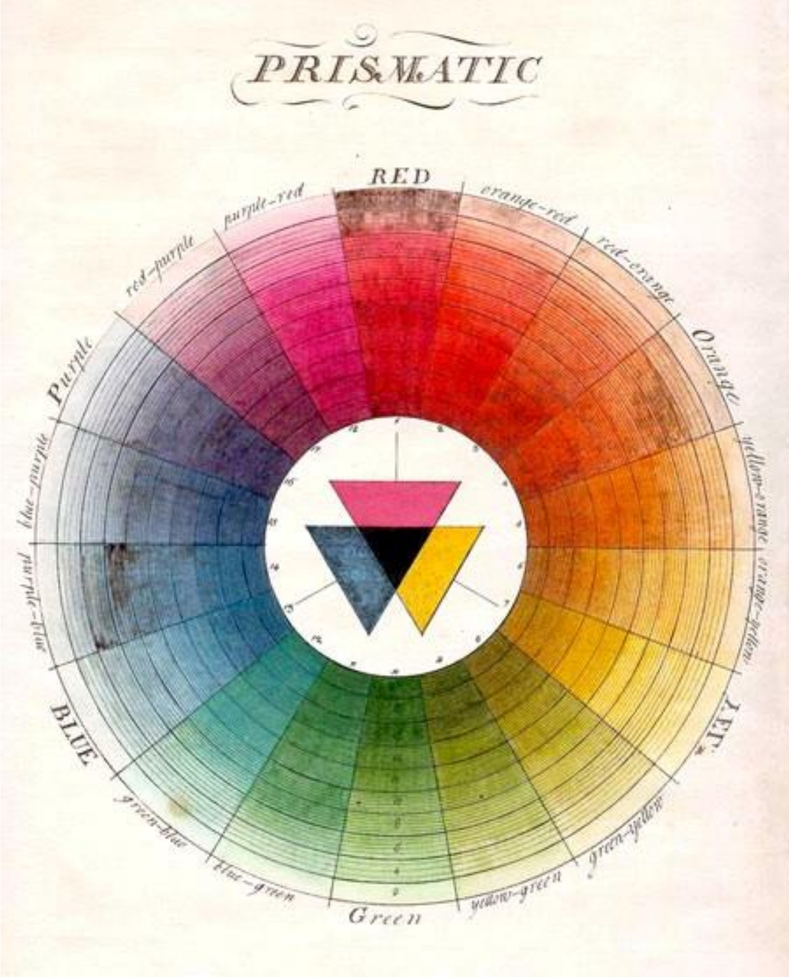

Figure 9: Moses Harris's colour wheel from the *Natural System of Colours* (1769-1776)[106]

In his *Natural System of Colours* (1769-1776) the engraver Moses Harris constructed a colour circle based on the three painter's/printer's primaries. As we can see from Figure 9, there is a demonstration of subtractive colour mixing at the centre of the circle. Interestingly, the choice of hues to represent "red", "yellow" and "blue" at this centre are very close to what we would call "magenta", "yellow" and "cyan" today – the three modern subtractive colour mixing primaries. This is not surprising, since Moses Harris's aim was to achieve the widest possible gamut of colour.

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[105] Lambert, J.H. (1772) *Beschreibung einer mit dem Calauschen Wachse ausgemalten Farbenpyramide.* Haude und Spener, Berlin 1772.

[106] Harris, Moses. (1769-68) *Natural System of Colours* (Laidler)

THOMAS YOUNG'S BAKERIAN LECTURE

On November 12, 1801 Thomas Young gave his Bakerian Lecture "On the Theory of Light and Colours" to the Royal Institution. In this lecture he gave two suggestions that led to very significant developments in the physical science of colour:

1. The idea that light is a wave, and that a specific wavelength of light will cause a specific sensation of colour.
2. The idea that the eye contains three "particles" which act as receptors of colour and form the basis of colour vision.

YOUNG ON COLOUR AND WAVELENGTH

Robert Hooke in his *Micrographia* of 1665 had compared the spreading of light to the spreading of waves in water.[107] In his *Treatise on Light* of 1690, Christiaan Huygens posited that at every point on the wavefront there was a spherical (longitudinal) wave that was emitted. Francesco Maria Grimaldi (1618-1663) described diffraction fringes observed when light passed by sharp edges, and that when light passed through a small aperture, it took on the shape of a cone. However, since Newton had erred towards a "corpuscular" view of light, it was this view that prevailed in the 18th century among physicists. There were only a few exceptions such as Euler and Benjamin Franklin who advocated for the wave view.

In 1801 Young performed his famous "double-slit" experiment, in which two sources of light interfered with one another and cast a predictable interference pattern on the opposite wall, in accordance with his "general law of interference".[108] Young believed that waves propagated themselves through an all-pervading ether, and that the undulations of the waves were longitudinal (in accordance with the doctrine of Huygens).[109]

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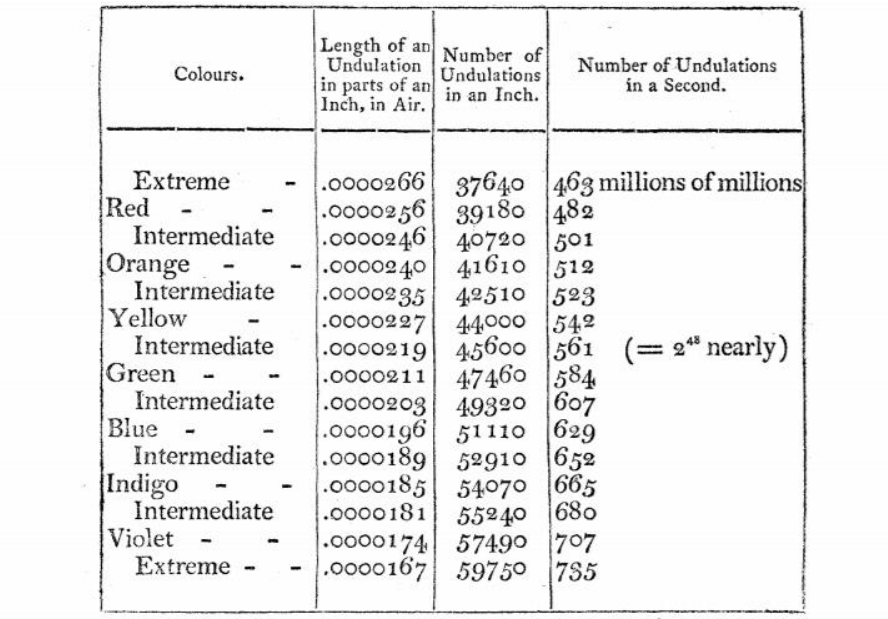
[107] Observation IX, *Micrographia*

[108] Published in Young, T. (1802). *A syllabus of a course of lectures on natural and experimental philosophy*. London: Royal Institution.

[109] Rather than transverse, as Fresnel later showed them to be.



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

Figure 10: Table showing wavelength and frequency of the spectral colours, from Young's Bakerian Lecture.[110]

By 1801 Young had understood that the colours of thin films/plates and of "Newton's rings" [111] could also be explained by the concept of constructive and destructive interference.[112]

> But the general law, by which all these appearances are governed, may be very easily deduced from the interference of two coincident undulations, which either cooperate, or destroy each other, in the same manner as two musical notes produce an alternate intension and remission, in the beating of an imperfect unison.[113]

Young was the first to measure the wavelengths of different colours of light. He was able to do this by supposing that the coloured rings were a result of constructive interference. Young was thus able to calculate their phase value, and ultimately their wavelength. These measurements and the methods used to obtain them were given in the Bakerian Lecture.[114] These measurements were remarkable in their accuracy (compared to modern day measurements), and confirmed that the wavelength of light waves was six orders of magnitude shorter than that of sound. A table of Young's results is shown in Figure 10.

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[110] Young, T. (1802). The Bakerian Lecture: On the Theory of Light and Colours. *Phil. Trans. R. Soc. Lond.* 1802 92, 12-48, published 1 January 1802.

[111] Two further observations from the *Opticks*. "Newton's rings" were actually first described in Hooke's *Micrographia*, however.

[112] Young, T. (1801) A letter respecting sound and light in reply to some observations of Prof. Robison. *J. Nat. Phil. Chem. Arts* 5

[113] Young, T. (1802). *Op cit.* p.117

[114] See Mollon J.D. (2002). *The origins of the concept of interference* for a full treatment.

In the same lecture Young also hinted that there were other (non-visible) waves that could be responsible for the propagation of "heat":

> But the affectations of heat may perhaps hereafter be rendered more intelligible to us; at present, it seems highly probable that light differs from heat only in the frequency of its undulations or vibrations; those undulations which are within certain limits, with respect to frequency, being capable of affecting the optic nerve, and constituting light; and those which are slower, and probably stronger, constituting heat only.[115]

However, the wave view of light was not instantly accepted after Young's work. Certainly, its explanatory success swayed opinion in that direction. A number of further developments added further evidence in support of the wave theory. The work of Ampère (1775-1836) and Fresnel (1778-1827) explained the nature of polarization. Léon Foucault's experiment of 1850 proved that light travelled slower in a denser medium, supporting the wave theory.

YOUNG'S "THREE PARTICLES"

As we have seen, Newton suggested that each coloured ray caused a corresponding "bigness of vibration" in the optic nerves and propagated it into the sensorium. In the Bakerian Lecture, Young however suggested that Newton's system was simply not economical when it came to the physiology of the eye. There could not possibly be a nerve to propagate every single refrangibility of light (in theory an infinite number):

> Since, for the reason here assigned by Newton, it is probable that the motion of the retina is rather of a vibratory than of an undulatory nature, the frequency of the vibrations must be dependent on the constitution of this substance. 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 $6\frac{1}{2}$, will affect equally the particles in unison with yellow and blue, and produce the same effect as light composed of those two species; and each sensitive filament of the nerve may consist of three portions, one for each principal colour.[116]

Young later changed his opinion in 1802 and decided on red, green and *violet* as the three primaries after new measurements of the spectrum were given by William Hyde Wollaston (1766-1828).[117]

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[115] Young, T. (1802). The Bakerian Lecture: On the Theory of Light and Colours. *Phil. Trans. R. Soc. Lond.* 1802 92, 12-48, published 1 January 1802.

[116] *Ibid.* p.20

[117] Boring, Edwin G. (1942). *Sensation and Perception in the History of Experimental Psychology* (New York: D. Appleton-Century Company. Inc., 1942) p.111

He suggested that the last passage (quoted) should be modified, "respecting the proportions of the sympathetic fibres of the retina; substituting red, green, and violet, for red, yellow, and blue, and the numbers 7, 6, and 5, for 8, 7, and 6." [118]

Although Aristotle had also considered red, green and violet to be primary colours, it would not make sense to refer to him as the progenitor of the trichromatic theory. The trichromatic theory is the point at which colour came to be regarded as a construct starting *inside* the eye rather than a simple relaying of the information contained in colour-corresponding rays. This idea is not present in the ideas of Aristotle or the artists and printers who discussed the three primaries. These latter practitioners were only interested in the three primaries from a purely practical (colour-mixing) point of view. James Clerk Maxwell made this point clear:

> 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 explanation of this fact, not in the nature of light, but in the constitution of man.[119]

HELMHOLTZ AND SUBTRACTIVE VS ADDITIVE COLOUR

The scientific celebrity of Hermann Ludwig Ferdinand von Helmholtz (1821-1894) was first launched when he successfully measured the rate of propagation of the nervous impulse in 1850.

It was in this decade that he would turn his attention to light and colour. Until 1852 it was assumed that the rules for mixing pigments and the rules for mixing coloured light were the same. We have seen with the work of Moses Harris, among others, that from a practical point of view, artists and printers had worked out that what we now call "subtractive colour mixing" was the way to achieve the widest gamut of colours. However, it was not until the work of Helmholtz that it came to be understood *why* the rules for mixing pure light, and the rules for mixing pigments were different. Helmholtz discovered that pigment mixing is governed by the rules of *subtractive* colour mixing, and that light mixing was governed by the rules of *additive* colour mixing.[120]

Helmholtz carried out experiments with "light boxes" for mixing colours from two prismatic spectra. He noticed that the combination of yellow and indigo-blue produced white, and not green (as would be expected in pigment mixing).[121] He realised that the pigments in paint actually serve

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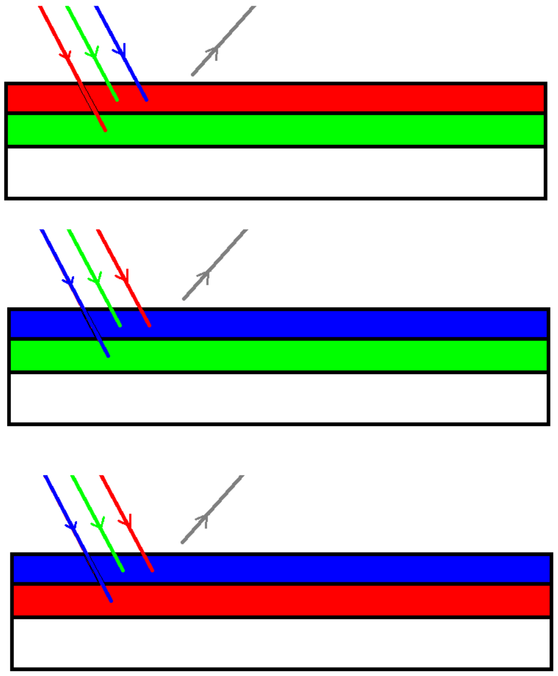
[118] Young, T. (1802). *An Account of some Cases of the Production of Colours, not hitherto described.* By Thomas Young, M.D. F.R.S. F.L.S. Professor of Natural Philosophy in the Royal Institution. In *Phil Transactions of the Royal Society of London for the year MDCCCIII, Part II.* (London: Bulmer) p.395

[119] Maxwell, J. C. (1871). On colour vision. *Proc. R. Inst. GB* (24 March), 260-271.

[120] See Shapiro (1994) *Artist's Colors and Newton's Colors* for full treatment

[121] Helmholtz, H. (1895). *Wissenschaftliche Abhandlungen*. 3 vols. Leipzig: J. A. Barth, 1895. 2:22, no.23.

as *filters* of colour, only letting that colour through and absorbing the rest. They are not *sources* of light as the colours in additive light mixing are. So, he gave the example that when yellow and blue (cyan) paints are mixed, the yellow pigment lets through red, yellow, and green light, and the blue (cyan) pigment lets through cyan-blue, blue, and green. The only light that is let through both pigments is thus green. This is illustrated in the top right of Figure 11. Helmholtz thus concluded that "additive" colour mixing (with the primaries red, green and blue-violet) could only be demonstrated by lights, not pigments.



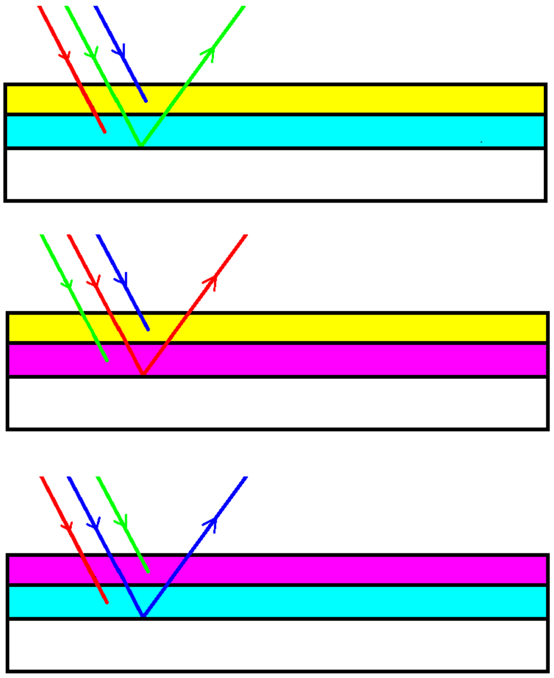
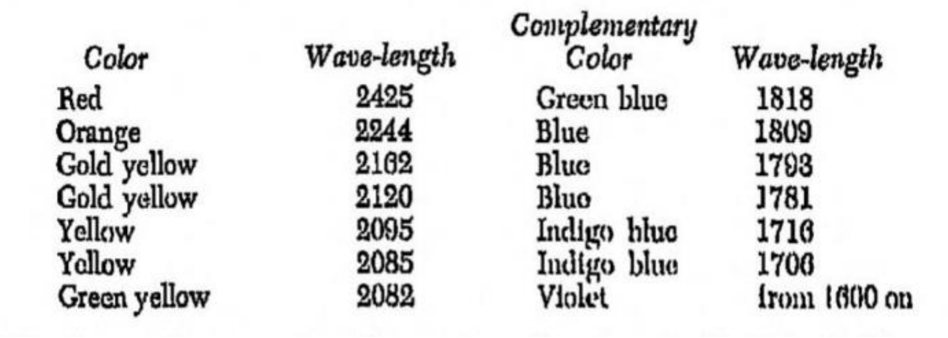


Figure 11a: (left) showing why additive colour mixing does not work for pigments. The colours represent layers of paint and the white represents the page. The pigments act as filters. This is why RGB is used for computer screens (which is *light* mixing) and not for printers, and painters do not use RGB as their primaries.

Figure 11b: (right) showing how the three primaries (and thus a full gamut of colours) can be produced through subtractive colour mixing of pigments. This is the CMYK model of printing. Of course, most modern paints/inks are opaque to light shining through – however they still act as filters for the light that they *reflect*. K refers to black, which is added because the exact mix of most CMY inks does not produce a perfect black, and it saves ink to have only one ink for black. Painters have not traditionally use these "process colours" (cyan, magenta, yellow) but they still use the principle of subtractive colour mixing. The painter's primaries were traditionally blue (in place of cyan), yellow, and red (in place of magenta).

HELMHOLTZ AND COMPLEMENTARY COLOURS

The next year, in 1853, Helmholtz's contemporary Hermann Grassmann (1809-1877) argued that Helmholtz's experiment mixing indigo with yellow lights implied that there were exact complementaries for *all* colours.[122] Helmholtz took this on board and in 1855 produced a table of exact complementaries, as shown in Figure 12.[123]



Color	Wave-length	Complementary Color	Wave-length
Red	2425	Green blue	1818
Orange	2244	Blue	1809
Gold yellow	2162	Blue	1793
Gold yellow	2120	Blue	1781
Yellow	2095	Indigo blue	1716
Yellow	2085	Indigo blue	1706
Green yellow	2082	Violet	from 1600 on

Figure 12: Helmholtz's complementary colour table, reproduced in Boring E. (1942) p.142. As Boring writes, "the figures for wave-lengths are in millionths of a Paris inch. The millimerion as a unit came to Germany with the metric system a few years later. In the second edition of his *Optik* (1896) Helmholtz could show that these original determinations of his were very close to the later and supposedly more accurate ones by von Frey and von Kries (1881) and by König and Dieterici (1887). In fact, there is little difference in these results from the most recent figures founded by Sinden (1923). Differences between observers are greater than any error which there may have been in Helmholtz's measurements of 1855."

Significantly, he discovered that the "complementary" colour to green was a non-spectral purple colour, produced from and exact mixture of spectral red and blue/violet, the extremes of the Newtonian spectrum.[124] This colour would later be named "magenta". It did not appear on Newton's colour circle, as I mentioned above.

In this process, Helmholtz also discovered that the intensity ratios between the two complementary hues is rarely 1:1. To produce white, most of the time, one of the hues had to be increased in intensity.[125] This is why Helmholtz did not display the gamut of colours on a perfectly symmetrical colour circle, but rather on a "chromaticity diagram" which compensated for this fact (see Figure 13).

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[122] As we shall see in Chapter Two, colour complementarity was a concept which had originated around half a century earlier with the work of Count Rumford.

[123] Helmholtz, H. (1855). *Ueber die Zusammensetzung von Spectralfarben.*, *Ann. Phys. Chem.,* 170, 1855, 1-28; reprinted in *Wiss. Abhandl.,* 2, 1883, 45-70

[124] *Ibid.* 2:45-70, no. 35

[125] The reason for this is that the receptors (cone cells) vary in sensitivity.

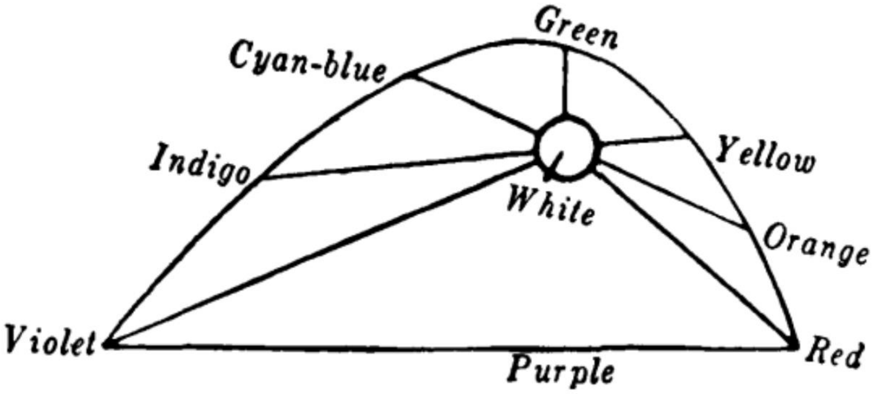

Figure 13: Helmholtz's "chromaticity diagram" from *Ueber die Zusammensetzung von Spectralfarben* (1855).

At first Helmholtz did not accept Young's premise that there were three "particles" in the eye that formed the basis for colour vision. In both the 1853 and 1855 papers he made no mention of Young's theory, and earlier in 1852[126] he actively rejected it on the basis that he was unable to obtain colours as highly saturated as the spectral colours when he combined Young's three additive primaries – red, green, and blue-violet:

> According to the above we must also abandon the theory of three primitive colours, which, according to Thomas Young, are three fundamental qualities of sensation. If the sensation of yellow by the yellow rays of the spectrum were due to the fact that by them the sensations of red and green were simultaneously excited, and both working together produced yellow, exactly the same sensation must by the simultaneous action of the red and green rays; nevertheless by the latter we can never obtain so bright and vivid a yellow as that produced by the yellow rays. The same remarks apply to blue, which would be formed from the mixture of green and violet; and to violet, which would be formed from a mixture of blue and red. To retain in this sense the theory of primitive colours, five such, at least, must be assumed. On the contrary, to represent and classify the dull and comparatively impure colours of natural bodies, in the sense of Lambert and Forbes, three primitive colours would be quite sufficient. But, for a sure and scientific classification, it would be necessary to apply a method of combining colours different from the mixing of pigments.[127]

James Clerk Maxwell read this paper and as we shall see in the next section, he overcame this problem by postulating that the colours that correspond to Young's three "particles" actually exist *outside* of the colour space that they create.

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[126] Helmholtz, H. (1852). *Ueber die Theorie der zusammengesetzten Farben, Ann. Phys. Chem.,* 163, 1852, 45-66, (Ser. 2, v. 87).

[127] Helmholtz, H. (1852). "On the theory of compound colours" The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science. Series 4, Volume 4, 1852 - Issue 28. pp 519-534

MAXWELL'S FORMALISATION

James Clerk Maxwell (1831-1879) was twenty-four years old when he read his paper *Experiments on Colour, as perceived by the Eye* to the Royal Society of Edinburgh in 1855.[128] He had been conducting experiments in colour vision since as early as 1849. This paper is quite extraordinary in that it provides three suggestions that served to further three quite distinct areas of colour science:

1. The first formal additive colour model, which allowed for the fact that colours could be mapped by either the coordinates of red, green and blue, or by hue, "shade" and "tint".
2. An attempted explanation of colour blindness in terms of the trichromatic theory.
3. The first practical proposal for colour photography.

MAXWELL ON ADDITIVE COLOUR

The persistence of human vision had been known for a while – the reader will recall Newton's experiment with the cogged wheel. Then, in the early 19th century toys and curiosities were invented which exhibited this phenomenon. Good examples are John Paris's "thaumatrope", Joseph Plateau's "phenakistoscope", and William Horner's "zoetrope". Maxwell is known to have enjoyed these toys as a child, and a good account of this is given by Longair (2008).[129]

At the start of his 1855 lecture Maxwell described his famous experiment with the spinning top:

> The different tints are produced by means of a combination of discs of paper, painted with the pigments commonly used in the arts, and arranged round an axis, so that a sector of any required angular magnitude of each colour may be exposed. When this system of discs is set in rapid rotation, the sectors of the different colours become indistinguishable, and the whole appears of one uniform tint. The resultant tints of two different combinations of colours may be compared by using a second set of discs of a smaller size, and placing these over the centre of the first set, so as to leave the outer portion of the larger discs exposed. The resultant tint of the first combination will then appear in a ring round that of the second, and may be very carefully compared with it.[130]

This experiment is similar to the one carried out by Newton with the cogged wheel. The difference is that Maxwell was able to adjust the sizes of the sectors of the different colours to yield results other than white. He realised that the largest gamut of colours could be achieved if the three sectors were coloured "vermilion" red, "emerald green", and "ultramarine" blue.

> It may be asked, why some variety of yellow was not chosen in place of green, which is commonly placed among the secondary colours, while yellow ranks as a primary? The

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[128] Maxwell, James Clerk. (1855). "Experiments on Colour, as Perceived by the Eye." *Transactions of the Royal Society of Edinburgh* 21:275-98. (*CPMaxwell* 1:126-54)

[129] Longair, M. S. (2008) "Maxwell and the Science of Colour" Philos Trans A Math Phys Eng Sci. 2008 May 28;366(1871):1685-96

[130] Maxwell, James Clerk. (1855). *Op cit.* p.275

reason for this deviation from the received system is, that the colours on the discs do not represent primary colours at all, but are simply specimens of different kinds of paint, and the choice of these was determined solely by the power of forming the requisite variety of combinations. Now, if red, blue, and yellow, had been adopted, there would have been a difficulty in forming green by any compound of blue and yellow, while the yellow formed by vermilion and emerald green is tolerably distinct.[131]

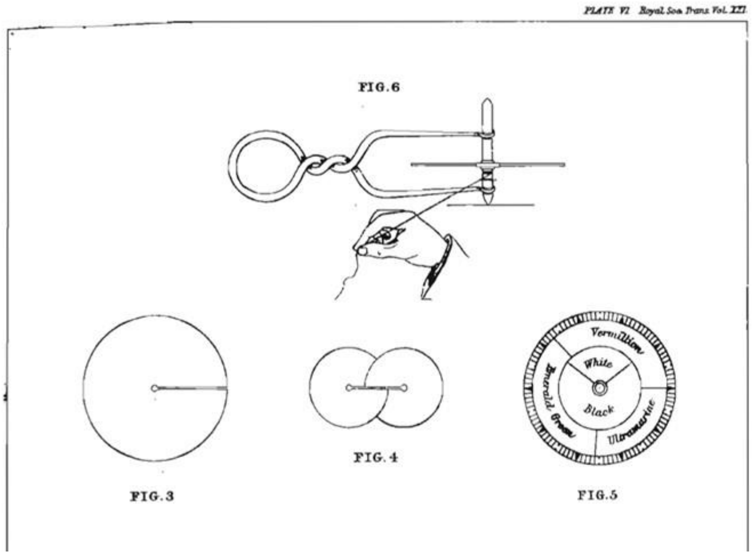

Figure 14a: (top) Operation of the top, from Maxwell, James Clerk. (1855)
Figure 14b: (bottom) Maxwell's colour-mixing top, built c. 1854. Image courtesy of the Cavendish Laboratory, University of Cambridge. The smaller disc in the middle is the sample that is supposed to be matched by the three-colour disc on the outside. Maxwell later used "light boxes" similar to those used by Helmholtz to directly mix coloured light, rather than rely on the coloured paper of his coloured top. See Longair (2008) for a comprehensive treatment.

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[131] Maxwell, James Clerk. (1855). *Op cit.* p.276

Maxwell essayed different hues until he came up with the closest approximation of the three primaries – those which, if the spinning top was equally divided into thirds, would produce a colourless grey. Thus, the first trichromatic additive colour equation was given in this paper:

$$0.37\ V + 0.27\ U + 0.36\ EG = 0.28\ SW + 0.72\ Bk$$ [132]

Other spectral colours could be produced with different linear combinations of these primaries:

> Hence it appears that the nature of a colour may be considered as dependent on *three* things, as, for instance, redness, blueness, and greenness. This is confirmed by the fact, that any tint may be imitated by mixing red, blue, and green alone, provided that tint does not exceed a certain brilliancy.[133]

For Maxwell, the whole gamut of possible colours could be defined by a triangle with red, green and blue at the vertices:

> If we place the three elementary colour-sensations (which we may call, after Young, red, green, and violet) at the angles of a triangle, all colours which the eye can possibly perceive (whether by the action of light, or by pressure, disease, or imagination), must be somewhere within this triangle, those which lie farthest from the centre being the fullest and purest colours. Hence the colours which lie at the middle of the sides are the purest of their kind which the eye can see, although not so pure as the elementary sensations.[134]

The reader will recall from the last section that the reason Helmholtz had originally rejected Young's theory in 1852 was because he was unable to obtain colours as highly saturated as the spectral colours when he combined Young's three additive primaries – red, green, and blue-violet. Maxwell was able to overcome this problem by postulating that the three "particles" represented colours that are actually of *higher* saturation than the spectral red, green and blue. As we can see from Figure 15, Maxwell's RGB primaries exist *outside* of the gamut. In a paper from later in 1855, Maxwell even suggested a means for subjectively observing these supersaturated colour sensations:

> It may be possible to experience sensations more pure than those directly produced by the spectrum, first by exhausting the sensibility to one colour by protracted gazing and then suddenly turning to its opposite.[135]

As we shall see in the next section, Helmholtz proved that this was true in his 1858 paper on colour after-images.

Maxwell then built on Young's hypothesis that there are three "particles" in the eye that would be sensitive to red, green, and blue respectively. He noted that this does not mean that they are only

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[132] Where V is Vermilion, U is Ultramarine, EG is Emerald Green, SW is "Snow" White, and Bk is Black

[133] Maxwell, James Clerk. (1855). *Op cit.* p.279

[134] *Ibid.* p.295

[135] Maxwell, J.C. (1855). On the theory of colours in relation to colour-blindness, in George Wilson's *Researches on Colour-Blindness*, 1855, 153-159

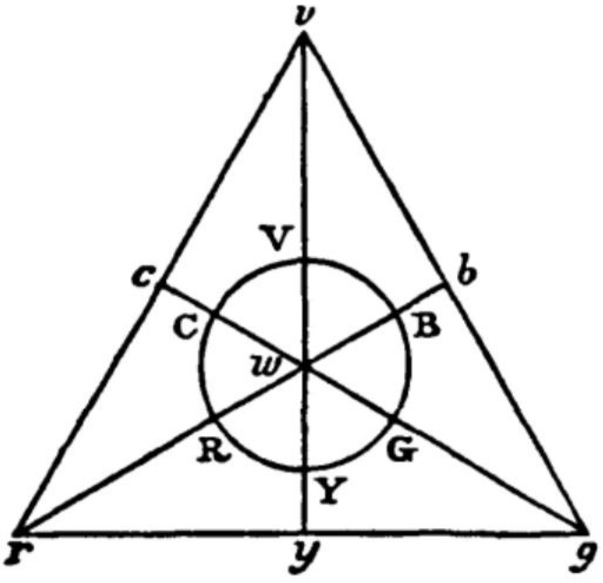

Figure 15: Maxwell's sketch of the spectral locus (the gamut of visible colours) represented as a circle, inside the triangle formed by the colour points of Young's three "particles". Note that the colour points representing the three particles lie *outside* of the circle.[137]

sensitive to one very distinct wavelength of red green or blue – but rather red green and blue are their *peak* sensitivities, and they still cover the rest of the spectrum but at a lower sensitivity:

> In order fully to understand Young's theory, the function which he attributes to each system of nerves must be carefully borne in mind. Each nerve acts, not, as some have thought, by conveying to the mind the knowledge of the length of an undulation of light, or of its periodic time, but simply by being *more* or *less* affected by the rays which fall on it. The sensation of each elementary nerve is capable only of increase and diminution, and of no other change. We must also observe, that the nerves corresponding to the red sensation are affected chiefly by the red rays, but in some degree also by those of every other part of the spectrum; just as red glass transmits red rays freely, but also suffers those of other colours to pass in smaller quantity.[136]

As Helmholtz had done, Maxwell noted that this colour model included the non-spectral "fine purples" (what we would now call magenta):

> It may be easily seen that this arrangement of the colours corresponds to that of the prismatic spectrum; the only difference being that the spectrum is deficient in those fine purples which lie between ultramarine and vermilion, and which are easily produced by mixture. The experiments necessary for determining the exact relation of this list to the lines in the spectrum are not yet completed.[138]

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[136] *Ibid.* p.283

[137] Maxwell, J.C. (1855). "Experiments on Colour, as Perceived by the Eye." *Transactions of the Royal Society of Edinburgh* 21:275-98. (*CPMaxwell* 1:126-54)

[138] *Ibid.* p.282

Maxwell also described another way of defining colour other than RGB. He suggested that a colour could be mapped by the coordinates of "shade", "hue", and "tint". [139] This is still based on the same RGB model, it is just a different way of mapping the colours.

> Another way of showing that colour depends on *three* things is, by considering how two tints, say two lilacs, may differ. In the first place, one may be *lighter* or *darker* than the other, that is, the tints may differ in *shade*. Secondly, one may be more *blue* or more *red* than the other, that is, they may differ in *hue*. Thirdly, one may be more or less *decided* in its colour; it may vary from purity on the one hand, to neutrality on the other. This is sometimes expressed by saying that they may differ in *tint*.
>
> Thus, in shade, hue, and tint, we have another mode of reducing the elements of colour to three. It will be shown that these two methods of considering colour may be deduced one from the other, and are capable of exact numerical comparison.[140]

MAXWELL ON COLOUR BLINDNESS

In the same paper Maxwell offered an explanation for colour blindness (which was then commonly called "Daltonism").[141] John Dalton (1766-1844) had famously revealed the phenomenon of colour blindness in his 1798 paper *Extraordinary Facts Relating to the Vision of Colours* in which he diagnosed himself and his brother with the condition, an inability to distinguish reds and greens. In the same paper Dalton attempted an explanation of the phenomenon. Having no reason to believe anything other than Newton's account of the nerve endings in the eyeball, Dalton thought that his colour blindness was caused by a discoloration of the liquid medium of the eyeball. Dalton instructed his executor to allow a postmortem examination of his eyeball in order to test this hypothesis, and this was carried out in accordance with his wishes. It was found that that Dalton's eyeball was perfectly normal, and that there was no discoloration.

Maxwell however maintained that trichromacy was the key to understanding colour blindness. He held that in the "more definite cases of colour-blindness, the phenomena can be tolerably well accounted for by the hypothesis of an insensibility to red light; and this is, to a certain extent, confirmed by the fact, that red objects appear to these eyes decidedly more obscure than to ordinary eyes".[142] He was suggesting here that the red "particle"/receptor was missing for these subjects:

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[139] "Shade" is now commonly referred to as luminance, and "tint" as saturation.

[140] *Ibid.* p.279

[141] This was effectively a restatement of the hypothesis of Dr George Wilson

[142] *Ibid.* p.284

> The phenomena seem rather to lead to the conclusion that it is the red *sensation* which is wanting, that is, that supposed system of nerves which is affected in various degrees by all light, but chiefly by red.[143]

However, Maxwell was confused by the fact that for these "red-blind" subjects, "though the red appears much more obscure than other colours, it is not wholly invisible, and, what is more curious, resembles the green more than any other colour", and the fact that their perception of green also seemed to be affected:

> The spectrum to them appears faintly luminous in the red; bright yellow from orange to yellow, bright but not coloured from yellow-green to blue, and then strongly coloured in the extreme blue and violet, after which it seems to approach the neutral obscure tint of the red. It is not easy to see why an insensibility to red *rays* should deprive the green rays, which have no *optical* connection with them, of their distinctive appearance.[144]

From this passage we can see that Maxwell had clearly been working on the assumption that the three RGB channels worked independently of one another. He assumed that in colour blindness the red channel was "knocked out" and thus was curious as to why the perception of green was affected – if the green channel was not "knocked out" and was working, why, he asks here, was the subject's perception of green affected?

A tentative answer to this problem would not come until the work of Christine Ladd-Franklin (1847-1930). Ladd-Franklin had worked in the laboratories of G.E. Müller and Hermann von Helmholtz as a young researcher. In 1929 she published her *Colour and Colour Theories* which laid out her "evolutionary theory of colour sensations".[145] She proposed that colour vision evolved in three stages; achromatic vision (black and white), then blue-yellow sensitivity developed, then red-green. The red and green channels had evolved from an earlier unified "yellow" channel. Thus, the red and green channels had evolved for a particular purpose – to distinguish wavelengths within the range of what we call "red" and "green". If one of them is "knocked out", there can no longer be any distinguishing of "red" and "green" – and thus Maxwell's problem is solved. Instead, the subject will perceive what our dichromat ancestors perceived – a colour world in which there are two poles, "yellow" ("redgreen") and "blue". Ladd-Franklin's theory also seemed to explain the fact that red-green colour blindness is far more common than blue-yellow colour blindness. Ladd-Franklin's hypothesis has since been proven in genetic studies. It is now understood that between

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[143] *Ibid.* p.284

[144] *Ibid.* pp.284-285

[145] Note that Maxwell would not have been able to think in these terms in 1855. Darwin's *Origin* was published in 1859, and was not widely accepted until long after.

45 and 30 million years ago, the M ("green") and L ("red") cones slowly emerged and distinguished themselves from their common ancestor.[146] I will discuss this further in the next chapter.

MAXWELL ON COLOUR PHOTOGRAPHY

If the visual information of the world was processed through three channels in the retina, Maxwell assumed that it was possible that the light could be captured and represented in these three channels. In the 1855 paper Maxwell laid out the first proposal for colour photography:

> This theory of colour may be illustrated by a supposed case taken from the art of photography. Let it be required to ascertain the colours of a landscape, by means of impressions taken on a preparation equally sensitive to rays of every colour.
>
> Let a plate of red glass be placed before the camera, and an impression taken. The positive of this will be transparent wherever the red light has been abundant in the landscape, and opaque where it has been wanting. Let it now be put in a magic lantern, along with the red glass, and a red picture will be thrown on the screen.
>
> Let this operation be repeated with a green and a violet glass, and, by means of three magic lanterns, let the three images be superimposed on the screen. The colour of any point on the screen will then depend on that of the corresponding point of the landscape; and, by property adjusting the intensities of the lights, &c, a complete copy of the landscape, as far as visible colour is concerned, will be thrown on the screen. The only apparent difference will be, that the copy will be more subdued, or less pure in tint, than the original. Here, however, we have the process performed twice—first on the screen, and then on the retina.[147]

This is the first description of additive colour photography in scientific literature. Six years later on 17 May 1861 the first demonstration of a colour image using this process was presented by Maxwell, a year after he had already won the Royal Society's Rumford Medal for his work in colour vision.[148]

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[146] Yokoyama, S.; Xing, J.; Liu, Y.; Faggionato, D.; Altun, A.; Starmer, W. T. (2014). "Epistatic Adaptive Evolution of Human Color Vision". *PLoS Genetics. **10** (12): e1004884.*

[147] Maxwell, James Clerk. (1855). "Experiments on Colour, as Perceived by the Eye." p.284

[148] Domb, C. (1980) *James Clerk Maxwell In London 1860-1865. Notes and Records of the Royal Society of London*. Vol. 35, No. 1 (Jul., 1980), pp. 67-103 (37 pages)

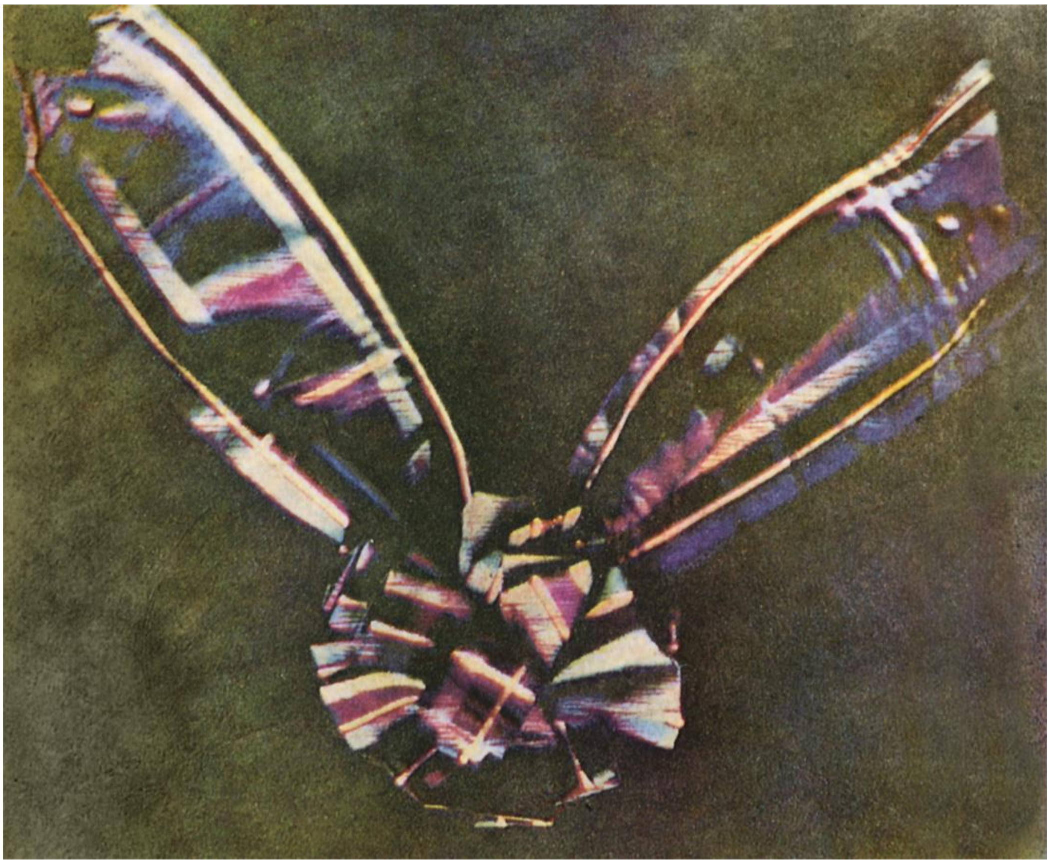

Figure 16: This image of a tartan ribbon is, first shown in Maxwell's lecture of May 1861, is considered to be the first permanent colour image. It was taken by Thomas Sutton and is recorded in three glass plates. What we see here is a superimposed projection of the images recorded on each of those glass plates, with each image being projected with light of its own colour, red, green or blue. The three photographic plates now reside in a small museum at 14 India Street, Edinburgh, the house where Maxwell was born. Scanned from *The Illustrated History of Colour Photography*, Jack H. Coote, 1993.

HELMHOLTZ'S CONVERSION

The reader will recall (again) that in 1852 Helmholtz's main objection to the trichromatic theory was that he was unable to obtain colours as saturated as those exhibited in the spectrum when he mixed two others. The reader will also recall that in 1855 Maxwell suggested that the colour values of the three "particles" actually lay *outside* of the visible gamut (as shown in Figure 15), and that Maxwell had further suggested it could be possible to observe something close to the supersaturated colour corresponding to the three "particles", "first by exhausting the sensibility to one colour by protracted gazing and then suddenly turning to its opposite." [149]

As we shall see in Chapter Two, colour afterimages had been discussed in the scientific literature for at least one hundred years by this point. Georges-Louis Leclerc, Comte de Buffon (1707-1788) had noticed that the colour of the afterimage was always the complementary colour to the original test colour. In 1858 Helmholtz also wrote a paper on colour after-images.[150] In this paper Helmholtz went ahead with Maxwell's suggestion and did indeed obtain such supersaturated sensations. This was enough to quell his doubts about the trichromatic theory.

In a short paper "On Colour Blindness" in 1859, Helmholtz confirmed Maxwell's hypothesis on the origin of colour blindness, and indicated that he agreed with Maxwell's trichromatic equations.[151] Then in 1860 he published the second volume of his *Handbuch der physiologen Optick*. By this point Helmholtz had accepted trichromacy in its Maxwellian form.[152] It is in this work that Helmholtz introduced his celebrated hypothetical spectral energy curves for the "three distinct sets of nerve fibers", shown in Figure 17.

The idea of separate channels of "nerve fibers" which stimulated sensations of a specific section of the spectrum (red, green, or blue) sat well in the context of contemporary German physiology. The law of specific nerve energies, given by Johannes Peter Müller in 1835, proposed that a sensation is defined by the pathway over which the sensory information is carried. Thus, the colours created in Newton's experiments with the bodkin needle pressing on his eyeball could be rationalised as a force being applied to the optic nerve, a nerve which could only cause visual sensations, and not for example pain. In the *Handbuch* of 1860 Helmholtz made it clear that the trichromatic theory established specific nerve energies in relation to the three additive primaries, and that "Young's hypothesis is only a more special application of the law of specific sense energies". [153]

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[149] Maxwell, J.C. (1855). On the theory of colours in relation to colour-blindness, in George Wilson's *Researches on Colour-Blindness*, 1855, 153-159

[150] Helmholtz, H. (1858). Ueber die subjectiven Nachbilder im Auge, *Verb. D naturhist. Ver. Zu Rheinland u. Westphalen, 15,* 1858, 98-100; reprinted in *Wiss. Abbhandl.,* 3, 1895, 13-15

[151] Helmholtz, H. (1859). Ueber Farbenblindheit, *Verb. d. naturhist. med. Ver. zu Heidelberg,* 2, 1859, 1-3; reprinted in *Wiss. Abhandl.* 2, 1883, 346-349.

[152] See Turner, R.S. (1994) p.104 for full treatment.

[153] Helmholtz, H. (1962) (1860). *Helmholtz's Treatise on Physiological Optics*. Ed. James P.C. Southall. 3 vols. In 2. New York: Dover, 1962. p.145

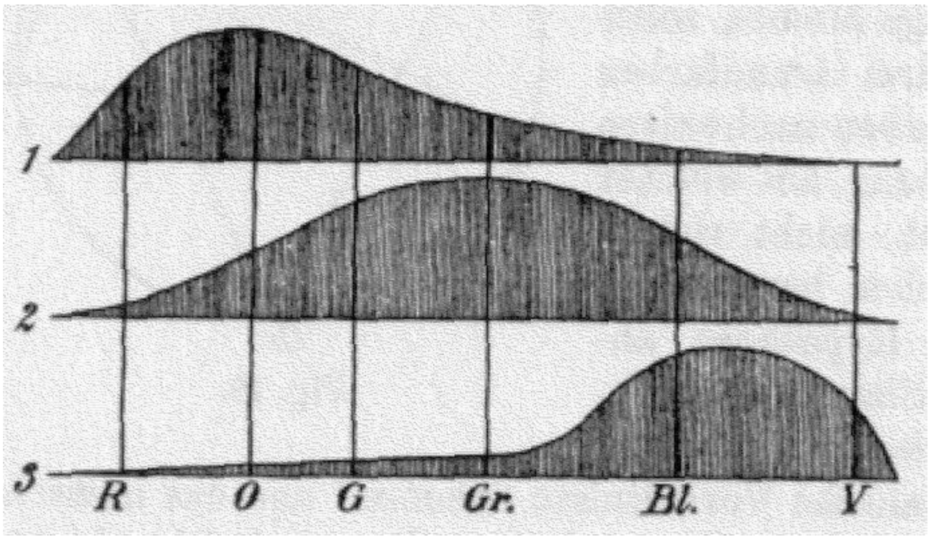

Figure 17: Helmholtz's hypothetical spectral energy curves for the "three distinct sets of nerve fibers" From *Helmholtz's Treatise on Physiological Optics*. Ed. James P.C. Southall. 3 vols. In 2. New York: Dover, 1962. 2:143. In modern curves the red and green curves are a lot closer together, but the underlying principle is the same.

The trichromatic theory was not automatically accepted by all, even after Helmholtz's endorsement. Notable dissidents included Fechner and Ernst Mach. However, as R.S. Turner (1994) notes, its efficacy in explaining the affliction of colour blindness (eventually) won the day: "The reception of Young's theory turned primarily on the theory's adequacy to explain color blindness. Helmholtz and Maxwell both considered that the theory's great triumph, and in the early 1870s Preyer, Brücke, and the young Eduard Raehlmann still took the theory as the indispensable starting point for any understanding of that affliction." [154]

Richard Kremer (1993) has noted that Helmholtz "acted as a creative borrower and synthesizer who clarified others' ideas, removed conceptual problems from others' experiments, collected scattered research of others into unified programs of research, and sought to define orthodoxy by formulating an authoritative discourse for the field." [155] R.S. Turner wrote that this "genius for synthesis was nowhere more evident than in the second volume of the *Handbuch*, in which Helmholtz drew upon the work of Jan Purkinje, Johannes Müller, Thomas Young, Heinrich Dove, Ernst Brücke, Joseph Plateau, Heinrich Meyer, and especially that of Gustav Fechner and Clerk Maxwell to forge a new basis for the study of colour perception." [156]

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[154] Turner R.S. (1994). p.118

[155] Kremer (1993). "Innovation Through Synthesis: Helmholtz and Color Research" in *Hermann von Helmholtz and the Foundations of Nineteenth-Century Science*. (ed. David Cahan) Berkeley/Los Angeles: University of California Press. p.2

[156] Turner R.S. (1994). p.105

PARTICLES TO CONES

In 1828 the German biologist Gottfried Reinhold Treviranus (1776-1837) had identified "rod-shaped terminations of the nervous fibers upon the internal surface of the retina … a layer of cylinders arranged closely side by side." [157] In 1851 the structure and relation of rods and cones were described by Heinrich Müller (1829-1864), and the following year these descriptions featured in the *Mikroskopische Anatomie* by Albert von Kölliker (1817-1905). In 1866 Max Schultze (1825-1874) found that the structure of these cones did not differ within any of the regions of the retina.

Helmholtz had initially identified retinal cone cells as the RGB receptors in the first 1860 edition of the *Handbuch*. Then in a later reissue of 1867, he went back on this and suggested that the retinal rod cells were also responsible. This idea was then overthrown by Johannes von Kries (1853-1928) who proposed his *Duplizitätstheorie* in 1894, in which he held that daylight vision is governed by the retinal cones, and twilight and night vision by the retinal rods.

Sixty years later it was finally established that the "cone" cells were exclusively responsible for photopic vision. Three kinds of "cone" cells with peak sensitivities to "red", "green" and "blue" were announced in a paper published by the Swedish-Finnish physiologist Gunnar Svaetichin (1915-1981) in 1956.[158]

We can see that in the century that passed after Helmholtz's final acceptance of the trichromatic theory, the basic model did not change – only that the "particles" were replaced with "cones". The fundamental assumption remained the same; the colour perceived at a point in the visual field is completely determined by the physical properties of the light rays entering the retina at that point.

The acceptance of the trichromatic theory of colour marks the point at which colour came to be regarded as a construct starting inside the eye rather than a simple reading of physical world. However, the trichromatic theory, although it involves the human, it is the human as a *mechanism*, not the human as a subjective observer of the world. The cones simply convert light energy into variable activation of three different cells. The activation of these cells is simply a causal effect of the wavelength and intensity of the incident light. Thus, we are still on the level of physical science when we talk about the trichromatic theory.

The modificationism theory put the colour-determining mechanism inside the modifying medium. The separationism theory put the colour-determining mechanism inside the coloured rays themselves. The trichromatic theory put the colour determining mechanism inside a point on the

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[157] Treviranus, G.R. (1828) *Beiträge zur Lehre von den Gesichtswerkzeugen und dem Sehen des Menschen und der Thiere*

[158] Svaetichin, G. (1956). Spectral response curves from single cones, Actaphysiol. scand. 39, Suppl. 134, 17-46.

retina. Throughout this time the colour atomism hypothesis remained unchanged. As we will see in the next chapter, from the eighteenth century onwards a number of observations appeared which seemed to challenge this hypothesis.

CHAPTER TWO

The Phenomenological Science of Colour

The theory of colours, in particular, has suffered much, and its progress has been incalculably retarded by having been mixed up with optics generally, a science which cannot dispense with mathematics; whereas the theory of colours, in strictness, may be investigated quite independently of optics.

Johann Wolfgang von Goethe, *Zur Farbenlehre* (1810)

INTRODUCTION

In the last chapter I argued that the physical science of colour was founded upon what I have called the *colour atomism hypothesis*. A good characterisation of the colour atomism hypothesis was Newton's statement from his *Opticks* of 1704 that colours at a point in the visual field were "nothing but a Disposition to reflect this or that sort of Rays more copiously than the rest".[159] As we have seen, the colour atomism hypothesis remained unchanged despite radical changes in the physical model of light and colour.

Notwithstanding the fact that this "classical" picture was adopted by the majority of eighteenth-century investigators, towards the end of that century a growing number of treatises questioning this view began to appear, mostly originating from continental Europe. These treatises reported colour phenomena in which colours were *induced* by other colours in the surrounding scene, such as "coloured shadows", "coloured afterimages", "simultaneous colour contrast", and "colour complementarity" – phenomena which could not be accounted for by the colour atomism hypothesis. Whereas practitioners of the physical school studied individual points of coloured light in isolation, investigators of what I will call the "phenomenological" school studied colour as it appears in the wider visual field, as it is normally perceived by human subjects.[160]

The tension between the physical science of colour and these phenomenological observations was well understood by Edwin Land. In his 1959 paper "Experiments in Color Vision", Edwin Land asked rhetorically:

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[159] Newton, I. (1952) [1704]. *Opticks*. p.109

[160] The "phenomenological tradition" was identified by Edwin G. Boring's *Sensation and Perception in the History of Experimental Psychology* of 1942 (esp. pp.155-6). This is a work which, as I discussed in the introduction to this thesis, Edwin Land often cited when discussing the history of his discipline. It is also used by R.S. Turner to describe Ewald Hering's school (Turner 1994, p.239).

> Is something "wrong" with classical theory? This long line of great investigators cannot have been mistaken. The answer is that their work had very little to do with color as we normally see it. They dealt with spots of light, and particularly with pairs of spots, trying to match one another. The conclusions they reached were then tacitly assumed to apply to all of color sensation.[161]

In a response to letters received after publication of that 1959 paper, Land acknowledged the importance of the "inductive" experiments of those practitioners "from the middle of the 17th century to the middle of the 20th … [whose] endless chronicles of amazement about colored shadows, and a variety of speculations about the reality of these colors so remote from the color associated with the wavelengths or wavelength mixtures of the stimuli" led to the development of a science of "color as we normally see it".[162] In the face of criticism from contemporaries who were reluctant to abandon the classical picture in favour of this "inductive" one, Land asserted:

> We must stand our ground and insist not only that the colors produced by induction are just as real as any other colors, but also that without it many of the colors in everyday life would simply not be there.[163]

The figures featured in this chapter have been chosen for their influence on the body of knowledge that Land and his contemporaries inherited, and as we shall see in the next chapter, Land acknowledged their influence both explicitly and implicitly.

COMTE DE BUFFON, "ACCIDENTAL COLOURS", AND "COLOURED SHADOWS"

Over a period spanning more than half a century, between 1749 and 1804, the monumental encyclopaedia of natural history – the *Histoire Naturelle, Générale et Particulière* – was published by the French naturalist and polymath Georges-Louis Leclerc, Comte de Buffon and his colleagues.[164] It was intended to be a record of all the natural historical knowledge available at the time. The thirty-six volumes published during his lifetime included a methodological treatise[165], a general treatise on geology and animals [166], a treatise on the natural history of mankind[167], twelve volumes on quadrupeds, nine volumes on birds, five volumes on minerals, and seven volumes of supplements.

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[161] Land, Edwin H. (1959). "Experiments in Color Vision", *Scientific American*, Vol. 200, pp.84-94, 96-99, May 1959

[162] Land, Edwin H. (1959). "Letters to the Editors, September 1959", *Scientific American*, Vol. 201, Issue 3, September 1959

[163] *Ibid.*

[164] Buffon lived from 1707-88. 36 volumes were published in his lifetime, and the remaining 8 were published posthumously by his colleagues, led by Bernard Germain de Lacépède.

[165] *De la manière d'étudier l'histoire naturelle* in Leclerc, Comte de Buffon. (1749). *Histoire Naturelle, Générale et Particulière, avec la Description du Cabinet du Roy. Tome Premier*

[166] *Théorie de la Terre, Histoire Générale des animaux* in *Ibid. Tome Second*

[167] *Histoire Naturelle de l'homme* in *Ibid. Tome 3*

The first volume of these seven supplements, published in 1774, contained a series of disconnected essays dealing with, variously, the nature of the elements (light, heat, fire, air, water, and earth)[168], Newton's law of gravitation[169], essays on the interchangeable nature of heat and light (with an analysis of Archimedes' mirrors)[170], and finally, his seventh treatise on "accidental colours" and coloured shadows; *Observations sur les couleurs accidentelles, et sur les ombres colorées.* I am unaware of any English translation of this treatise, and so have provided my own in the appendix of this volume.

Buffon began his treatise by remarking that "even though a great deal of attention has lately been given to the physics of colours, it does not seem that much progress has been made since Newton. This is not because he exhausted the subject, but because most physicists ["Physiciens"] have worked more to oppose him rather than to understand him, and though his principles are clear, and his experiments incontestable, there are so few individuals who have made an effort to deeply examine the entire set of his discoveries and their interrelationships, that I feel that I should not speak of a new kind of colour phenomena without first presenting a clear picture of the production of colours in general."[171] The hostile *physiciens* Buffon refers to could have been contemporary opponents of Newton such as Hooke and Huygens, or later, French contemporaries of Buffon who continued to defend Cartesian ideas until the mid-eighteenth century.

Buffon, unlike them, did not set out to challenge the fundamental tenets of Newton's *Opticks*. He was even contented to accept Newton's delineation of the seven colour domains, despite acknowledging his own ability to discern more than seven colours in the spectrum:

> With a little perseverance one sees even more than seven, since by successively catching different parts of this purified light spectrum on a piece of white string, I have often counted as many as eighteen or twenty colours for which the differences were perceptible to my eyes. With better organs or greater attention, one could count yet more. This does not mean however that we should not fix the number of denominations at seven, no more, no less. This is all for a good reason, since by dividing the pure light spectrum into seven intervals, and following the proportions given by Newton, each of these intervals contains colours which, when taken together, are indecomposable by the prism or by any other method, and this is why we call them *primitive colours.*[172]

Here Buffon accepted Newton's "primitive colour" definition; a primitive spectral colour is one that cannot be broken down into further perceptible colours when it is subjected to decomposition

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[168] *Première Partie. De la Lumière, de la Chaleur et du Feu* and *Seconde Partie. De l'Air, de l'Eau et de la Terre* in Leclerc, Comte de Buffon. (1774). *Histoire Naturelle, Générale et Particulière* : *supplément à l'histoire naturelle. Tome premier.*
[169] *Réflexions sur la Loi de l'Attraction* in *Ibid.*
[170] Mémoires 1-6 and Articles I-III in *Ibid.*
[171] Leclerc, Comte de Buffon. (1774). "Septième Mémoire. Observations sur les couleurs accidentelles, et sur les ombres colorées" in *Histoire Naturelle, Générale et Particulière: supplément à l'histoire naturelle. Tome premier.* [Trans: Brown, J.P. (2017)], p.517. (Author's translation is included as an appendix to this volume).
[172] *Ibid.* p.519

by a second prism. Buffon challenged neither Newton's experimental results nor his fundamental colour taxonomy.

However, he did challenge one aspect of Newton's thesis, that is, the significance he gave to the link between the seven colour intervals and the seven musical tones (see Figure 6). For Buffon, this was "a coincidence which we should not give serious attention to. These two results are independent of one another, and one would have to blindly invest oneself in this hypothesis to pretend that by virtue of such a fortuitous coincidence we should construct common scientific laws for the workings of the eye and the ear, and treat one of these organs as if it conformed to the laws of the other, and imagine that it be possible to play a concert to the eyes or to perceive a landscape with the ears."[173]

ACCIDENTAL COLOURS

Of greater interest to us are Buffon's observations of what he called "accidental colours". He defined these as colours which "depend as much on our sense organ, as on the action of the light itself" [174], such as the colours produced in Newton's foolhardy experiments with a bodkin needle and his own eye. Buffon believed these colours to be as much *psychological* as physical in nature:

> When the eye is struck or pressed, one sees colours in the dark, and when this organ is fatigued or debilitated, one sees colours again. It is these kinds of colours that I thought I should call *accidental colours*, to distinguish them from natural colours, and because they effectively never appear unless the organ is forced or has been impressed too vigorously.[175]

With the exception of one of his contemporaries and correspondents, Dr. James Jurin FRS FRCP, Buffon claims to be the first to have made this distinction.[176] Buffon then goes on to describe a series of experiments in which he subjected his gaze to various colour test stimuli and reported back the "accidental colours" they engendered. The first went as follows:

> When one fixes one's gaze for a long period on a mark or on a red figure on a white background, for example a small square of red paper on a white sheet of paper, one sees a sort of crown of a weak green colour appear around the small red square. Ceasing to look at the red square and turning one's gaze to the white paper, one sees, very distinctly, a square of a pale green colour, approaching blue in hue. This appearance subsists for quite some time, depending on how strong the impression of the red colour had been. The size of the imaginary green square is the same as that of the real red square, and the green only

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[173] *Ibid.* p.520

[174] *Ibid.* p.528

[175] *Ibid.* p.528

[176] Jurin, J. (1738). "An essay on distinct and indistinct vision." in Smith R. (Ed.), *A compleat system of opticks in four books, viz. a popular, a mathematical, a mechanical, and a philosophical treatise* (pp. 115–171). Cambridge, UK: Author.

> vanishes after the eye has been reassured by gazing successively at many other objects whose images destroy the overbearing impression caused by the red.[177]

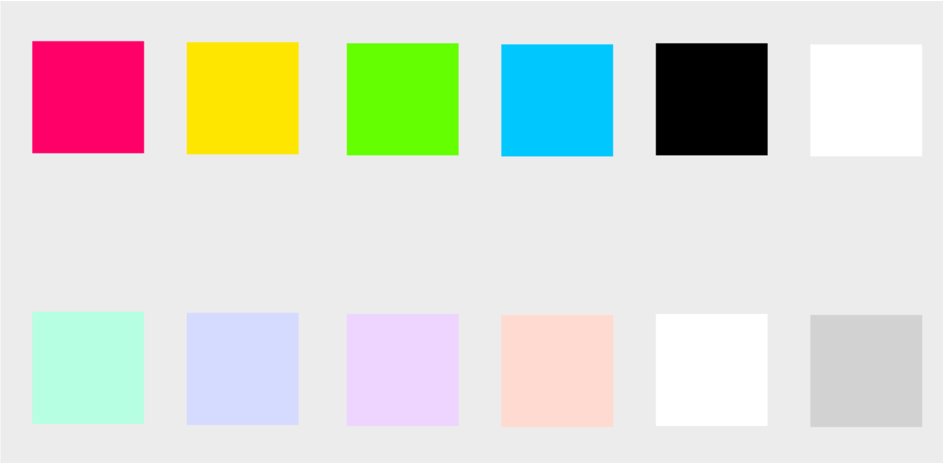

Figure 1: Simulation of Buffon's colour patch experiments. The test samples form the top layer. The bottom layer is composed of the corresponding "accidental colour" perceptions induced after long exposure to each test sample. The reader will be able to confirm these him/herself by gazing intensely at each test sample in isolation and then transferring their gaze to a white/neutral background.

Buffon then conducted the same experiment with a yellow figure, begetting a blue afterimage ; with a green figure, begetting a "pale purple colour, similar to the colour of a pale amethyst" ; and with a black mark, begetting a "brilliant white similar to the intense and radiant white of the coloured rings described by Newton".[178] Significantly, Buffon noticed the striking regularity of the colour pairings:

> So there we have it – a set of accidental colours which are related to the set of natural colours. Natural red produces accidental green, yellow produces blue, green produces purple, blue produces red, black produces white, and white produces black.[179]

Curiously Buffon used the broad description "blue" twice here to refer to two quite different shades (see Fig. 1). We must appreciate the fact that at Buffon's time colour names were assigned purely by linguistic convention, and were not used with the same care that would become the norm from the late 19th century onwards. Nevertheless, Buffon's observations are consistent with the modern understanding of the complementary colour pairings – for example, for the three additive

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[177] Leclerc, Comte de Buffon. (1774). "Septième Mémoire. Observations sur les couleurs accidentelles, et sur les ombres colorées" in *Histoire Naturelle, Générale et Particulière: supplément à l'histoire naturelle. Tome premier.* [Trans: Brown, J.P. (2020)], p.528-9.

[178] *Ibid.* p.530

[179] *Ibid.* p.531

primary colours (red, green and blue), the complementary pairs are red-cyan, green-magenta, and blue-yellow. Buffon's red figure begets "a pale green colour, approaching blue in hue", a colour close to what we would now refer to as cyan[180]. His yellow figure begets blue. His green square begets a "pale purple colour, similar to the colour of a pale amethyst", a colour close to what we would now refer to as magenta.

However, we should be cautious in using the term "complementary colours" to categorise Buffon's observations, since it does not seem that he saw a necessary and universal link between these colour pairs. As we shall see, it was Benjamin Thompson, Count Rumford who introduced this term into the scientific republic of letters.

Buffon also noticed that when these mental "accidental colours" mixed with the physical "natural colours", the results of these mixtures followed the same rules as regular mixing within the "natural colours":

> I found that these accidental colours change upon mixture with natural colours, and that they follow the same rules of appearance; since when an accidental green colour, produced by a natural red, is imposed on a brilliant red background, this green colour turns yellow; if an accidental blue colour, produced by a vivid yellow, is imposed on a yellow background, it turns green. Thus, the colours which result from the mixture of these accidental colours with natural colours, follow the same rules and have the same appearances as the natural colours in their composition and in their mixture with other natural colours.[181]

This is quite significant – it seems here that Buffon was suggesting that the visual mechanisms for generating "natural colour" perceptions were the same as those which generated the "accidental colour" perceptions, that purely "mental" colours and colours "out in the world" have the same origin.

It is curious that Buffon continued to use the word "accidental" to describe these induced colours – after all, he had succeeded in showing that they followed a regular law. It was not until the 19th century that they were referred to as "afterimages" (*Nachbilder*), first by Gustav Fechner (1801-1887), and the term "accidental colours" dropped out of use.[182]

Buffon's laws were confirmed by the Viennese Jesuit and priest Karl Scherffer (1716-1783) in his *Treatise on Accidental Colours*, in which he noted that the colour reversals always occur between the colours on either side of Newton's colour circle. Scherffer was also the first to propose the idea

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[180] The word « cyan » (from Greek κύανος « kyanos ») was not used as a colour term in the English-speaking world until the mid-19th century.

[181] *Ibid.* p.533

[182] Boring, Edwin G. (1942), p.160

that the afterimages occur because the eye becomes fatigued after long exposure to the test sample.[183]

As we saw in Chapter One, Hermann von Helmholtz wrote a paper on colour after images in 1858 which confirmed Buffon's laws.[184] Additionally, he proved that supersaturated colour sensations could be induced when the subject gazes at a colour, and then turns away and looks at a surface coloured with the complement to that colour. Helmholtz found that this colour will be supersaturated since it combined the afterimage effect with the stimulus of the colour itself. He and his contemporary Fechner both followed Scherffer in offering the "retinal fatigue" hypothesis as the best explanation of this phenomenon.[185]

COLOURED SHADOWS

Before concluding his treatise, Buffon announced "one more observation which will perhaps seem extraordinary":

> … an observation which I am astonished that no one has made before; this is the fact that the shadows of bodies which by their essence should be black, since they are nothing but the absence of light, that these shadows, I say, are always coloured at sunrise and sunset. During the summer of the year 1743, I observed more than thirty dawns and as many dusks, and all the shadows which were cast on white surfaces, for example on white walls, were sometimes green, and more often blue, and a blue as vivid as the most beautiful azure. I showed this phenomenon to many people who were as surprised as I. The season did not have any effect on this, since it was only eight days ago (today's date being the 15th November 1743) that I saw blue shadows, and whosoever makes the effort to observe the shadow of one of their fingers cast on a piece of white paper at sunrise or sunset, will see this blue shadow as I did. I do not know any astronomer, any physicist (*Physicien*), anyone, in a word, who has spoken of this phenomenon, and I believed that in virtue of it being a novelty, one might permit me to give more precise details of this observation.[186]

What is interesting about this account is the *surprise* Buffon had at his "discovery". Painters had known for centuries that shadows should not be painted exclusively in shades of grey – indeed, Leonardo da Vinci had observed this fact in his notebooks.[187] Later in the essay Buffon acknowledged that this observation "that the physicists have missed on shadows, and on dark

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[183] Boring, Edwin G. (1942), p.158

[184] Helmholtz, H. (1858). Ueber die subjectiven Nachbilder im Auge, *Verb. D naturhist. Ver. Zu Rheinland u. Westphalen, 15,* 1858, 98-100; reprinted in *Wiss. Abbhandl.,* 3, 1895, 13-15

[185] Helmholtz, H. [1860] (1962). *Helmholtz's Treatise on Physiological Optics*. Ed. James P. C. Southall. 3 vols. In 2. New York: Dover., pp.258-62

[186] *Ibid.* p.536-7

[187] Da Vinci, Leonardo. (1519) [1888] The Notebooks of Leonardo da Vinci. Volume 1 : V. Theory of Colours. Translated by Jean Paul Richter

objects viewed from afar, has not been missed by the most able painters, and must effectively be used as a basis for the colours of distant objects".[188] He suggested here that what painters had discovered through direct observation of nature, physicists had missed due to their over-dependence on the Newtonian optical scheme. Since the colours of objects, according to Newton, were "nothing but a Disposition to reflect this or that sort of Rays more copiously than the rest"[189] it would of course seem inconceivable to the strict Newtonian that shadows, being "nothing but the absence of light" as Buffon says here, could be coloured. Buffon's surprise here can thus perhaps be understood as a consequence of his "Newtonian" education.

Buffon went on to describe further observations of shadows of different shades, which turned out to depend on the colour of the sky at the time of observation. On a day when "the sky was clear, with the exception of the setting Sun, which, although free of clouds, was covered by a transparent curtain of reddish-yellow vapours, and the Sun itself was of a strong red colour" Buffon saw "very distinctly, the shadows of the trees which were at 20 and 30 feet from the white wall, coloured in a delicate green that was approaching blue. The shadow of a trellis which was 3 feet from the wall, was perfectly traced on this wall, as if one had just painted it in a greenish grey."[190] The next day, at sunrise, he wrote: "I went to look at other shadows on a white wall, but instead of finding them to be green, as I was expecting, I found them to be blue, or rather the colour of the most vivid indigo. The sky was calm, and there was only a thin curtain of yellowish vapours to the east … On the same day at sunset I saw the green shadows again, as I had seen them the day before."[191] As with his "accidental colour" observations, Buffon noticed the regularities of the colour pairings.

These observations were all made in the year 1743, and the original treatise containing them was printed by the Académie Royale des Sciences that same year. The version published as an appendix in Buffon's *Histoire Naturelle* of 1774 contains further remarks as he revisited the subject thirty years later:

> More frequent observations have made me recognise that shadows never appear green at sunrise and sunset, and only appear when the horizon is dense with red vapours. In all other cases the shadows are always blue, and even bluer than the clearest sky.[192]

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[188] Leclerc, Comte de Buffon. (1774). *Ibid.* p.539

[189] Newton, Isaac. (1704). p.109

[190] Leclerc, Comte de Buffon. (2020) [1774]. "Observations on accidental colours, and on coloured shadows" [Septième Mémoire. Observations sur les couleurs accidentelles, et sur les ombres colorées.] ; translated in appendix to Brown, Joseph P. (2020) *The Land Experiments in Colour Vision. Colour as a Physical, Phenomenology*

[191] *Ibid.* p.537-8

[192] *Ibid.* p.538

Buffon did not make a connection between the apparent complementarity of the "accidental colours" and the apparent complementarity of the coloured shadows and the light of the sky that engendered them. Instead, Buffon saw the blue shadow as

> … nothing other than the colour of the air, and I do not know why some physicists have defined the air as an invisible fluid, odourless, and innocuous, because it is certain that the celestial azure is nothing other than the colour of the air …[193]

Instead, Buffon hazarded his own rather elaborate and convoluted Newtonian explanation of how the colour of the air painted itself onto the shadows:

> It is certain that the small quantity of air – which only amounted to three feet between the trellis and the wall, could not have given such a strong shade of blue to the black colour of the shadow. If that had been the case, one would see blue shadows at midday and at all other times of the day, as one sees them at sunrise and sunset. Thus, this appearance does not depend uniquely on the extent of the air between the object and the shadow, but rather almost doesn't depend on it at all. However, it must be considered that at sunrise and sunset, the light of this star, being weakened by the surface of the Earth – which at this time is at the most oblique angle relative to the star – therefore the shadows are less dense, that is to say relatively less black. At the same time the Earth is only being illuminated by the weak light of the Sun which only glances off its surface, and the mass of air which is at the highest altitude, and consequently still receives the light of the Sun much less obliquely, deflects this light towards us, and illuminates us at least us much, perhaps more than the Sun itself. Yet this pure and blue air can only illuminate us by sending us a great quantity of rays of that same blue colour, and as soon as these air-reflected blue rays fall on objects like shadows that lack all other colours, they tint them with a more or less strong shade of blue, depending on how little direct sunlight there is, and how much reflected atmospheric light there is. I could add many other things which would be relevant to support this explanation, but I think that what I have just laid out is sufficient for the understanding and satisfaction of reasonable minds.[194]

The Newtonian picture of colour was clearly too strong to be abandoned, and the counter-intuitive phenomenon of the coloured shadows could easily be patched over in Thomas Kuhn's sense. One may ask then; "why did Buffon not attempt an elaborate Newtonian explanation such as this for the "accidental colours" reported in the first part of his treatise?"

It is possible that Buffon did not attempt a Newtonian explanation of the "accidental colours" phenomenon because they were mere *mental phenomena*, disturbances of the fatigued or otherwise abnormally functioning eye; more akin to maladies than revelations on the functioning of healthy human colour vision. Indeed, Buffon stated that his observations "could be of some use to increase knowledge of the ailments of the eyes, which probably come from the damage caused by impressions of light that are too strong."[195] In contrast, since coloured shadows were "natural

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[193] *Ibid.* p.538-9
[194] *Ibid.* p.539-40
[195] *Ibid.* p.534

colour" phenomena – that is, they were observed under the "normal" working condition of the eye – it seems that Buffon thought it important to subject them to Newtonian analysis.

THE PARADOX OF MONGE

Another "extraordinary" colour phenomenon was reported in the city of Paris in the year 1789. Gaspard Monge (1746-1818) is better known as the pioneer of both descriptive and differential geometry. He was a prominent Jacobin, one of the official signatories of the record of execution of Louis XVI, and after the Revolution Minister of the Marine and founding director of the new Ecole Polytechnique. He was a personal friend of the emperor Napoleon, whom he accompanied on the Italian and Egyptian campaigns, and who named him as president of the senate, and a senator for life. Unlike many of his French scientific contemporaries, he managed not only to survive, but to deftly negotiate top positions in all the administrations from the late *ancien régime* to the fall of First Empire. The author of this thesis first heard his name as a student in Paris – the métro stop he alighted at every day bears Monge's name.

Despite the omnipresent political and social turmoil of late 1780s Paris, Monge still seems to have had the leisure to ponder the nature of colour perception and design experiments to test his hypotheses. As he detailed in his *Mémoire sur quelques phénomènes de la vision*, Monge demonstrated his experiments before the Académie Royale des Sciences in April 1789 (little over two months before the Storming of the Bastille).[196] Fortunately, there already exists an excellent contemporary account of Monge and the history of his colour vision experiments[197], so I will limit my account to Monge's results and their significance for our subject.

The Académie met in the Salle Henri II, the king's old antechamber in the Louvre palace. One of the eyewitnesses to the experiment, the astronomer Guillaume Le Gentil (1725-1792) wrote an account of the meeting:

> During the summer of 1789, M. Monge conducted a remarkable experiment at the Académie, which seemed completely opposed to the Newtonian system. M. Monge placed a sheet of red paper against the west-facing wall of a house which was opposite the windows of the hall of the Académie, at a distance of around 15 yards more or less – the distance is not important; then having viewed the paper through a lightly red-tinted glass,

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[196] Monge, Gaspard. (1789). Mémoire sur quelques phénomènes de la vision. Annales de Chimie 3, 131–147

[197] Mollon, John. (2005). *Monge.* Visual Neuroscience (2006) 23, 297–309

> it appeared to be white. What's more, a red cloak which that day one of us was wearing, appeared whitish.[198]

As Le Gentil remarked, this result was astonishing at the time because it directly contradicted the Newtonian view that the perception of colours was necessarily linked with the composition of kinds of light rays received by the eye. As Monge acknowledged in his subsequent address to the Académie, "apropos red bodies of the same shade as the rays which the glass lets pass, it seems that one could be forgiven for believing that the rays sent by these bodies, having the faculty to pass through the glass, the only change to the perception of them could be a slight weakening of clarity caused by the imperfect transparency of the glass; and that otherwise their colour should appear the same whether one uses the intermediate glass or not", but "precisely the contrary happens in the experiment".[199] Whereas Buffon's observations had posed *implicit* challenges to the Newtonian doctrine of light ray/colour identity, this appears to be the first time in the republic of letters that the colour atomism hypothesis was *explicitly* challenged.

Monge then went on to reveal further counter-intuitive experiments, this time including white objects viewed through the red glass. In this case, in the Newtonian model one would expect "that the rays of all colours emanating from their surfaces are reduced to only red rays by passing through the glass, and that the images of these bodies will be as if their surfaces were red, and the alterations caused by the interposition of the coloured glass can be reduced to, (1) a diminution in clarity induced by the suppression of intercepted rays; (2) a change in colour from white to red."[200] However, Monge noticed that "precisely the contrary happens in the experiment … the white bodies and the red bodies appear in truth to be of the same colour, but we do not see them as red as it would seem natural to think, but rather white."[201] Monge repeated the experiment with yellow glass and yellow paper and achieved the same results, and from this surmised that "an analogous phenomenon should take place … when we view the objects with a glass tinted with any other colour".[202] John Mollon has called this "the Paradox of Monge"[203]. Monge himself generalised it thus:

> When glass only lets through homogenous rays of a certain kind, the bodies which only reflect the rays of the latter kind should appear to be white.[204]

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[198] Le Gentil, Guillaume. (1791). Sur la couleur qu'assedent les objects peints en rouge ou en jaune lorsqu'on les regard à travers des verres rouges ou jaunes. Annales de Chimie 10, 225–254. p. 226 [Author's translation]

[199] *Ibid.* p.230

[200] *Ibid.* p.229-30

[201] *Ibid.* p.230-1

[202] *Ibid.* p.231

[203] Mollon, John. (2005)

[204] Le Gentil, Guillaume. (1791). p.231

Monge then took a tube and observed his red-filtered objects, and to his surprise, the assumed "white" colour was revealed to be an illusion:

> … If having placed the red glass at the end of an opaque tube, one views an isolated object, white or red, one does not see them as white any longer, neither one nor the other; one sees them as red because, not having any neighbouring objects that are familiar to us, there is nothing that obliges us to take the red rays to be rays of white light; we are not judging anymore the nature of the rays that we see by comparing them to those we experienced a moment earlier, when we saw them with the unconstrained eye, and we take them in effect to be red rays.[205]

Monge also realised that this same illusion was at play in the phenomenon of coloured shadows.[206] Later in his treatise he describes an experiment in which an object casts a blue shadow on a white piece of paper, while being illuminated by a combination of ambient daylight and a (yellow) candle. This experiment was a reconstruction of one that was first briefly described in two sentences of Otto von Guericke's *Experimentum novum Magdeburgicum* of 1672:

> … a cerulean shadow can be clearly projected on a white paper at dawn when a finger or some other object is so inserted between the paper placed beneath a lighted candle that it casts its shadow on the paper. This shadow will then appear not as black but pure cerulean.[207]

Monge then proceeded to (implicitly) destruct Buffon's Newtonian explanation of the blue shadow being a result of the blue rays of the sky "painting themselves" onto to the shadow, *reductio ad absurdum:*

> But if at this moment one extinguishes the candle, the entire piece of paper is in the same situation in which a moment earlier the shadow was … it should, therefore, appear to be blue and of the same colour the shadow previously had; however, it has a white appearance.[208]

As we shall see, in a 1977 paper Edwin Land reconstructed a very similar experiment himself in order to test the applicability of his retinex algorithm. In this paper Land acknowledged the importance of von Guericke's original experiment:

> Perhaps the first observation pointedly relevant to the mechanism of color formation in images is not Newton's spectrum but the phenomenon of colored shadows, described in 1672 by Otto von Guericke.[209]

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[205] Monge, Gaspard. (1997) [1789]. Memoir concerning certain phenomena of vision [Mémoire sur quelques phénomènes de la vision. English] ; translated by Kuehni, R. G. (1997), Color Res. Appl., 22: 199–203. p.202

[206] It is worth noting here that Monge seems to challenge Buffon's claim to priority on the discovery of coloured shadows: "… This is not a new observation, it has been made a very long time ago by the Abbé de Sauvages of the Societé de Montpellier, who informed M. de Buffon about it at the time." (*Ibid.* p.201)

[207] Von Guericke, Otto. (2012) [1672]. *The New (So-Called) Magdeburg Experiments of Otto Von Guericke.* Book IV, Chapter 12. Trans. Margaret Glover Foley Ames. (Springer Science & Business Media, 6 Dec 2012)

[208] Monge, Gaspard. (1997) [1789]. p.201

[209] Land, Edwin H. (1977). "The retinex theory of color vision" in *Scientific American, Vol. 237, No.6, December 1977*, pp.108-128

As we shall see in the next section, Benjamin Thompson, Count Rumford, repeated this experiment under more controlled conditions.

In relation to his colour filter experiments, Monge also noticed – as Edwin Land would almost two centuries later[210] – that "the illusion in question is the more striking the more highly illuminated the objects viewed through the coloured glass, the more objects are present and if among them there is a considerable number that one knows to be naturally white", and inversely that "the mentioned illusion never takes place when the number of objects one can see through the red glass is not considerable, nor when the objects are of scant colour." [211,212] All these observations led Monge to the following conclusion:

> One can rightfully conclude, after the observations I have reported, that into the judgements we make about the colors of objects there enters, so to speak, something mental (*morale*), and that we are not solely influenced by the absolute nature of the light rays that the objects reflect. [213]
> … our judgments can be altered by the context, and it is likely that we are influenced more by the ratio of particular properties of the light rays rather than by the properties themselves, considered in an absolute manner.[214]

Monge was suggesting here that what is important in determining colour at a particular point is the *ratio* of different light rays over the entire visual field, rather than their "properties themselves, considered in an absolute matter" at a point in the visual field.

Monge's observations of course begged the following question: "why is it that the same visual information coming to our eye from a point in the visual field can cause a radically different colour perception, depending on the colours in the surrounding scene?" Monge attempted the following rationalisation:

> Now then, when we look through a red glass, of all the white light reflected by the colored objects, and that, without interposition of the red glass, would have contributed to the formation of the image of objects on the retina, only the red rays traverse the glass and arrive at the eye; these rays, thus, are the only ones that, by their number, can determine for us (and which in effect are determining them) the surface angles in our judgements; they thus exercise in vision the same necessary function that we are accustomed to see the white rays perform, and because this occurs evenly for all the objects before our eyes, we are conditioned by converging cues; we are forced to take these rays to be rays of white light. After that, all other red rays of the same nature will, by inevitable consequence, be taken to be rays of white light, and we conclude that naturally white objects and naturally

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[210] Land, Edwin H. (1959). "Experiments in Color Vision", *Scientific American*, Vol. 200, pp.84-94, 96-99, May 1959
[211] Monge, Gaspard. (1997) [1789]. p.201
[212] *Ibid.* p.202
[213] *Ibid.* p.201
[214] Monge, Gaspard. (1789). Translated in Mollon, John. (2005). p.299

> red objects, the images of which on the retina are formed in equal manner by red rays, are one as well as the other white objects.[215]

Monge's answer could thus be rephrased in modern terms something like this – "in the absence of an absolute white (a consequence of applying the red filter), the white balance has to shift to accommodate red as the new centre of white balance". As we shall see later in this chapter, this view was expressed by Hermann von Helmholtz in his attempt to explain colour constancy, and as we shall see in the next chapter, it is the basic assumption of Edwin Land's *retinex* theory of colour vision. As Land put it, "it is [this] ratio-making sense which keeps a [red] apple looking like an apple in blue sky light when more blue light than red is coming from the skin of the apple to our eyes."[216]

Monge's experiments have since been repeated and expanded, and not only by Edwin Land. The Paradox of Monge can "equally be obtained by placing the filter in front of the illuminant instead of the eye"[217], notes John Mollon. A neat example of this is Judd and Wyszeski's (1963) observation that viewing butter with yellow filtered light makes it look like lard.[218] This is another experiment that the enthusiastic reader may be tempted to try at home.

COUNT RUMFORD AND "COMPLEMENTARY COLOURS"

Late in 1793, twenty years after the publication of Comte de Buffon's treatise on coloured shadows, the American-born British scientist Benjamin Thompson, Count Rumford (1753-1814) penned his own *Account of some Experiments on Coloured Shadows* in a letter to Sir Joseph Banks, which was read before the Royal Society on 20th February 1794.[219]

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[215] Monge, Gaspard. (1997) [1789]. p.202

[216] Land, Edwin H. (1974). "The retinex theory of colour vision", *Proceedings of the Royal Institution of Great Britain*, 47, 23–58.

[217] Mollon, John. (2005). p.299

[218] Judd, D.B. & Wyszecki, G. (1963). Color in business, science, and industry. New York: Wiley.

[219] Thompson, Count Rumford. (1794). An Account of Some Experiments upon Coloured Shadows. By Lieutenant-General Sir Benjamin Thompson, Count Rumford, F. R. S. In a Letter to Sir Joseph Banks, Bart. P. R. S Thompson, B Philosophical Transactions of the Royal Society of London (1776-1886). 1794-01-01. 84:107–118

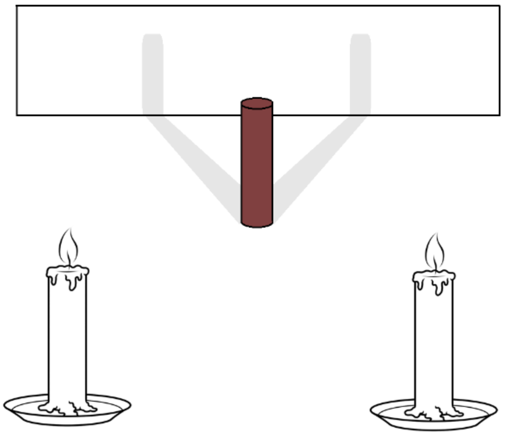

Figure 2: Simulation of Thompson's experiment before introduction of the yellow glass.

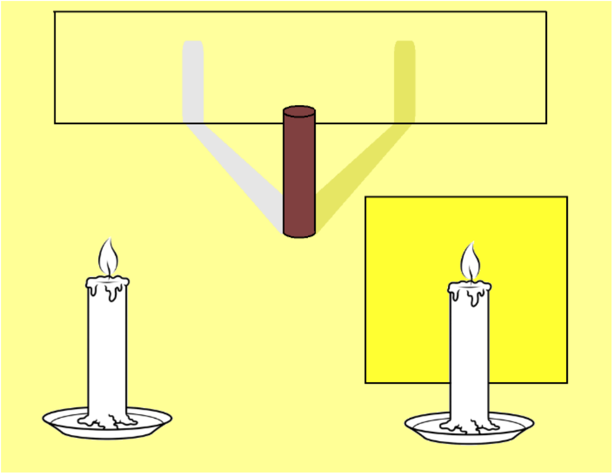

Figure 3: Simulation of Thompson's experiment after introduction of the yellow glass. The blue colour of the left shadow becomes more pronounced if the reader keeps only the yellow background in his field of vision, does not focus his gaze directly on the shadow, and squints a little.

We have seen how Buffon described the phenomenon of coloured shadows in a natural setting, and then attempted to explain them in Newtonian terms. As we shall see, Count Rumford ("Thompson" from here on in) went further by experimentally recreating the phenomena in a controlled indoor setting, and coining his own term – "complementary colours" – to understand the patterns in his observations. While staying at an inn in Florence and using only found materials, Thompson conducted the following experiment, a more elaborate and controlled version of the one that had been demonstrated by Otto von Guericke and repeated by Gaspard Monge:

> I darkened my room, and letting the daylight from the north (coming through a hole near the top of the window-shutter) fall at an angle of about 70° upon a sheet of very fine white paper, I placed a burning wax candle in such a position that its rays fell upon the same paper, and, as nearly as I could guess, in the line of reflection of the rays of daylight from without; when, interposing a cylinder of wood, about half an inch in diameter, before the centre of the paper, and at the distance of about two inches from its surface, I was much surprised to find that the two shadows projected by the cylinder upon the paper, instead of being merely shades, *without colour*, as I expected to find them, the one of them – that which, corresponding with the beam of daylight, was illuminated by the candle – was *yellow*; while the other, corresponding to the light of the candle, - and consequently illuminated by the light of the heavens, - was of the most beautiful *blue* that it is possible to imagine.[220]

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[220] Thompson, Count Rumford. (1794). "An Account of Some Experiments upon Coloured Shadows" in Thompson, Count Rumford. [1876]. *The Complete Works of Count Rumford, Volume 5*. (Macmillan: Baths). p.51

Like Buffon, Thompson's first reaction was to attribute the blue colour of the shadow to a reflection of the blue-coloured sky. However, since Thompson had created his coloured shadows in a controlled, indoor setting, he was able to take a selective sample of light which he knew to be white, and repeat the experiment:

> I at first thought that it might arise from the blueness of the sky; but finding that the broad daylight, reflected from the roof of a neighbouring house covered with the whitest new-fallen snow, produced the same blue colour, and if possible of a still more beautiful tint, I was obliged to abandon that opinion.[221]

Thompson then posited that "the difference in the whiteness of the two kinds of light" was the cause of the different colours of the shadows. He then modified the experiment to exclude light entering from the outside, in order to have full control over the variables:

> In a room previously darkened, the light from two burning wax candles being made to fall upon the white paper at a proper angle in order to form two distinct shadows of the cylinder, these shadows were found not to be in the least coloured; but upon interposing a pane of yellow glass, approaching to a faint orange colour, before one of the candles, one of the shadows immediately became *yellow* and the other *blue.*
>
> …
>
> When equal panes of the same yellow glass were interposed before *both* the lights, the white paper took an orange hue, but the shadows were to all appearance *without the least tinge of colour;* but *two* panes of the yellow glass being afterwards interposed before *one of the lights*, while only *one* pane remained before the other, the colours of the shadows immediately returned.[222]

Thompson then tried the same experiment on the daylight coming through the slit in his window, proving that the results were universal and valid for all natural light and artificial light combinations:

> I now endeavoured, by bringing daylight to be of the same yellow tinge with candlelight, by the imposition of sheets of coloured glass, to prevent the shadows being coloured when daylight and candlelight were together the subjects of the experiment; and in this I succeeded. I was even able to *reverse* the colours of the shadows, by causing the daylight to be of a *deeper yellow* than the candlelight.

Thompson suspected that the coloured shadows "might in many cases, notwithstanding their apparent brilliancy, be merely an optical deception, owing to contrast or to some effect of the other *real* and neighbouring colours upon the eye." [223] To test this hypothesis, as Gaspard Monge had done in his red-filter experiments, Thompson fashioned "a tube of about 12 inches long and near an inch in diameter, lined with black paper" in order to examine the shadows in isolation

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[221] *Ibid.* p.54

[222] *Ibid.* p.55-6

[223] *Ibid.* p.60

from the potential influence of the colours in the surround, "while an assistant repeatedly interposed a sheet of yellow glass before the lamp whose light corresponded to the shadow I observed, and as often removed it." [224] (See Figure 4)

> The result of the experiment was very striking, and fully confirmed my suspicions with respect to the fallacy of many of the appearances in the foregoing experiments.
>
> So far from being able to observe any change in the shadow upon which my eye was fixed, I was not able even to tell when the yellow glass was before the lamp and when it was not; and, though the assistant often exclaimed at the striking brilliancy of the blue colour of the very shadow I was observing, I could not discover in it the least appearance of any colour at all. But as soon as I removed my eye from the tube, and contemplated the shadow with all its neighbouring accompaniments, – the other shadow rendered *really* yellow by the effect of the yellow glass and the white paper, which had likewise from the same cause acquired a yellowish hue, – the shadow in question appeared to me, as it did to my assistant, of a beautiful blue colour.[225]

Thompson then proudly wrote, "I believe it is a new discovery – at least it is undoubtedly a very extraordinary fact – that our eyes are not always to be believed, *even with respect to the presence or absence of colours*." Having searched to the best of my ability to ascertain the priority of this discovery, I have no reason not to believe Thompson when he states this as a "new discovery" in relation to coloured shadows being grey upon closer examination – although as we saw in the preceding section, Gaspard Monge made a similar observation with his coloured filter experiments.

Thompson was effectively suggesting that the phenomenon of coloured shadows was just another optical illusion – to be considered as part of the same class of phenomena as Buffon's afterimages. Whereas Buffon believed the shadows to be *really* coloured – and therefore attempted a Newtonian explanation of their coloration – Thompson realised that their coloration was purely "imaginary".

Just as Buffon had contrasted "natural" and "accidental" colours, Thompson contrasted "real" and "imaginary" colours:

> In the experiment of the coloured shadows, the colour exhibited by one of the shadows only is real, that of the other is *imaginary*, being an optical deception, occasioned in some way unknown to us by the colour actually present and by the effects of the different lights and shades. The *imaginary colour*, which may be said to be *called up in the mind* by the other *real colour*, does not, however, appear to be at all inferior to the real colour either in lustre or in the directness of its hue.[226]

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[224] *Ibid.* p.60
[225] *Ibid.* p.61
[226] *Ibid.* p.66

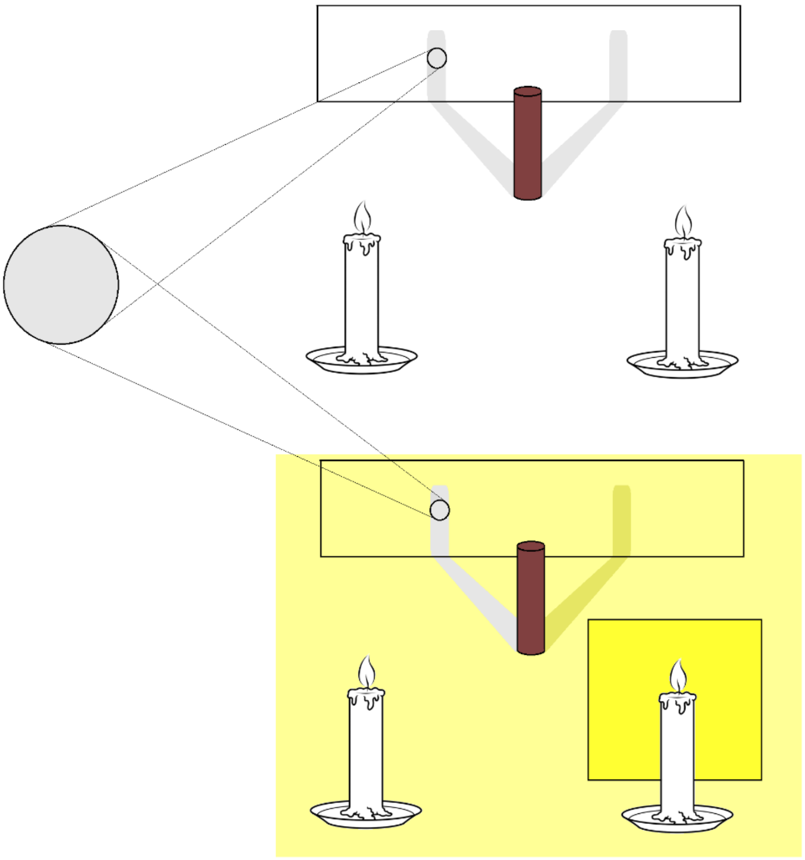

Figure 4: Simulation of the same experiment, showing what Thompson saw through the tube. As Thompson discovered to his surprise, the shadows were exactly the same shades of grey: "So far from being able to observe any change in the shadow upon which my eye was fixed, I was not able even to tell when the yellow glass was before the lamp and when it was not; and, though the assistant often exclaimed at the striking brilliancy of the blue colour of the very shadow I was observing, I could not discover in it the least appearance of any colour at all."[227] The blue colour of the left shadow becomes more pronounced if the reader keeps only the yellow background in his field of vision, does not focus his gaze directly on the shadow, and squints a little.

Johann Wolfgang von Goethe (1749-1832) would later decry what he saw as a denigration of status of these kinds of colours, in an explosive riposte to Thompson's treatise: "It is blasphemy to say there is such a thing as an *optical illusion*".[228] For Goethe, as we shall see later, these so-called "illusions" were truthful illustrations of how human minds construct colour. It could be argued however that this was just a question of semantics. Goethe did not deny Thompson's results – only his separation of "real" and "imaginary" colours.

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[227] *Ibid.* p.61

[228] Sepper, Dennis. (1988). *Goethe contra Newton: Polemics and the project for a new science of color* (Cambridge University Press) p.89

COMPLEMENTARY COLOURED SHADOWS

Later in his treatise, Thompson returned to an observation that Buffon seemed to have let slip – the fact that the same coloured shadows always appeared together in pairs:

> I cannot finish this paper without mentioning one circumstance, which struck me very forcibly in all these experiments upon coloured shadows – and that is, the most perfect harmony which always appeared to subsist between the colours – whatever they were – of the two shadows; and this harmony seemed to me to be full as perfect and pleasing when the shadows were of different tints of brown as when one of them was blue and the other yellow. In short, the harmony of these colours was in all cases not only very striking, but the appearances altogether were quite enchanting; and I never found anybody to whom I showed these experiments whose eyes were not fascinated with them.[229]

These colour pairs were so striking to Thompson that he undertook to conduct further experiments with them, which he documented in another treatise, *Conjectures respecting the Principles of the Harmony of Colours*, which was appended to the previous treatise in all subsequent publications of his essays.[230] In this paper he emphasised the fact that the two colours exhibited by the two shadows "are always such that, if they could be intimately mixed together, the result of that mixture would be *perfect whiteness;* and, as whiteness results from the mixture of all the different colours in certain proportions, the two shadows may be considered as containing all the colours in their just proportions, and the colour of the one shadow may with propriety be said to be the *complement* of the other."[231] This paper is the origin of the term "complementary colour", which Thompson thus defined formally:

> Two neighbouring colours are then, and only then, in perfect harmony when the intimate mixture of both would produce perfect whiteness; and hence it appears that, when two colours harmonize, one of them at least must necessarily be a compound colour.[232]

By "compound colours", Thompson meant a mixture of what he believed to be "elementary colours". The elementary colours at the time of writing were generally acknowledged to be red, blue, and yellow, as these were the most common primary colours used by artists. After further colour mixing experiments, Thompson was able to conclude that there were in fact an infinitude of these complementary pairs:

> To every colour without exception, whatever may be it hue or shade, or however it may be compounded, there is another in perfect harmony to it, which is its complement, and may be said to be its companion.[233]

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[229] Thompson, Count Rumford. (1876). p.61-2

[230] Thompson, Count Rumford. (1802). "Conjectures respecting the principles of the harmony of colours" in *Philosophical Papers,* Vol. 1. London : Cadell and Davies.

[231] Thompson, Count Rumford. (1802). "Conjectures respecting the principles of the harmony of colours" in Thompson, Count Rumford. [1876]. *The Complete Works of Count Rumford, Volume 5.* (Macmillan : Baths). p.66

[232] *Ibid.* p.66

[233] *Ibid.* p.67

This statement can be represented pictorially in the form of a "colour wheel". Isaac Newton had of course observed that white could be created by mixing two opposing colours from his own colour wheel, however because of his omission of the non-spectral colour magenta (see Figure 6), the colour combinations to make white were never exactly on the opposite side of the colour wheel. As we shall see, Goethe was the first scientific investigator of colour to depict a fully complementary, symmetrical, equally-tempered colour wheel; a visual manifestation of Thompson's idea.

Although the experiments with coloured shadows showed a remarkably consistency and certain logical beauty in their neatness, it seems that Thompson was anxious to show that he had discovered *universal* properties of the colours, rather than just isolated and curious 'shadow-specific' phenomena. In order to do this, he recreated the coloured shadow experiments in a pictorial simulation (see Fig 5) which seem to have been just as effective as the original experiments:

> As it might very naturally be suspected that the colours called up by means of shadows owe their existence to *something peculiar to shadows*, and that similar effects could not be produced without shadows, by means of coloured pigments, to remove all doubts on that subject, I made the following decisive experiment.
>
> …
>
> On the middle of the floor of a spacious room I laid down a very large sheet of black paper, and on the middle of this I placed a circular piece of crayon paper, which, in order that it might supply the place of the illuminated plane surface on which the shadows were projected in my experiments, I covered or coloured it with such a mixture of red lead (*minium*) and pure white lead, both finely powdered and well mixed together as brought it to be of the same tint, as nearly as possible, with the surface illuminated by the red and by the white light. I then took two oblong slips of crayon paper, half an inch wide and two inches long each: then, colouring one of them as highly as possible with red lead, in a dry powder, and covering the other with a powder composed of white lead and lamp-black, in such proportions that the quantities of light reflected from the two slips so prepared should be equal, I placed these slips in contact with each other, in the middle of the circular piece of paper on the floor; when retiring backwards a few steps, and looking through my hand with one eye, to exclude all other objects, I had the pleasure to perceive that the slip of paper which was covered with a gray powder now appeared to be of a beautiful greenish blue colour, while the other was of the most vivid red.[234]

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[234] *Ibid.* p.68-9

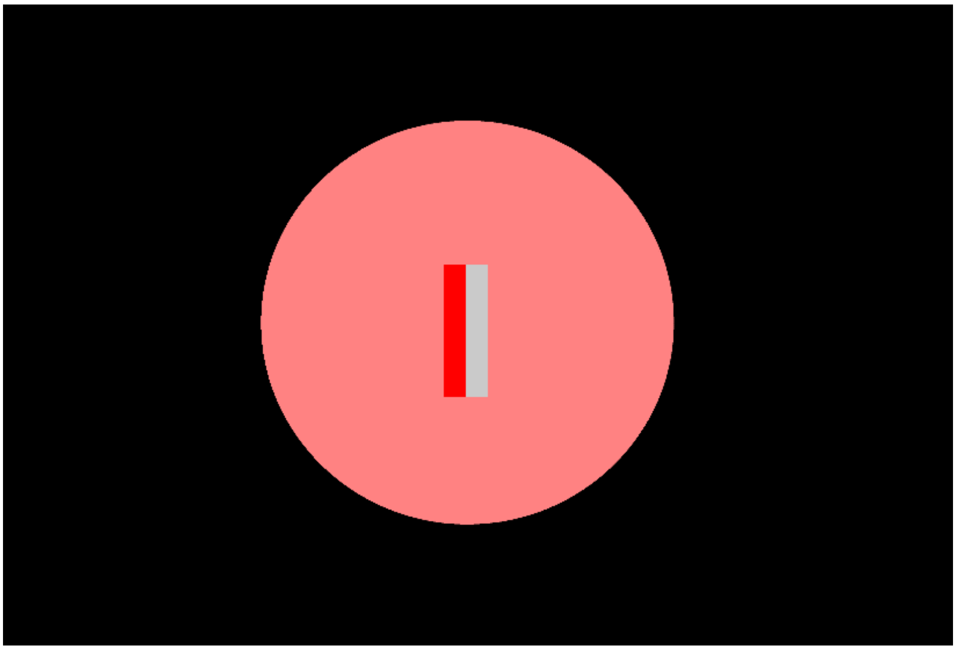

Figure 5: Simulation of Thompson's own simulation of his coloured shadow experiment. The "imaginary" cyan colour is more perceptible of the viewer keeps only the figure in his field of vision, and squints a little.

Thompson added that the first time he conducted this experiment, at an inn in Florence in the year 1793, he called two of his fellow guests, Lord and Lady Palmerston, to be witnesses:

> When I told them there was no blue there, and that what they took to be blue was merely a deception, they did not believe me; but they were very much surprised, and convinced that what I told them was true, when they saw on my removing the red slip that its companion, which was left behind, instantly *faded* and *lost its colour*.[235]

It seems that with the work of Thompson and contemporaries, the science of colour perception was no longer constricted to incidental observations of curious phenomena. Reproducible optical illusions could be identically replicated, reprinted, and distributed to those interested.

COLOURED SHADOWS IN THE VISUAL ARTS

Later in the same paper – *Conjectures respecting the Principles of the Harmony of Colours* – Thompson contented himself to note that his observations would prove useful in the visual arts:

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[235] *Ibid.* p.69

> By experiments of this kind, which might easily be made, ladies may choose ribbons to their gowns; or those who furnish rooms may arrange their colours upon principles of the most perfect harmony and of the purest taste.
>
> The advantages that painters might derive from a knowledge of these principles of the harmony of colours are too obvious to require illustration.
>
> Upon a careful examination of the works of the great masters of the art of colouring, it will appear that they have frequently practised upon these principles, though it is not likely that they were acquainted with the scientific foundation of their practice. They have certainly produced *appearances* of colours or tints, when their pictures are viewed in a proper light and at a proper distance, which we search for in vain upon the canvas. This may well be called the "*magic of colouring*;" for it is in fact calling up, as by enchantment, and presenting to the mind colours the most pure and vivid, which have no real existence.[236]

However, it is easy to forget here that painters do not mix "colour" as such, but rather *pigments*, which as we saw in Chapter One, are subject to different rules of colour mixing (subtractive mixing) compared to the rules for mixing light (additive mixing). Indeed, as Thompson noted, "the impossibility of producing perfect whiteness by any mixture of painters' colours is a proof of the want of purity of those colours, and of the difficulty of imitating by means of them any of those very striking effects which are exhibited in experiments with the pure prismatic colours"[237] – painters throughout the ages have – of course – had to use other elementary pigments to obtain as wide a gamut as possible. Yet Thompson believed that that this fact did not detract from the utility value of his work:

> There is one most important advantage which painters may certainly derive from a knowledge of the principles of the harmony of colours: it will enable them, on sound philosophical principles, to contrast their colours in such a manner as to give to their pictures, or rather to what they choose to make the prominent parts of them, a great degree of force and brilliancy. For, if any and every simple and compound colour has such a power on objects near it as to cause a neighbouring *colourless shadow* to assume the appearance of a colour, there can be no doubt that if, instead of the shadow a *real colour*, nearly of the same tint and shade as that so *called up*, be substituted in its place, *this colour will appear to great advantage*, or will assume an uncommon degree if strength and brightness.[238]

In hindsight these remarks seem to have been prescient. However difficult it may be to judge to what extent complementary colours in the arts were discovered "independently", it is certainly true that throughout the 19th century, as the observations of Thompson, Chevreul, and Goethe among others gained greater prominence, complementary colours took on a greater significance for painters, especially when depicting shadows. The artistic obsession with complementary colours reached its zenith with the Impressionists, post-Impressionists, and Fauves.

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[236] *Ibid.* p.67-8

[237] *Ibid.* p.71

[238] *Ibid.* p.71

THE SKY IS NOT BLUE?

In the late 1810s Georg Wilhelm Muncke, a German physicist, was interested in Count Rumford's coloured shadow/tube experiments and wondered that if blue coloured shadows could be an optical illusion, then maybe the blue colour of the sky could be.

In his paper *On Subjective Colours and Coloured Shadows* ("Ueber subjective Farben und gefärbte Schatten") published in 1820, he repeated Rumford's experiments. In this paper he commented how difficult it was to obtain the same results as Rumford, and for this reason he did not believe him, "and since then I really wanted to distance myself from the coloured shadows phenomenon".[239] Eventually, he recounted, as time passed, he "found these observations to be true, although these new results were achieved with great difficulty".[240] It appears that Muncke had originally experienced problems with fashioning a tube to observe Rumford's "coloured" shadow in isolation from light pollution. This is why this time Muncke "took a tube so narrow that the impression of the light coming from the shadow was *completely* isolated" and that "it did not appear to be coloured", thus confirming Rumford's result.[241] Muncke admitted here that "in the past I did not take this last observation into account, and conducted the experiment with a tube that was too white in the interior, and so I did not achieve the same results as Rumford".[242]

In a further almost identical experiment, Muncke noted that "if one observes the complementary coloured shadow through an adequately long and thin tube, blackened on the inside, so that only that shadow is visible, one can see that it is no longer coloured; but if the other original coloured shadow, or indeed any other coloured light enters the same field of view, the shadow becomes coloured again".[243]

Muncke later repeated an analogous experiment, taking a long pipe blackened on the inside, and pointed it at the sky, and looked through it with one eye. The sky's blue as seen through the pipe began to appear lighter and lighter, eventually fading to white. He concluded:

> Most interesting of all is the observation that the atmospheric air does not have a weak blue colour, as is widely held to be the case; in the thickest layer of the atmosphere where we think the blue colour is generated, the colour is actually only subjective, being the complementary colour to the yellowish white light reflected off the earth and the objects on it.[244]

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[239] Muncke, G. W. "Ueber subjective Farben und gefärbte Schatten," *Journal für Chemie und Physik* 30 (1820): 81 . Translated by Joseph Brown (attached to this volume).

[240] *Ibid*

[241] *Ibid*

[242] *Ibid*

[243] *Ibid.*

[244] *Ibid.*

He noticed how the sky appears colourless on its own, and then coloured when parts of cloud get into the field of view. Again, as with Count Rumford's experiments, we get the idea that it is what is in the field of view of the human eye that matters when determining the colour of individual points in that view.

GOETHE'S THEORY OF COLOURS

Johann Wolfgang von Goethe (1749-1832), like Buffon and Thompson before him, was also intrigued by the beauty and harmony exhibited in the phenomenon of coloured shadows – and all the more because they seemed to contradict the strict Newtonian view of colour. Goethe's *Zur Farbenlehre* ("Theory of Colours") was published in 1810. The first part of the first volume contained the original observations I will describe below.[245] The second part contained his infamous "polemic" against the Newtonian physical school of colour.

Goethe discovered, apparently independently of Buffon and Thompson, that the illumination of objects by certain coloured lights was always accompanied by a shadow of a certain colour. This formed the basis of his "harmonic" ("harmonisch") colour wheel, shown in Figure 7. In addition to the colours of Newton's spectrum, Goethe's colour wheel – crucially – also included the non-spectral colour "purpur".[246] Purpur is produced by the mixing of equal amounts of the colours at the ends of the Newtonian spectrum, red and blue, and is the complementary colour to spectral green. As we saw in Chapter One, Newton's colour wheel only counted the spectral colours as fundamental and therefore did not include purpur/magenta. This meant that Goethe's colour wheel, unlike Newton's, was completely symmetrical – with every colour placed opposite its complementary colour:

> The chromatic circle … is arranged in a general way according to the natural order … for the colours diametrically opposed to each other in this diagram are those which reciprocally evoke each other in the eye. Thus, yellow ["gelb"] demands blue ["violet"]; red ["orange"], cyan ["blau"]; magenta ["purpur"], green ["grün"]; and *vice versa* : thus again all intermediate gradations reciprocally evoke each other; the simpler colour demanding the compound, and *vice versa*.[247],[248]

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[245] Edwin G. Boring described this part as containing Goethe's « useful contributions to the psychology of vision » - Boring 1942, p.113

[246] This colour is approximately the same hue which is often referred to today as "magenta".

[247] Goethe, Johann Wolfgang von. (2006) [1810]. *Theory of Colours* [Zur Farbenlehre. English] (Dover : New York) ; translated with notes by Charles Lock Eastlake (Original publication – London : John Murray, 1840) p.12

[248] I have edited his translation of *violet* as « purple » to « blue », *blau* as « blue » to « cyan », and *purpur* as « red » to « magenta » in order to be more faithful to modern-day usage of colour terms when referring to Goethe's colour wheel in Figure 7.

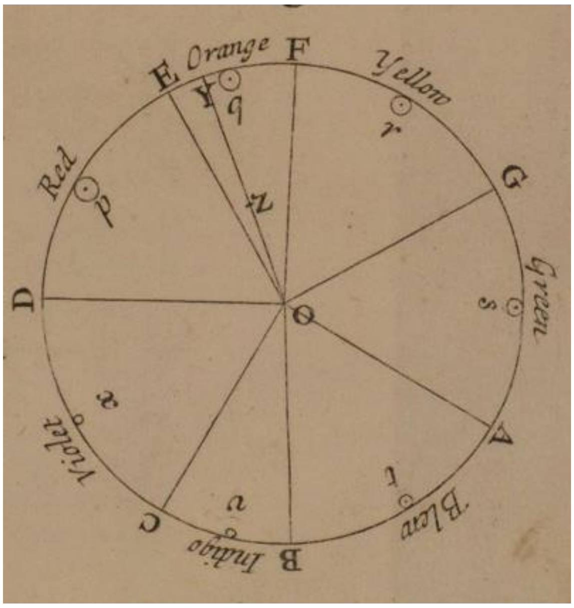

Figure 6: Newton's unsymmetrical colour wheel, which illustrates the relationship between diatonic note intervals and colours as explained in the *Opticks of 1704*. Each of the seven diatonic intervals is represented by a segment. A full octave from D to D is displayed. Newton's wheel is simply constructed from the observed spectrum from prism experiments, bent back on itself. There is no symmetry because Newton omitted the non-spectral colour magenta. On Newton's wheel magenta would be rendered by mixing the two extremes of the spectrum – red and violet – or according to the analogy, one D played with another D, one octave apart. Image: Whipple Library, Cambridge University

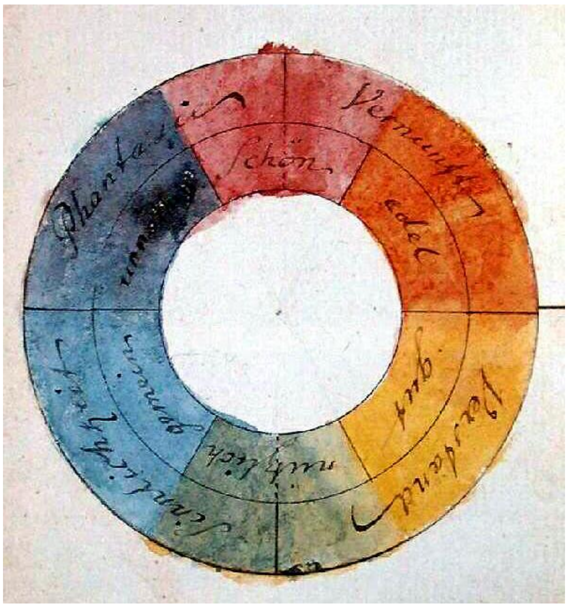

Figure 7: Goethe's symmetrical, equally-tempered colour wheel, with each colour labelled alongside its symbolic qualities. Like Newton's it can be seen as a colour spectrum bent back on itself, but unlike Newton's it includes the non-spectral colour *purpur* (what we would now call "magenta") in between blue (top left) and red (top right). It is this inclusion of magenta that allows Goethe's wheel to be fully complementary and symmetrical, making it a more accurate description of *subjective* human colour perception than Newton's. This colour wheel is essentially the same as those used by visual artists in the modern day, albeit that now the colour gradations are finer (almost infinite rather than just 6) as we shall see later in this chapter. Image: (Goethe 1809)

Goethe's colour wheel seems to have been the first to contain, approximately, the modern additive primary colours – red ("gelbrot"/"orange"), green ("grün"), and blue ("violette/blaurot") – in symmetrical opposition to their complementary colours – cyan ("blau"), magenta ("purpur"), and yellow ("gelb"). However, it must be said here that Goethe would have been unaware of the importance of the additive primary colours red, green and blue, since his work came before the that of Young, Helmholtz and Maxwell, the pioneers of trichromatic theory. What was of primary interest to Goethe was rather the *harmony* and *balance* of the complementary pairs as they appeared in nature.

The exact shades of the six colours in Goethe's painted colour circle (or "Farbenkreis") were not of any particular consequence, since there is an infinitude of complementary colour pairs – in fact, as many as there are sides to a circle. Goethe seems to have taken a cross section of six shades that he deemed to have particular psychological qualities – the reader will notice that each colour in Figure 7 is labelled alongside its psychological quality.

What was of more significance to the 20th-century visual scientist such as Edwin Land looking back at the history of his discipline, was the visual manifestation of the concept of colour complementarity. Goethe, like Thompson before him, appreciated that such colour complementarity was a fundamental characteristic of human vision:

> When the eye sees a colour it is immediately excited and it is its nature, spontaneously and of necessity, at once to produce another, which with the original colour comprehends the whole chromatic scale.[249]

Goethe also seems to have discovered, as Thompson had done, that "coloured shadows" were really grey upon closer examination:

> To experience this completeness, to satisfy itself ["um sich selbst zu befriedigen"], the eye seeks for a colourless space next to every hue in order to produce the complemental hue upon it.[250]

For Goethe, the complementary colour ("geforderte Farbe"), was *demanded* or *called* in existence by the other. Thus, along with Buffon, Monge and Thompson, Goethe was one of the first to appreciate that colour perception at a point in the visual field is affected by the colours surrounding that point. Thompson had realised that these effects can be predicted with a knowledge of complementary colours and their pairings. Goethe's further step was to produce an accurate visual representation of this complementary system.

In the "polemic" section of the *Farbenlehre*, Goethe attacked the Newtonian tradition for neglecting the subjective phenomena of colour. In addition to this, Goethe advocated for a modificationist view of colour – arguing that colour arises as a result of a mixture of light and darkness – on the basis that all colours appear to be darker than white. This is similar to the doctrine of Aristotle which was discussed in the last chapter. He advocated this view after he noticed that in the classic prism experiment the spectral colours appear to form from the edges of the light beam – the interface between "light" and "darkness" – and that it is only after we follow the trajectory of the beam for quite some time that the seven colours of the Newtonian spectrum appear.[251] This

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[249] Goethe, Johann Wolfgang von. (2006) [1810]. p.174

[250] *Ibid.* p.174

[251] Goethe was correct in his observation that the colours appear to form at the edges of the beam, however was mistaken as to the cause of this. The colours appear to form at the edges of the beam because the middle "white" part is a mixture of the colours of different parts of the spectrum that are still in the process of separating from the others. The red colour appears first at the top edge of the beam because it is least affected by the prism, and the other shorter wavelength colours are diverted downwards away from the trajectory of the red rays. The violet colour appears first

modificationist view was the primary reason that Goethe's work was dismissed by most 19th century physicists. In hindsight this would seem to be unfortunate, since as we have seen there are important subjective phenomena which Goethe correctly identified.

Deane B. Judd, the 20th century's most eminent colorimetrist, wrote in his introduction to Goethe's *Zur Farbenlehre* that "the advantage of trying to follow Goethe's explanations of color phenomena is that, by the time you have succeeded in doing so, your thoughts have become so divorced from the wavelength explanation of color, that you can begin to think about color theory relatively unhampered by prejudice, either ancient or modern."[252] Just as Newtonian optics is irrelevant while considering phenomena such as colour complementarity, colour complementarity is irrelevant to understanding the decomposition and recomposition of white light by prisms, and the differential refrangibility of the component rays of refracted white light. Goethe made this point clear in the *Farbenlehre*:

> The theory of colours, in particular, has suffered much, and its progress has been incalculably retarded by having been mixed up with optics generally, a science which cannot dispense with mathematics; whereas the theory of colours, in strictness, may be investigated quite independently of optics.[253]

As Shapiro (1990) notes, while Newton's goal was to discover and prove experimentally the fundamental *physical* factors governing the phenomena, and later to construct a theory to explain them, Goethe's aim was to capture purely the phenomena "in themselves" through a triangulation between experiment and simple observation of colour as it appears in nature.[254] Or, as we could put it more concisely though perhaps more crudely; Newton studied light, and Goethe colour.

GOETHE AND "EXPLORATORY EXPERIMENTATION"

The historians of science Neil Ribe and Friedrich Steinle have branded Newton's experimental approach as "theory-oriented", and Goethe's as "exploratory experimentation".[255] They define the latter kind as "the systematic and extensive variation of experimental conditions to discover which

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at the bottom edge of the beam because it is most affected by the prism, and the other longer wavelength colours are not diverted downwards as much. See Koenderink, J. (2010) Chapter 6 for a full explanation with diagrams.

[252] Goethe, Johann Wolfgang von. (1970) [1810]. *Theory of Colours* [Zur Farbenlehre. English] (MIT : Cambridge) ; translated by Charles Lock Eastlake, with introduction by Deane B. Judd (Original publication – London : John Murray, 1840) p.xiv

[253] Goethe, Johann Wolfgang von. (2006) [1810]. p.157

[254] Shapiro, Alan E. (1990). Review of Goethe contra Newton. Polemics and the Project for a New Science of Color. *Journal of the History of Philosophy* 28, no. 4 (1990): 621-622.

[255] Ribe, N. and Steinle, F. (2002). **"**Exploratory Experimentation: Goethe, Land, and Color Theory". *Physics Today*. (July 2002, page 43). 55(7), 43 (2002)

of them influence or are necessary to the phenomena under study"[256] The aim is to probe nature in as many different ways as possible in order to establish a hierarchy, and eventually to be able to explain complex phenomena in terms of elementary ones – Goethe called these primordial phenomena. The most important aspect which differs from what we could call classical "Popperian" science is that such practitioners approached investigations without a framing set of hypotheses. Ribe and Steinle cite Faraday's investigations into the properties of solenoids and experiments on induction as prominent examples of such "exploratory" science. This kind of investigation, they argue, has been neglected by philosophers of science as they have tried to build models of science based on theories and their falsification. For Goethe, "theory" was not to do with mathematical modelling or rational hypotheses, but something more akin to the ancient Greek θεωρία (*theoria*), which relates to the activity and recognition of the spectator – in his native German this is also conveyed by *Anschauung* ("on-looking").[257] As the philosopher Ludwig Wittgenstein would later formulate it in his (posthumously published) *Remarks on Colour*:

> Goethe's theory of the constitution of colours of the spectrum has not proved to be an unsatisfactory theory, rather it really isn't a theory at all. Nothing can be predicted with it. It is, rather a vague schematic outline of the sort we find in James's psychology. Nor is there any *experimentum crucis* which could decide for or against the theory.[258]

What Goethe did was attempt a sort of *rational description* of colour based on his "exploratory" experiments and observations of nature. For Goethe, white light, and darkness can be considered as fundamental "building blocks" for the purposes of human perception.

Ludwig Wittgenstein was interested in this topic because he realised that some propositions about colour could neither be classed as "empirical", nor "a priori" – rather, they were something in-between; what he called *phenomenological.* These remarks are useful to us in distinguishing what Newton and Goethe were trying to do with their respective investigations, or as Wittgenstein would formulate it – distinguishing between the *language games* that were in play.[259] For example, if we were to object to the Newtonian idea that white light is formed from the combination of other colours, a pedantic philosopher of language might point out to us that what we are doing is analogous to objecting to the idea that, for example, "numbers" are coloured:

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[256] Ribe and Steinle (2002), p.46

[257] This is pointed out in Sepper (1988), p.17

[258] Wittgenstein, Ludwig. (1977). *Bemerkungen über die Färben* [Remarks on Colour]. Edited by G.E.M. Anscombe. Translated by Linda L. McAlister and Margaret Schättle. (Basil Blackwell – Oxford). p11, §70

[259] Wittgenstein, Ludwig. (1953). *Philosophische Untersuchungen* [Philosophical Investigations]. Translated by G.E.M. Anscombe. (Basil Blackwell – Oxford)

> "Light is colourless". If so, then in the sense in which numbers are colourless.[260]

Newtonian light is a different class of grammatical object to Goethean colour. In Goethe's science it is thus equally senseless to say that white light is formed of the colours of the spectrum, as it is to say "the number seven is red". For Wittgenstein, Goethean phenomenological analysis "is analysis of concepts and can neither agree with nor contradict physics."[261]

> One thing was clear to Goethe: no lightness can come out of darkness – just as more and more shadows do not produce light. This could however be expressed as follows: we may, for example, call lilac a "reddish-whitish-blue", or brown a "reddish-blackish-yellow", but we *cannot* call white a "yellowish-reddish-greenish-blue" (or the like). And *that* is something that Newton didn't prove either. White is not a blend of colours in *this* sense.[262]

CHEVREUL AND "SIMULTANEOUS COLOUR CONTRAST"

With its basis in complementary colour pairings, Goethe's colour wheel was undoubtedly of more use than Newton's to the visual artist. As Goethe wrote in his preface to the first edition of *Zur Farbenlehre* (1810):

> To the practical man, to the dyer, on the other hand, our labour must be altogether acceptable; for it was precisely those who reflected on the facts resulting from the operations of dyeing who were the least satisfied with the old theory: they were the first who perceived the insufficiency of the Newtonian doctrine.[263]

Michel-Eugène Chevreul (1786-1889) was one such dyer. Chevreul is better known as a chemist, principally for his discovery of margaric acid and creatine. He also served as director of the Manufacture des Gobelins tapestry factory in Paris. In this occupation, he often received complaints that colours of garments received by patrons differed from those which had been ordered, particularly for those in which blacks appeared next to blues. Upon taking the garments apart, Chevreul noticed that the dyes were exactly as the patrons had ordered – there had been no mistakes – yet when viewed together, it appeared that certain coloured yarns seemed to affect the appearance of others in the surround. He named this phenomenon *the law of simultaneous colour contrast* ("la loi du contraste simultané des couleurs"):

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[260] Wittgenstein, L. *Remarks on Colour* p.7, §35
[261] Wittgenstein, L. *Remarks on Colour* p.16, §16
[262] Wittgenstein, L. *Remarks on Colour* p.33, §126
[263] Goethe, Johann Wolfgang von. (2006) [1810]. p.xxxi

> In the case where the eye sees at the same time two contiguous colours, they will appear as dissimilar as possible, both in their optical composition and in the strength of their colour.[264]

Simultaneous colour contrast, in other words, is the exaggerated difference between colours that share a border. But how exactly is this difference exaggerated? Recall Count Rumford's experiment (seen in Figure 5), in which a grey strip assumes a colour complementary to the contiguous coloured strip. Chevreul realised that exactly the same effect occurs when *any* two colours are juxtaposed contiguously – that is, the brain adds a little of the complementary colour to each juxtaposed hue (see Figures 8 and 9).

Figure 8: An illustration of the importance of colour borders for the simultaneous colour contrast effect. Comparing two adjacent bars on the left, it is difficult to discern any difference in colour, yet when they are placed together, sharing an edge (on the right), the difference becomes obvious. Just like Chevreul's yarns, the isolated strips have a slightly different appearance when isolated, compared to when they are juxtaposed with others. This effect is best achieved if the reader covers up one half of the image while viewing the other. All strips have the same luminosity, only a different saturation.

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[264] Chevreul, Michel-Eugène (1987). [1854]. The Principles of Harmony and Contrast of Colours and their Application to the Arts, a newly revised edition by Faber Birren, based on the first English edition of 1854, West Chester, Penn., Schiffer Publishing Ltd., 1987, § 16.

It is essential that the colours are placed completely contiguously for this effect to be realised, with no gap in between. Edwin Land and his colleague John McCann made explicit reference to this observation by Chevreul when they cited his earlier 1839 paper on simultaneous colour contrast in their 1971 paper "Lightness and Retinex Theory" [265] which introduced their first retinex algorithm based on the comparison of light reflectance across contiguous boundaries. This paper will be discussed more thoroughly in the next chapter.

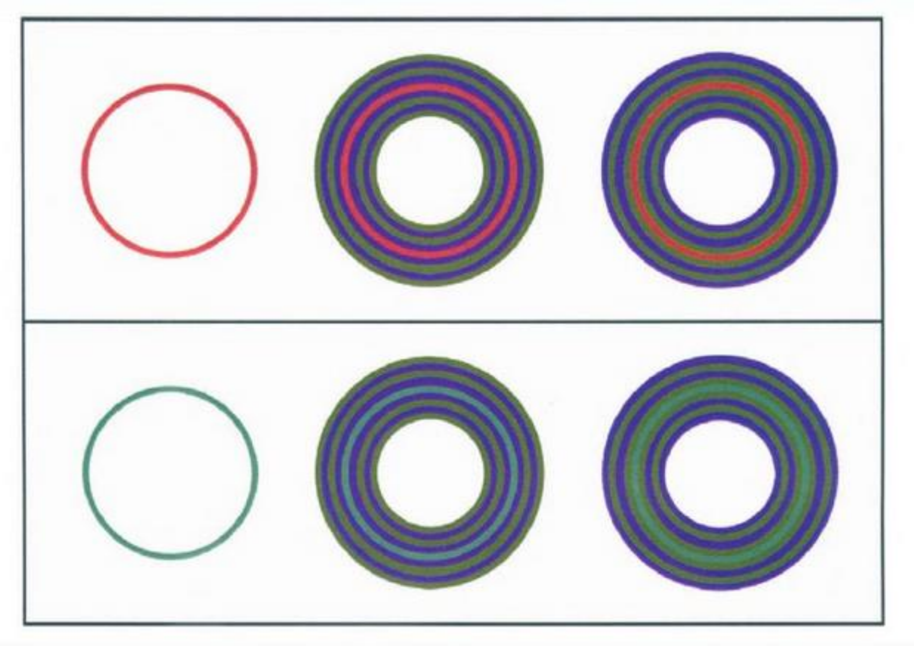

Figure 9: Believe it or not, the three red rings in the top row are identical, as are the three green rings in the bottom row. They appear to be different because of the simultaneous colour contrast effect induced by the surrounding rings. From The Science of Colour Chapter 4 – Steven K. Shevell

CHEVREUL'S COLOUR WHEELS

Chevreul realised, as Thompson and Goethe had done, that the presence of a colour next to a grey patch would cause the grey patch to assume a colour complementary to that of the original. He also recognised the significance, as Buffon had done, of the complementary-colour afterimages caused by staring at one colour for a sustained period. In addition to this, Chevreul noticed that the simultaneous colour contrast effect (shown in Figures 8 and 9) could be cancelled out by

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[265] Land, Edwin H. and McCann, John J. (1971). "Lightness and Retinex Theory", *Journal of the Optical Society of America*, Vol.61, No.1, pp.1-11, January 1971

adding a little of the complementary colour to the other. For example, a grey patch which seems to look slightly blue next to a yellow strip, can be made to look grey by tinting it a little yellow – cancelling out the "psychological" blue caused by the simultaneous contrast effect. Indeed, this is how Chevreul solved the coloured garment issues for his Parisian clients.

Chevreul was able to triangulate from these empirical sources to construct accurate complementary colour wheels (shown in Figures 10 and 11). This process has been described well by Rolf G. Kuehni and Andreas Schwarz.[266] His colour wheels, with their finer gradations of colour, were far more useful to visual artists than Goethe's had been. Goethe's wheel was created primarily to prove a principle, whereas Chevreul's was created to be a utility to practitioners such as himself. It is for this reason that although Goethe's colour wheel was technically accurate, Chevreul's is more commonly cited as having influenced the emerging art movements of the 19th century.

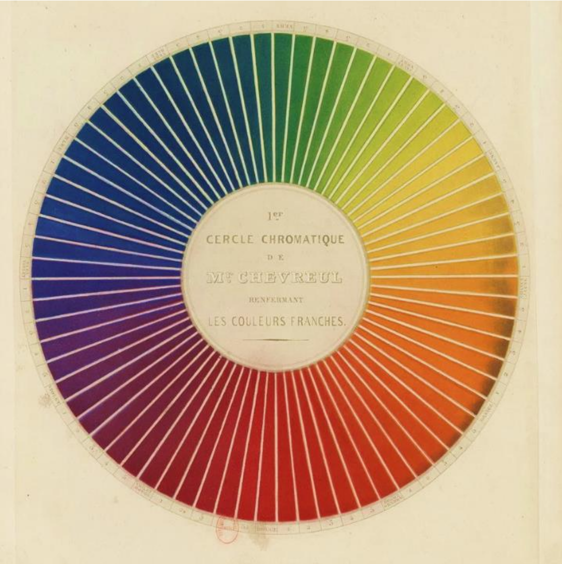

Figure 10: 72-hue colour wheel, from 1855. Cercles chromatiques de M. E. Chevreul, reproduits au moyen de la chromocalcographie, gravure et impression en taille douce combinées par R.-H. Digeon 1855

Figure 11: Cercles Chromatiques de M. E. Chevreul (Paris: Didot, 1861)

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[266] Kuehni, R.G. and Schwarz, A. (2008). *Color Ordered : A Survey of Color Order Systems from Antiquity to the Present (Oxford University Press)*. Chapter 4 – From Two to Three Dimensions.

HERING, "COLOUR CONSTANCY", AND "OPPONENT-PROCESS" THEORY

From the 1840s onwards, with the rapid expansion of the German university system, and the establishment of a great number of autonomous university physiology departments, the structure and function of the mammalian nervous system was investigated in greater depth.[267] The historian of 19th-century German science R.S. Turner noted that "the literature on physiological optics grew in a roughly exponential fashion between 1840-44 and 1880-84 with a doubling time of about ten years".[268] As the workings of the eye and brain became a subject of intense interest and debate amongst physiologists, it is unsurprising that unifying theories were proposed to account for the perplexing phenomena discussed in this chapter. The most influential of these was offered by the German physiologist Karl Ewald Konstantin Hering (1834 -1918) – commonly known as Ewald Hering – in his *Outlines of a Theory of the Light Sense*, first published in its entirety in 1874.[269]

HERING AND "COLOUR CONSTANCY"

Hering was curious as to how the eye could possibly accomplish its job of keeping both the brightness and hue of familiar objects as constant as it does, despite the fact that the intensity and spectral distribution of the light illuminating those objects varied so wildly. He was puzzled as to why he saw "the paper of a book as white and the letters black at every convenient reading illumination, whether in the morning, at midday, or in the evening, and whether we read under blue or grey sky, or under the green arbour roof, or in daylight, gaslight, electric arc light, or incandescent light".[270] Hering went so far as to measure the intensity ratio between the light reflected from the black ink of the letters of a book and the surrounding white page, and "in favourable cases found it to be approximately 15:1".[271] Hering then proceeded to compare the intensity of illumination on his "work table in the early morning, when there was just enough light for comfortable reading, with the illumination on the same table at midday of a bright day when there were white clouds in the sky and found the ratio equal to 1:50".[272] This meant that "at midday illumination of the black letters were about three times as intense as the white paper was in the morning, and the light intensity of the paper in the morning amounted only to about $^1/_3$ the light

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[267] See R.S. Turner – In the Eye's Mind (1994) pp.10-31 for a full discussion of this development.

[268] Turner R.S. (1994) p.10

[269] Hering, Ewald. (1874). *Zur Lehre vom Lichtsinne. Sechs Mittheilungen an die kaiserl. Akademie der Wissenschaften in Wien*. Wien: Carl Gerold's Sohn, 1872-4.

[270] Hering, Ewald. (1964) [1874]. *Outlines of a Theory of Light Sense*. Trans. Hurvich, Leo M. and Jameson, Dorothea. (Harvard University Press), p.14-15

[271] *Ibid.*

[272] *Ibid.*

intensity that the letters had a noonday".[273] This seemed to be counter-intuitive if one followed the strict Newtonian view – how could an object he had called "black" at midday be three times as luminous as what he had called "white" that same morning? Hering concluded that the eye must have a compensatory mechanism which acted to discount the illuminant and keep the brightness constant: "continual change in this illumination … [would] make it difficult or entirely impossible for the eye to fulfil its essential task if it were not offset to some extent by compensating mechanisms".[274]

The next question for Hering was whether the same principle applied to colour vision. Hering designed the following experiment (see Figure 12) to investigate whether hue perception also adapted according to illumination:

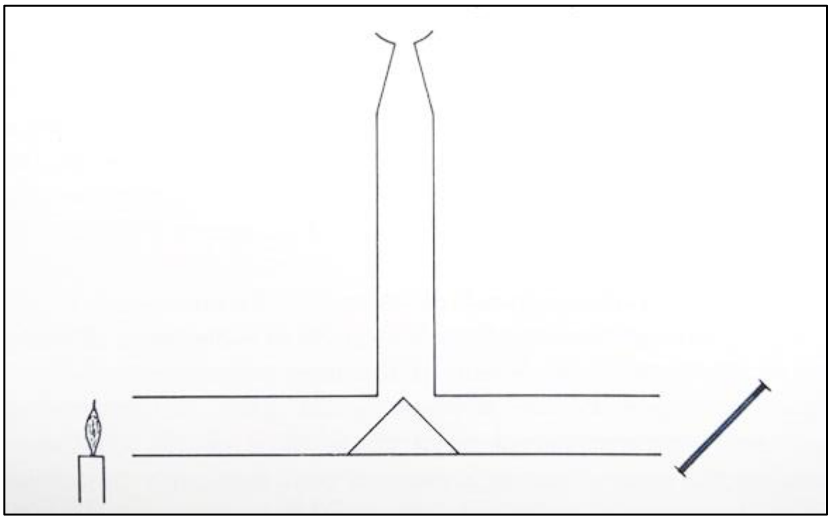

Figure 12: Hering's two-colour experiment with the Bouger photometer. The right side of the apparatus consists of a brown paper illuminated by reflected daylight. The left side of the apparatus consists of an ultramarine paper illuminated by a lamp, with the lamp's intensity adjusted such that the ultramarine paper appears to be brown to the observer who looks down from the viewer at the top. (Image: Hering, Ewald. (1964) [1874]. p.15)

> I covered one surface of the right-angle in a Bouguer photometer with a perfectly smooth, nonlustrous brown paper and the other with a similar ultramarine-blue one, both of which were carefully selected for the experiment. I illuminated the brown paper by means of a mirror by the light of the white sky, the other by an ordinary gas flame or an Edison lamp, as shown in the figure. Observed through the vertical tube of the photometer, the "blue" paper at a suitable intensity of the artificial light appears exactly like the "brown", that is, also brown, because in such light the blue-effective rays are completely dominated by those

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[273] *Ibid.*
[274] *Ibid.*

> that are yellow-effective. Then if I close the window shutters, illuminate the whole room with gas or Edison lamps, and take both papers out of the apparatus, instantaneously the "blue" paper ceases to look brown, even though it is now illuminated by the same artificial light as before and continues to reflect the same mixture of rays into my eye, but it now appears blue as in daylight even if darker, while the "brown" paper is now brown as it was before. In this demonstration it does not matter at all whether the observer knows the "real" colors of the paper or not.

By illuminating the ultramarine paper with lamps which lacked "blue-effective" (short wavelength) rays, Hering had tricked his eye into equating the colour of the ultramarine paper with the brown paper illuminated by the daylight. Then, upon removing the papers and observing them both under the light of the lamps, his perception of the ultramarine paper changed from brown to its "natural" blue, even though the ultramarine paper was being illuminated with the same lamplight as before. The spectral distribution reflected from the ultramarine paper had not changed, yet Hering's perception of its colour changed as it was removed from its context next to the daylight-illuminated brown paper. At the same time, the spectral distribution reflected from the brown paper had changed as it was exposed to daylight and then to lamplight, yet Hering's perception of its colour did not change – it kept its colour *constant*. Hering considered the results of both his achromatic and chromatic experiments, and concluded:

> If the white paper printed with black letters gave us an example of the extent to which achromatic colors of seen objects are independent of the *intensity* of the general illumination, then we have here an example of the extent to which the chromatic color of a seen object is independent of the *quality* of the general illumination.[275]

If colour perception adapted to the illuminant by comparing the spectral distribution of a point to that in the visual field surrounding it, as his experiments seemed to suggest, how, Hering asked, did the eye achieve this?

Hering devised two hypothetical mechanisms to account for how the observer discounts the illuminant – "memory colour" and "opponent colours". "Memory colour" was the idea that through learned experience, the observer learns the "true colour" of objects in the world, and then uses this memory to discount the illumination and see the true colour of an object.[276]

> The colour in which we have most consistently seen an external object is impressed indelibly on our memory and becomes a fixed property of the memory image. What the layman calls the real colour of an object is a colour of the object that has become fixed, as it were, in his memory; I should like to call it the memory colour of the object … Moreover, the memory colour of the object need not be rigorously fixed but can have a certain range of variation

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[275] *Ibid.* p.16

[276] This hypothesis was disproved by Land in the experiments detailed in Chapter Three.

> depending on its derivation … All objects that are already known to us from experience, or that we regard as familiar by their colour, we see through the spectacles of memory colour.[277]

HERING'S "OPPONENT COLOURS"

Hering's "opponent colours" model was governed by two mechanisms:

> This self-regulation of light sensitivity is mediated by two different mechanisms: on the one hand by reciprocal interactions among areas of the somatic visual field … on the other hand by the fact that with every persisting total illumination, be it weak or strong, the inner eye can be brought by a gradual change in state into a sort of equilibrium, by virtue of which the average brightness of the visual field always remains about the same.
>
> …
>
> The adjustment in light sensitivity brought about through this reciprocal interaction is thus accomplished at nearly the same time instant as the change in illumination. For this reason I have called this *simultaneous* or momentary adaptation [*Moment-Anpassung*], whereas successive adaptation assumes the continuation of a stronger or weaker illumination, which is why some people have called this kind of adaptation fatigue or recovery.[278]

Hering was proposing here: (1) a local system of reciprocal interactions between adjacent parts of the retina which acts with instant effect ("simultaneous" adaptation); and (2) a global system which measured the average illumination of the entire retina and adapted to that over time ("successive" adaptation). Thus, for Hering, phenomena such as colour complementarity and colour constancy would be considered as "simultaneous" adaptive effects, and phenomena such as Buffon's colour afterimages would be considered as "successive" adaptive effects. It is of course the "simultaneous" adaptive effect which Edwin Land and colleagues would go on to investigate and greater depth almost a century later.

Hering proposed that the "simultaneous" adaptive mechanism worked when local points on the retina compared the spectral distribution they received with that received by neighbouring parts of the surrounding retina. These comparisons, Hering proposed, were based on the opponency of certain "unique hues" ("Urfarben"). As perception of brightness was tempered by the opponency of black to white, Hering held that hue perception was tempered with two fundamental scales – the opponency of primary red ("Urrot") and primary green ("Urgrün"), and primary yellow ("Urgelb") and primary blue ("Urblau"). These colour opponent pairs ("Gegenfarben") would form two perpendicular axes on the colour circle, so that all other complementary pairs could be formed from their linear combination (see Figure 13). As we saw in Chapter One, this position

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[277] Hering, E. (1964) [1874]. *Outlines of a Theory of Light Sense.* Trans. Hurvich, Leo M. and Jameson, Dorothea. (Harvard University Press), pp.7-8

[278] *Ibid.* p.18-19

contrasted with that of Helmholtz and followers who maintained that colour was processed through only three channels, with peak sensitivities to red, green and blue light respectively.

The choice of these four "unique hues" ("Urfarben") was not completely arbitrary, but made from a belief that they were in some way psychologically primary. Goethe in his *Farbenlehre* had also believed there to be something special about these hues, and believed that it was for this reason that they had oldest colour names in the German language:

> With regard to the German terminology, it has the advantage of possessing four monosyllabic names no longer to be traced to their origin, viz., yellow (Gelb), blue ["Blau"], red ["Rot"], green ["Grün"]. They represent the most general idea of colour to the imagination, without reference to any very specific modification.[279]

This view was also shared by Hering's contemporary Ernst Mach (1838-196).[280] Hering also believed that it was psychologically impossible to conceive of a reddish green, a greenish red, a yellowish blue, or a bluish yellow, which is another reason he chose red-green and blue-yellow as his opponent axes:

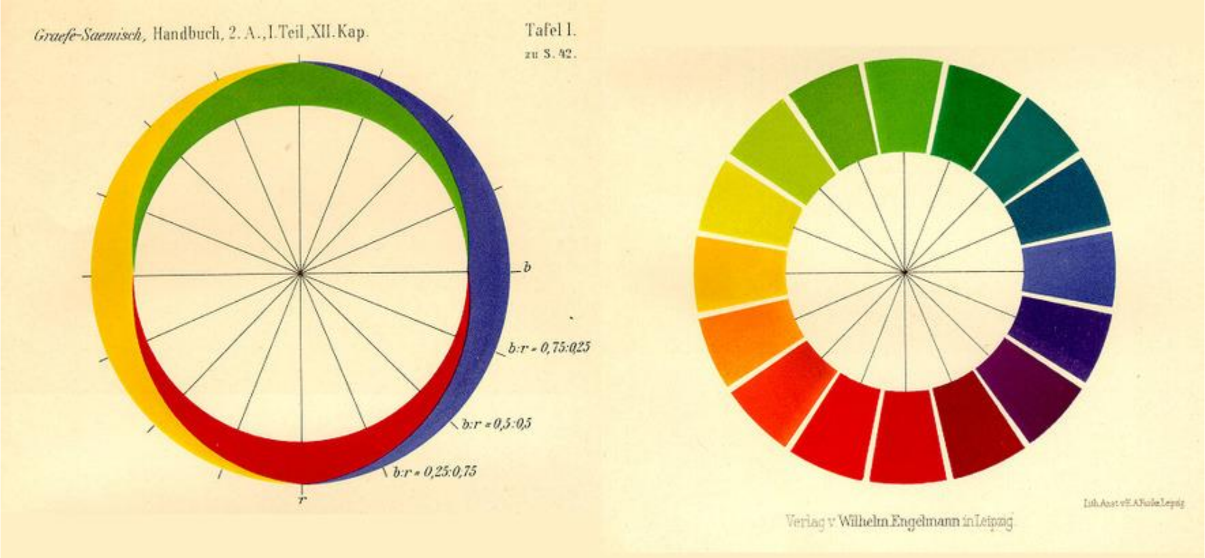

Figure 13: Hering's two opponent axes (left image), and a colour wheel constructed to favour the two-axis opponent theory (right image). Note that the trichromatic primaries, RGB, are not equally spaced on this colour wheel – it has been skewed to favour RYGB as « unique hues ». (Image : Plate 1 from Hering, Ewald. (1874))

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[279] Goethe, Johann Wolfgang von. (2006) [1810]. p.172

[280] Mach, E. (1865). Ueber die Wirkung der räumlichen Vertheilung des Lichtreizes auf die Netzhaut, *Sitzungsber. Akad. Wiss. Wien,* math,-naturwiss. Cl., 52(2), 1865, 303-322, esp. 319-321

> It seems highly striking from the start that between red and green, for example, there is not a series of intermediate chromatic colors as there is between red and yellow or between red and blue, that there are consequently no colors that appear simultaneously reddish and greenish, in the way that orange is simultaneously reddish and yellowish, or gray simultaneously whitish and blackish. We should conclude from this that in the inner eye a physiological process whose psychological correlate would be simultaneously both red and green or yellow and blue is either not possible at all or is possible only under quite special, unusual circumstances.[281]

Furthermore, Hering believed that the existence of a red-green axis, and its *absence* in some people, could also be used to explain the most common kind of colour-blindness – the inability to distinguish red and green hues. This issue gained even greater prominence in the years after Hering's initial 1874 publication of *Zur Lehre vom Lichtsinne*, after a particularly horrific head-on train collision in Lagerlunda, Sweden in November 1875 was allegedly caused by a misinterpretation of the hue of a signal. However, this justification for the existence of a red-green axis soon came into doubt, since by 1885, with the science of colour blindness having progressed with remarkable rapidity in the preceding decade, there was growing evidence to show that there was in fact more than one class of red and green blind. The German physiologist Johannes von Kries (1853-1928) named these newly discovered classes "protanopes" and "deuteranopes" – terms which are still in use today – though Hering, rather stubbornly it seems, denied the existence of these separate classes.[282]

HERING CONTRA HELMHOLTZ

Hering's general view on physiology was against the tide of contemporary German thinking, especially that represented by Hermann von Helmholtz, who is often cast as his "arch-rival". The historian of 19th century German science R.S. Turner has noted that Hering had a "lifelong opposition to any conception of the living organism as a machine waiting passively for an external stimulus to elicit organic response." Instead he held that "life is a dynamic equilibrium of antagonistic processes. External stimuli can disturb this equilibrium, but the processes themselves contain self-regulating mechanisms that act to restore it. Organic response to a stimulus therefore depends as much upon the state of the organism itself as upon the nature and intensity of the stimulus."[283] Hering told his students in a lecture to not "regard life as a physiochemical, machine-like process, but to affirm its intrinsic activity, the autonomous character of its controlling laws,

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[281] Hering, Ewald. (1964) [1874], p.50

[282] Turner, R. S. (1994) *In the eye's mind : vision and the Helmholtz-Hering* controversy (Princeton University Press) pp.184-5

[283] *Ibid.* p.121

and its goal-directedness, and to search for these characteristics in their particular manifestations."[284] In other words, whereas Helmholtz and his colleagues had viewed colour as a *passive* internal response to an external stimulus, Hering viewed colour the product of an *active* internal opponency mechanism, whose balance was modified by the external stimulus. It is for this reason that Helmholtz is often referred to as an "empiricist" and Hering, by contrast, a "nativist".[285]

Nevertheless, Helmholtz and Hering's positions on colour vision had more in common than it first seems. Both tried to reduce our complex visual experiences down to their component primitive sensations – they just differed on the number of these sensations, and the manner of determining them; Helmholtz through physical experimentation, Hering through introspection, tradition, and logic.

Turner (1994) concluded that Hering's unwillingness to compromise was what ultimately led to his scientific downfall. As was the case with Goethe and his vitriolic polemics against the adherents of Newtonian optics, Hering was vehement in his denial of the evidence in favour of the trichromatic theory. His school quickly perished after his death in 1918, as the success of RGB-based colour photography further vindicated trichromatic theory as the physiological basis of human colour vision. From our modern perspective this would seem quite unfortunate – the problems that Helmholtz and Hering and their schools were trying to address were, after all, rather different in nature. Helmholtz was concerned with understanding the fundamental wavelength sensitivities of each *individual* class of colour-sensitive cell in the retina, whereas Hering was concerned with understanding the phenomenon of colour constancy, which relies on a mechanism which links and compares the *collective* of retinal regions with one another.

"UNIQUE HUES" AFTER HERING

Hering's ideas were revived from the 1950s onwards. The *Opponent-Process Theory of Color Vision* promoted by Leo Hurvich and Dorothea Jameson introduced a generation of psychologists and visual scientists to the previously forgotten and discredited theory. Hurvich and Jameson argued, quite rightly, that taken alone the trichromatic model failed to explain the "apparent linkages that seem to occur between specific pairs of colors as either the stimulus conditions or the conditions

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[284] Tschermak-Seysenegg. (1934). *Der exakte Subjektivismus in der neuen Sinnesphysiologie*. 2d rev. Ed. Wien and Leipzig : Emil Haim (1st ed. Berlin : Springer, 1921), p.1232. Translation in Turner, R. S. (1994), p.150.

[285] Hurvichs, Leo M. and Jameson, Dorothea. (1964). Introduction to Hering, E. (1964) [1874]. *Outlines of a Theory of Light Sense.* Trans. Hurvich, Leo M. and Jameson, Dorothea. (Harvard University Press), p.xxvi

of the human observer are varied" [286] – we have seen these specific pairs of colours (complementary colours) exhibited in various phenomena throughout this chapter. Their work engendered a research program which attempted to find a neurophysiological mechanism for Hering's unique hue opponency system. However, despite much excitement, this approach has so far proved unsuccessful.[287,288,289,290,291,292]

An alternative colour system based on Hering's unique hues – called the Natural Colour System (NCS) – was developed at the Swedish Colour Centre Foundation from 1964 onwards, and has gained prominence among psychologists of human colour vision. This colour system claims to be based on the "phenomenology" of human colour perception, rather than on colour mixing as the RGB-based CIE-1931 colour space is. Ultimately, as the physicist Erwin Schrödinger showed in a series of papers in the *Annalen der Physik* in the 1920s, the choice between the four- and three-colour models merely boils down to a choice of basis in colour space.[293,294]

In recent years, a number of papers have been written expressing doubt over the existence of the "unique hues" at all. Van Brakel (1993)[295], Saunders et al. (1997)[296] and Ocelák (2015)[297] – the best of these – concentrate their attacks on the lack of real evidence other than subjective introspection and shaky linguistic arguments such as those we saw in the preceding section. Further to these criticisms, the colorimetrist Jan Koenderink, in his textbook *Color for the Sciences* has pointed out one of the more glaring logical inconsistencies of Hering's theory:

> Hering argues [that] a *pure yellow* contains neither *red* nor *green*, even though you may *know* that yellow can be obtained by additive mixture of red and green. In the mixture the components are absent; it is only "*yellow*" that you "see".

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[286] Hurvich, Leo M. and Jameson, Dorothea. (1957). "An Opponent-Process Theory of Color Vision" (Eastman Kodak Company) Psychological Review Vol. 64, No. 6, 1957, p.384

[287] Broackes, J. (2011). "Where do the unique hues come from?" Rev Philos Psychol 2:601–628

[288] Jameson, K. (2010). "Where in the World Color Survey is the support for the Hering primaries as the basis for color categorization?" In: Cohena JD, Matthen M (eds) *Color ontology and color science.* MIT Press, Cambridge, pp 179–202

[289] Krauskopf J., Williams D.R., Mandler M.B., Brown A.M. (1986). "Higher order color mechanisms." Vis Res 26:23–32

[290] Mollon, J. (2009). "A neural basis for unique hues." Curr Biol 19:R441– R442

[291] Saunders, B. and van Brakel, J. (1997). "Are there nontrivial constraints on colour categorization?" Behav Brain Sci 20:167–228

[292] Wuerger S.M., Parkes L. (2011). "Unique hues: perception and brain imaging." In: Biggam CP, Hough CA, Kay CJ, Simmons DR (eds) *New directions in colour studies.* John Benjamins, Amsterdam, pp 445–455

[293] Schrödinger, Erwin. (1920). « Grundlinen einer Theorie der Farbenmetrik im Tagessehen, » *Ann. Phys.* 63, pp.397-426, 427-456, 481-520

[294] Schrödinger, Erwin. (1924). "Über das Verhältnis der Vierfarben zur Dreifarben Theorie," *S.B. Akad. Wiss.., Wien IIa,* pp.471-490

[295] van Brakel, J. (1993). "The plasticity of categories: the case of colour." Br J Philos Sci 44:103–135

[296] Saunders, B. and van Brakel, J. (1997).

[297] Océlak, R. (2015). "The Myth of Unique Hues". Topoi October 2015, Volume 34, Issue 2, pp 513–522

> Hering did not extend the argument to cyan and magenta (purple). However, I fail to see *red* and *blue* in a *pure purple*, just as I fail to see *red* and *green* in a *pure yellow*.[298]

Hering argued that yellow was a not a combination of red and green, but rather a "unique hue", yet, rather arbitrarily, he did not consider the other two subtractive primary colours – magenta and cyan – to be "unique". As we have seen, this exclusion of cyan and magenta on Hering's colour circle also means that the additive primary colours (RGB) are not equally spaced, but are rather awkwardly skewed to make room for yellow (see Figure 13).

Despite all these drawbacks, a belief in the existence of Hering's four "unique hues" still holds sway with a large number of contemporary investigators of colour vision. This may be partly explained by recent discoveries in the evolutionary genetics of human cone cells which suggest that there may be a "hard" scientific basis for the existence of "unique hues" at higher levels of processing, and a way to reconcile their existence with the established trichromatic colour theory.

In animals with trichromatic colour vision, there are three types of cone cell, "S" (short wave), "M" (middle wave), and "L" (long wave) each with a peak sensitivity to what we call "blue", "green", and "red" light.[299] The consensus from recent genetic studies is that the evolutionary ancestors of trichromats (such as humans and old world monkeys) were dichromats, having only short wave "S" cones and one other, with a peak sensitivity somewhere between that of the M and L cones found in trichromats. Let's call this cone "X". It is understood that between 45 and 30 million years ago, the M and L cones slowly emerged and distinguished themselves from this common ancestor, cone X.[300] This is consistent with Christine Ladd-Franklin's hypothesis, which I discussed in Chapter One.

This suggests that the oldest colour distinction process which relied on cones "X" and "S", would have distinguished between what would have been "redgreen" (yellow) at one end of the spectrum, and blue at the other. Later, the M and L, green and red sensitive cones emerged from the X cones, perhaps at a time in evolutionary history when the red-green distinction became practically useful.

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[298] Koenderink, J. (2010). *Color for the Sciences* (MIT : Cambridge) p.579-80

[299] « S » cones have peak sensitivity at 420-440nm, "M" cones have peak sensitivity at 534-555nm, and "L" cones have peak sensitivity between between 564-580nm. [*Hunt, R. W. G. (2004). The Reproduction of Colour (6th ed.). Chichester UK: Wiley–IS&T Series in Imaging Science and Technology. pp. 11–12.*]

[300] *Yokoyama, S.; Xing, J.; Liu, Y.; Faggionato, D.; Altun, A.; Starmer, W. T. (2014).* "Epistatic Adaptive Evolution of Human Color Vision". *PLoS Genetics.* ***10*** *(12): e1004884.*

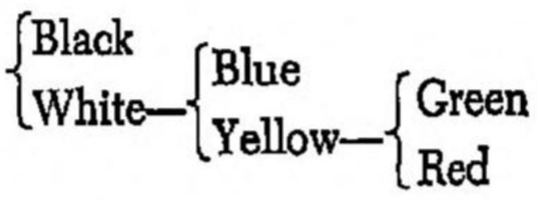

Figure 14: An illustration of Christine Ladd-Frankin's hypothesis, From Boring (1942), p.211. The evolution of colour vision moves from left to right.

From the perspective of evolutionary history then, it seems that the red-green and blue-yellow distinctions *do* have a privileged status. Perhaps this explains the psychological strength of the subjective sensations of "red" as opposed to "green", and "blue" as opposed to "yellow". After all, it is arbitrary exactly which subjective colour sensations – with their particular psychological qualities – are assigned to particular hue values on the colour wheel. Perhaps the "unique" feeling of the RYGB hues is a consequence of their practical importance in evolutionary history. This "ecological" approach to colour vision has been given a great deal attention by John Mollon of Cambridge University, among others.[301,302,303,304,305,306,307,308,309,310,311]

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[301] Mollon, J. D. (1987). "What can we learn about colour vision from a study of its evolution?" In 'Normal and Pathologic Colour Vision', Eds. E. Marré, M. Tost, H.J. Zenker, Martin-Luther-Universität Wissenschaftliche Beiträge 120 (R101), Halle (Saale)

[302] Mollon, J. D. and Jordan, G. (1988/1989) "Eine evolutionäre Interpretation des menschlichen Farbensehens." *Die Farbe* 35/36, 139-170

[303] Mollon, J. D. (1991) "The uses and evolutionary origins of primate colour vision." In J. Cronly-Dillon and R. L. Gregory (Eds.), 'Vision and Visual Dysfunction' vol 2, pp. 306-319, Macmillan, London (revised version of essay originally published in the Journal of Experimental Biology.)

[304] Dulai K. S., Bowmaker J. K., Mollon J. D. and Hunt D. M. (1994). "Sequence divergence, polymorphism and evolution of the middle-wave and long-wave visual pigment genes of Great Apes and Old World monkeys." *Vision Research* 34, 2483-2493

[305] Shyne J., Hewett-Emmett D., Sperling H., Hunt D. M., Bowmaker J. K., Mollon J. D. and Li W. (1995). "Adaptive evolution of color vision genes in higher primates." *Science* 269, 1265-1267

[306] Mollon, J. D. (1996). "The evolution of trichromacy: An essay to mark the bicentennial of Thomas Young's graduation in Göttingen." In N. Elsner & H.-U. Schnitzler (Eds) Brain and Evolution, Springer, pp. 125-139

[307] Bowmaker J. K., Hunt D. M. and Mollon J. D. (1997). "Primate visual pigments: their spectral distribution and evolution." In C. Dickinson, I. Murray and D. Carden (Eds) 'John Dalton's Colour Vision Legacy', pp. 37-46, Taylor and Francis, London

[308] Hunt D. M., Dulai K. S., Cowing J. A., Julliot C., Mollon J. D., Bowmaker J. K., Li W.-H. and Hewett-Emmett D. (1998). "Molecular evolution of trichromacy in primates." *Vision Research* 38, 3299-3306.

[309] Dulai K. S., von Dornum M., Mollon J. D. and Hunt D. M. (1999). "The evolution of trichromatic color vision by opsin gene duplication in New World and Old World primates." *Genome Research* 9, 629-638

[310] Mollon, J. D. (2000) "Cherries among the leaves": The evolutionary origins of colour vision. In S. Davis (Ed) Colour Perception: Philosophical, Psychological, Artistic, and Computational Perspectives, Oxford University Press, pp 10-30.

[311] Regan, B. C., Julliot, C., Simmen, B., Viénot, F., Charles-Dominique, P. and Mollon, J. D. (2001). "Fruits, foliage and the evolution of primate colour vision." *Philosophical Transactions of the Royal Society B* 356, 229-283.

In summary: the red-green and blue-yellow opponent processes, even if they do indeed exist as part of the hue value/colour sensation labelling system, are *not* credible rival explanations of colour constancy and the complementary colours, as Hering wanted them to be. As we have seen, it has been long established that the complement of red is cyan (not green), the complement of green is magenta (not red), and the complement of blue is yellow. The opponent process pairs, if they exist, operate at a higher perceptual level, giving psychological emphasis to *functionally* important hues in the colour wheel. They have no significance in calculating hue values (i.e. positions on the colour circle) of given points in the visual field, but perhaps have some significance in the *labelling* of particular hue values with particular subjective colour sensations.

Hering's "unique hues", construed in this evolutionary sense, are therefore of no consequence for Land's investigations into how colours effect the perception of others in the surround. As we shall see in the next chapter, Land dealt with the colours as they are, and did not go so far as to question why a particular subjective psychological colour sensation is assigned to a particular hue value.

HELMHOLTZ ON COLOUR CONSTANCY

Hermann von Helmholtz also proposed two mechanisms to account for colour constancy. The first was remarkably similar to Hering's "memory colour":

> Colours are mainly important for us as properties of objects and as means of identifying objects. In visual observation we constantly aim to reach a judgement on the object colours and to eliminate differences of illumination. So, we clearly distinguish between a white sheet of paper in weak illumination and a gray sheet in strong illumination, We have abundant opportunity to examine the same object colours in full sunlight, in the blue light from the clear sky, and the reddish yellow light of the sinking sun or of candlelight – not to mention the coloured reflections from surrounding objects. Seeing the same objects under these different illuminations, we learn to get a correct idea of the object colours in spite of difference of illumination. We learn to judge how such an object would look in white light, and since our interest lies entirely in the object colour, we become unconscious of the sensations on which the juidgement rests.[312]

The second was rather different to Hering's "opponent colours" theory. In the *Handbuch,* Helmholtz imagined an experiment much like Count Rumford's shown in Figure 5, in this case a grey patch placed on a desaturated green background.[313] When the viewer keeps only the green background in his field of vision, the grey patch assumes an apparent "red" tinge.

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[312] Helmholtz, Hermann von. (1866, p.408) *Physiological Optics.* Translated in Woodworth, R. S. (1938) *Experimental Psychology.* (New York : Holt), p.889

[313] Helmholtz, H. (1962) [1860]. *Helmholtz's Treatise on Physiological Optics*. Ed. James P.C. Southall. 3 vols. In 2. New York: Dover, 1962. pp.270-78

This observation is clearly inconsistent with the colour atomism hypothesis – under this hypothesis the grey patch should retain its colourlessness. Helmholtz needed to explain why the colour atomism hypothesis failed to explain this red tinge. He suggested that the eye must somehow take the illumination of the overall scene into account, in order to determine the "standard white" for the scene, which would act as a reference point for all other colours. Since in this example, the only colour available in the scene is the desaturated green, Helmholtz argued that the eye mistakes this green colour for the "standard white", and thus the grey will be proportionally far "redder" than this standard white.[314] In modern photographic parlance, he was suggesting that the "white balance" had been determined with reference to the green background. This is strikingly similar[315] to Gaspard Monge's statement that

> our judgments can be altered by the context, and it is likely that we are influenced more by the ratio of particular properties of the light rays rather than by the properties themselves, considered in an absolute manner. [316]

From this example, we can see that Helmholtz was forced to depart from the colour atomism hypothesis when no other explanation was available.

LAND ON THE PHENOMENOLOGICAL TRADITION

Edwin Land explicitly acknowledged Hering as the originator[317] of the idea that colour constancy requires a mechanism which takes into account the surrounding scene of a particular point in the visual field, but argued that he did not go far enough:

> Since the time of Newton, colour vision has been approached starting from the properties of the eye in viewing small areas and working from there to explain how colour in everyday life comes about. More recently, Hering introduced the idea that the regions surrounding the areas in question are also very significant. Nevertheless, I think all of us still tend to inhibit the recognition of the *overriding* importance of the *whole* area that is being viewed. Because of the meticulous measurements that can be made in colour-matching, one has attempted to start from the colour-matching laws and, by adding terms to their equations, to describe what happens in extended areas.[318]

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[314] *Ibid.*

[315] It is not clear if Helmholtz knew of Monge's experiments, since he never made any reference to them.

[316] Monge, Gaspard. (1789). Translated in Mollon, John. (2005). p.299

[317] As we have seen in this chapter, particularly the section on Gaspard Monge, Land was arguably wrong on this point of history.

[318] Land, Edwin H. (1965). "The Retinex", *Ciba Foundation Symposium – Color Vision Physiology and Experimental Psychology, A.V.S. DeBouck and Julie Knight, eds., pp. 217-227* (Little Brown and Company Boston, 1965), p.217

Land never made in any mention of "opponent-process" theory or the "unique hues" in any of his published papers. As we shall see, he embraced trichromatic theory as the basis for human colour vision, and thus probably regarded this aspect of Hering's work as a scientific dead end.

Land also acknowledged the influence of the "inductive" experimentation of Buffon, Thompson, and Goethe among others, but criticised them for their lack of "quantitative treatment":

> While we heartily favor placing a high value on induction, we are at a loss to see what there is in the long history of it … that would enable one to make any quantitative treatment of it whatsoever.
>
> …
>
> We believe that the reason induction did not develop into a science is that those who explored it tended to use what we regard as greatly oversimplified situations. We suggest that here is a domain in which an error in the technique of abstraction, a presumption that simplification of the field of view is permissible to understand the properties of an intricate field, prevented induction from becoming a mature principle. Our plea to contemporary experimenters is that they take any step away from normal, fully populated scenes with the utmost caution.[319]

For Land, while the early practitioners of the phenomenological science of colour had "done well" to move away from examining isolated spots of light, they had not gone far enough. What was needed were entire-field quantitative studies of scenes which were heavily populated with stimuli. As we shall see in the next chapter, this is precisely what Land and his colleagues at Polaroid's Vision Research Laboratory set out to achieve.

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[319] Land, Edwin H. (1959). "Letters to the Editors, September 1959", *Scientific American*, Vol. 201, Issue 3, September 1959

CHAPTER THREE

The Land Experiments in Colour Vision

The eye is a piece of brain that is touching light, so to speak, on the outside.

Richard Feynman, *The Feynman Lectures on Physics, Vol I* (1964)

INTRODUCTION

In Chapter One I argued that the colour atomism hypothesis was the commonly held assumption of practitioners of the physical science of colour. In Chapter Two I showed how several observations of colour phenomena called this hypothesis into question.

This chapter will explain how the "colour atomism hypothesis" and the phenomenological observations came to be reconciled, and the boundary disputes between the "physical" and "phenomenological" schools came to be resolved under Edwin Land's "retinex" model of colour vision. It was the problem of providing a satisfactory explanation for *colour constancy* that ultimately demanded such a resolution.

Land was well aware of the history of the colour atomism hypothesis and its inadequacy in explaining the phenomenon of colour constancy:

> Newton stated that 'Every Body reflects the Rays of its own Colour more copiously than the rest, and from their excess and predominance in the reflected Light has its Colour' (Newton, 1730). Today we might say that Newton believed that the wavelength-energy distribution determined colour sensations. Thomas Young (1802), while teaching at the Royal Institution, proposed the next idea in colour vision, namely that there were three kinds of receptors with three different spectral sensitivities and that they worked together at a point.
>
> …
>
> Helmholtz held firm to the idea that three energies at a point determine colour at that point. At the same time Helmholtz's observations persuaded him that: 'we are accustomed and trained to form a judgement of colours of bodies by eliminating the different brightness of illumination under which we view them' and 'we eliminate the colour of the illumination as well.'.[320]

We saw in Chapter Two that Helmholtz believed that colour constancy was made possible because the eye somehow "discounted the illuminant". Helmholtz argued – incorrectly in Land's view –

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[320] Land, Edwin. H. (1974). "The Retinex Theory of Colour Vision" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.111

that "memory colour" could explain how the eye "knows" about the properties of the light illuminating a scene:

> Helmholtz made the valid observation that we see the correct colours of objects in spite of variable illumination, but he was mistaken in his view that 'we are accustomed and trained to form a judgement of colours' and that 'we get accustomed to subtracting the illuminating colour from coloured surfaces'.[321]

This adjustment, according to Land, could be achieved by a spatial comparison of wavelength reflectance, which dispensed of the need for a "memory colour" system. The retinex algorithm was developed by Land and colleagues to simulate how such a spatial comparative mechanism could work. This computational model of colour vision was a powerful tool for understanding not only colour constancy, but also the many of the other "phenomenological" observations we saw in Chapter Two.

Edwin Herbert Land (1909-1991) was an inventor, scientist, and founder of the Polaroid Corporation. In 1926 he left Harvard University in his freshman year to pursue his interest in the commercial possibilities of polarizing light filters, and eleven years later founded the Polaroid Corporation. The company found some initial success in selling polarising sunglasses and polarising camera filters, but failed to break into the lucrative automobile industry with its anti-glare headlights product. During the Second World War, Polaroid was commissioned to produce military equipment for the U.S. Army, including anti-glare and fog-free goggles, periscopes for navy submarines, and a machine gun simulator which exploited the company's work in 3-D imaging. These efforts enabled Polaroid to thrive during the war years, but after the war the company needed new products to survive. In 1943 Land began developing an idea for instant photography, allegedly after his daughter asked him why she could not immediately see a photograph he had taken of her. The problem of creating a film that would develop itself instantly was a problem of chemistry, just as the problem of creating polarizing light filters had been. In 1947 Land astonished a meeting of the American Optical Society by introducing the "Land Camera" Model 95, the first self-developing film camera, which developed monochrome (sepia) images in sixty seconds. It was introduced in stores in time for Christmas that year.[322]

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[321] Ibid.

[322] McElheny, Victor K. (1998). Chronology xiii - xvi

LAND'S TWO-COLOUR "EUREKA"

On May 19th, 1955 Land delivered a lecture entitled "The Case of a Sleeping Beauty or a Case History in Industrial Research" at West Point, New York. As Land mentioned in this lecture, by 1955 the company was thinking about instant "color photography as something we must ultimately achieve".[323] Land stated that although he had understood that colour photography must be achieved with subtractive colour mixing processes, "the well-known beauty of additive processes for projection and the fact that our skill in producing black-and-white transparencies was constantly increasing … stimulated us to continued exploration of the additive approach".[324]

However, the practical "engineering" background to Land's interest in colour vision should not be overstated. In his biography of Land, Victor K. McElheny describes how "early in 1955 a small *accident* in the laboratory plunged Land into the mystery of colour vision. It became a passion, and for thirty years, it was his most intense effort in basic research. The work thrust him forward to the view, increasingly prevalent in the 1990s, of the brain as a physical entity, shaping and shaped by a physical world." McElheny added that "the unexpected turn did *not* arise from Land's usual approach of seeing a need and rustling up the basic science to meet it".[325] There was no concrete engineering problem to be solved, rather a general interest in understanding the subject of colour from *first principles* before he was to embark in engineering a new colour camera. We can see this from Land's account of his "two-colour experiment" in the 1955 lecture.

What follows is a description of this "first principles", "explorative" approach.[326] Interestingly, before launching into his description, Land felt it important to justify his "narrative" approach to reporting his experimental results:

> The hypothesis I want to explore with you tonight is that the way we feel and the way we act and the way we worry and the way we wonder and the way we dream while we are doing our work is as much a part of the scientific method and as important a part of the scientific method as is the reporting on results. I want to propose for our examination the idea that reporting on results is a small part of science, that by pretending that what we can show in rigorous conclusion supported by curves and equations impeccably correct is only a small part of what we know. So that when we confine ourselves to these rigorous final reports, we are not really living up to Bacon's ideal of scientific exchange but are indeed

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[323] This was achieved in 1963, with the introduction of *Polacolor* film. Later in 1972 the Polaroid SX-70 was introduced which simplified the process for the user so that they no longer had to time the development or peel the negative away from the positive.

[324] Land, Edwin. H. (1955). "The Case of A Sleeping Beauty or a Case History in Industrial Research" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.3

[325] McElheny, Victor K. (1998), p.245 [my italics]

[326] Ribe, N. and Steinle, F. in their 2002 paper **"**Exploratory Experimentation: Goethe, Land, and Color Theory" provide an interesting comparison of Goethe, Faraday, and Land's "explorative" approach to experimentation.

> concealing from each other many intangible contributions that we might make to our mutual purpose of building up and utilizing scientific knowledge.

For Land, the standard format of the contemporary scientific paper stifled the "exploratory" nature of experimentation. Land then launched into his description:

> I like to work by setting up classical experiments, watching them and ruminating about them. Accordingly, I asked Gretchen Baum to arrange such typical color subjects as bowls of fruit, to photograph them separately through red, green and blue filters onto our black-and-white transparency material, and to project them superimposed.

This was a repeat of Maxwell's colour "photograph" that we saw in Chapter One. The reader will recall that Maxwell's "photograph" consisted of three images of a tartan ribbon, taken through red, green, and violet filters respectively, and then projected through those filters again, and the images superimposed on one another. Land continued:

> It was while watching this elementary experiment in color photography, placing and removing color filters in front of the projectors, that the incident occurred which led to our interest in the beautiful phenomena you will see directly. The red and green projectors were on, giving a picture like this.
>
> I was casually playing with the green filter to produce this effect when Mëroe Morse said, "Why is there any color now?" My casual answer was, "Oh, that's just the color fatigue effect." As the day went on, my scientific conscience began to bother me and that night at two o'clock I awoke with the feeling that this phenomenon was a remarkable one, and with the notion that if the brightness of the white projector was reduced to match the brightness of red light (the intensity of light going through the red projector), the white might become a useful primary color, accordingly, I went down to the laboratory to test this idea. As you see now, I found it is indeed correct that by dropping the brightness of the white to be comparable with the red a remarkably extensive palette of colours can be obtained.
>
> Are you clear now about the whole experiment? The object in the real world is photographed twice – once through a red filter, once through a green filter – and black-and-white transparency positive images are prepared and projected on the screen with a red filter in the path of the projector which had the red image and with no filter in the path of the projector which had the green image. There is, on the screen, only red light and white light, nothing but pink everywhere of various brightnesses.

Effectively, Land's experiment was the same as Maxwell's but instead of using three images, he used two – red and green. When the images were projected, instead of projecting them with their original colours – red and green – they were projected through red and white. The red image was projected with red light, and the green image with white light.

What Land had realised here is that a good array of subjective colours can be produced with a combination of only red light and white light. He was startled as to why he could perceive green in the projected image even though the two projectors only shone red and white light. It seemed that the areas in the image where there was an absence of red light and a surplus of white (colourless) light were interpreted by the viewer's eye as if there was a relative surplus of green light. A recreation of this experiment is shown in Figures 2-7.

In the 1955 lecture Land then described how he tried to look for a precedent for this observation in the scientific literature:

> How well is it known? Who knows about it? What can we do with it? What can we learn about it? And so to our standard color photography texts and to our psychology books and to our psychologist friends, but no good leads. And then a request to one's associates to keep their eyes open for references. And finally, after a month, Howard Rogers comes across a page in Cornwell Clyne's book on "Color Cinematography." Here we find the key names. From here on, the reference work is easy. With the names we round out the past knowledge. But this knowledge, one notes, is apparently confined to motion picture technology, to corporate promotions, the phenomenon has not made the grade of being described by the psychologists.[327]

These practitioners were William Francis Fox and William H Hickey, who patented an invention for a two-colour cinema projector. This worked by alternately photographing the same scene through a red filter, and then through no filter, and projecting these images correspondingly. As Land noted in a later article, some years later another inventor, Bernardi, "used red and green filters for taking movies and red and white for projecting (Adrian Cornwell-Clyne, *Colour Cinematography* [London, 1951], p.261)".[328] The relevant passage from Cornwell-Clyne's book reads:

> But the full wonder of simultaneous contrast is revealed in the device of substituting the unfiltered light of the arc for the green-blue filter. This was invented by William Fox and William Harrison Hickey and Kinemacolor of America in the earliest days of colour films. It was later "re-invented" by A Bernardi for Raycol, who probably discovered the effect accidentally. In any case, it is surprising how much can be obtained if one picture be projected through a red-orange filter and the other with *no filter whatsoever*.[329]

The reader will recall the phenomenon of "simultaneous colour contrast" and the work of Eugène Chevreul from Chapter Two. Just as Chevreul had discovered "simultaneous colour contrast" in the context of the dying industry, Fox, Hickey and Bernardi rediscovered it in the context of the cinema industry. Now in 1955 Land had rediscovered the same phenomenon in the context of the colour photography industry. It is thus easy to see why Land titled his 1955 lecture "The Case of a *Sleeping* Beauty" – the phenomenon had been discovered in the context of "engineering" but, as he saw it, no purely "scientific" researchers had published a study of the phenomenon.

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[327] Land, Edwin. H. (1955), p.4

[328] Land, Edwin. H. (1959). "Color Vision and the Natural Image Part I" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.12

[329] Cornwell-Clyne, Adrian. (1951) [1936]. *Colour Cinematography* [London, 1951], p.261.

Figure 1: Polaroid photograph of John McCann and Edwin Land. John McCann worked in, and later managed the Vision Research Laboratory at Polaroid from 1961 to 1996. Permission from John J. McCann.

Land was aware that he too had discovered the phenomenon in the context of "engineering", but was proud of this fact. In April 1959 Land told a conference of Boston patent lawyers that:

> We have moved to the point where a need in applied science may be the precise stimulus for a discovery in pure science. The human mind is able to become integrated again – as it must have been before the Victorian era when purity became associated with lack of utility.[330]

Land saw practical utility as a useful stimulus for research into "basic science". In turn, the "basic science" discoveries could feed back into the practical side of the business. In the early 1960s Land set up a laboratory to research the possibility of applying the two-colour principle to the development of a simpler colour TV set. In August 1964 Polaroid signed an information-sharing agreement with Texas Instruments for the development of a two-colour TV set, and in 1967 Polaroid patented a design for a TV set which used only one electron gun instead of three. However, the project slowed down as the cost of traditional three-colour sets tumbled over the

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[330] Land, Edwin. H. (1959). "Thinking Ahead: Patents & New Enterprises" in *Edwin Land's Essays. Volume II. Science, Educatin and Industry.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.43

decade, and the commercial opportunity diminished.[331] The "basic" research into colour vision continued however as Land set up a Vision Research Laboratory at Polaroid.

Land liked to see himself in the tradition of the great "exploratory experimenters", as historian of science Fredrich Steinle has called them.[332] In a letter to the British chemist Sir George Porter (1920-2002), Land wrote:

> Whenever I am back near Faraday's laboratory I feel the kind of inspiration that might come at a shrine. I am always impressed by the homespun simplicity of his experiments, the earthly sequentially whereby they follow each other so simply and sensibly to arrive at conclusions of vast and romantic scientific significance.[333]

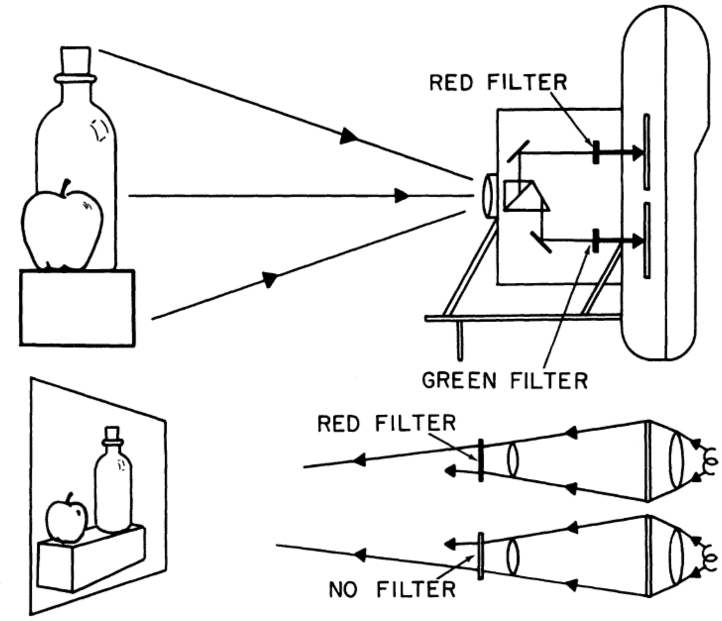

Fig. 1.—Diagram of camera and projector

Figure 2: Schematic diagram of the basic experiment.[334]

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[331] McElheny, Victor K. (1998), p.261-3

[332] Steinle, Friedrich and Ribe, Neil. (2002). "Exploratory Experimentation: Goethe, Land, and Color Theory". Physics Today, vol. 55, issue 7, p. 43

[333] Land, E. (1978). "Letter to Sir George Porter », also presented as the Franklin Institute Medal Day Address, on November 6, 1978" in *Edwin Land's Essays. Volume II. Science, Education and Industry.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.77

[334] Land, Edwin. H. (1959). "Color Vision and the Natural Image Part I" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.5

Figure 3: Two pictures, the top taken through a red filter, and the bottom taken through a green filter. Image: Taken by the author during a visit to John McCann (former head of the Polaroid Vision Research Laboratory) in July 2018. Permission from John J. McCann.

Figure 4: The Polaroid Vision Research Laboratory's Dual Beam Projector No E 1002, demonstrated by John McCann. Images: Taken by the author during a visit to John McCann (former head of the Polaroid Vision Research Laboratory) in July 2018, and included in this thesis with permission from John McCann.

Figure 5: Top image from Figure 3 (red image) projected through white light and bottom image from Figure 3 (green image) projected through green light.

Figure 6: Both images from Figure 4 superimposed. Remarkably, there is no red light in this image. The red seen by the observer is created by the context of the green light.

Figure 7: The same process as Figures 2-5, except this time the red light was projected through the red image, and white light through the green image. Remarkably, there is no green in this image. The green seen by the observer is created by the context of the red light.

COLOR VISION AND THE NATURAL IMAGE

Four and a half years after the "Sleeping Beauty" lecture, Land published a more complete study entitled "Color Vision and the Natural Image", printed in January 1959 in the *Proceedings of the National Academy of Sciences* after it was presented as a lecture in April 1958. It began:

> We have come to the conclusion that the classical laws of colour mixing conceal great basic laws of color vision. There is a discrepancy between the conclusions that one would reach on the basis of the standard theory of color mixing and the results we obtain in studying total images. Whereas in color-mixing theory the wave-lengths of the stimuli and the energy content at each wave-length are significant in determining the sense of color, our experiments show that in images neither the wave-length of the stimulus nor the energy at each wave-length determines the color. This departure from what we expect on the basis of colorimetry is not a small effect but is complete, and we conclude that the factors in color vision hitherto regarded as determinative are significant only in a certain special case. What has misled us all is the accidental universality of this special case.[335]

As we can see, Land had moved a long way since his report of an "unusual" experiment in 1955. He was now confident enough to conclude that "neither the wave-length of the stimulus nor the energy at each wave-length determines the color" – i.e. that the "colour atomism hypothesis" was false in the case of whole images, and only applied in the special case of points of light.

Land and his colleagues had also made further investigations into the history of the phenomenological science of colour. Land acknowledged the work of Goethe and his generalisation of the laws of colour complementarity (in his colour wheel), although expressed doubt that his observations could be *explained* with Goethe's system:

> … it seems that none of the previous work in any kind of color matching or system of complementary colored shadows (Goethe) can be the basis for the observed fact that the colors in our images, arising from unorthodox stimuli, correspond in hierarchical order to the colors that the observer would have seen had he been at the original site.[336]

At this stage Land was not proposing a mechanism to explain the phenomena of his experiments (as for example Hering did with his unique hue opponent-process system). He was simply interested in exploring the phenomena and showing that they were inconsistent with the theory that wavelength determines colour (what I have called the "colour atomism hypothesis"):

> The purpose of this paper, however, is not to discuss internal visual mechanisms, but rather to begin the description of the laws for a large *general* case – laws describing the relationship of the sense of color in the human eye to the structure of *total images*, laws in which wave-length of stimulus and intensity of stimulus will play entirely new roles.[337]

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[335] *Ibid.* p.5
[336] *Ibid.* p.12
[337] *Ibid.* p.5

I refer the reader to the original article for a full account of the colour vision experiments. I will provide a summary here of the experiments numbered 1 to 16:

1. Demonstration of projector apparatus – changing intensity of the red-filtered beam with no image.
2. Two black and white images (in this case a side profile of a woman) shown – one taken through red filter and one taken through green. Differences noted. For example, the (red) lipstick comes out black in the green-filtered image, and comes out white in the red-filtered image. See Figure 8.
3. The images are fused together (projected on top of one another). The red-filtered image is projected through the red filter. The green-filtered image is projected with no filter. A wide gamut of colours observed – "blonde hair, pale blue eyes, red coat, blue-green collar, and strikingly natural flesh tones." [338] This was a repeat of the experiment reported in the 1955 lecture.
4. Room lights turned on, and "it is shown that there is no visible time lapse between snapping off the lights and the appearance of full color in the picture." [339] This was an important experiment for Land, as it showed that retinal "adaption" or "fatigue" had nothing to do with producing the results.
5. Room light tested. Going from darkness to full strength, the colours of the image are unaffected. "It is shown that the eye sees color in the room and color on the screen at the same time and that, furthermore, the colours on the screen are not changed by having the surrounding room illuminated in white light. This experiment gives the first premonition that multiple color universes can coexist side by side, or within another." [340] That is, Land was saying, that the human brain does not adjust the white balance of the entire visual field together as a whole. The brain is not simply a camera where we change the entire film of a different colour temperature. Rather, it is computed at a local level. There can be different white balances in different areas of the same visual field.
6. Another experiment to show clearly that it is "not necessary to use traditional complementary colors to produce white" [341]
7. An experiment to show that color is not affected by angular subtend (Land in a later paper shows the borders between color regions to be important). "The observer finds the sweater to be green even when he stands so close to the screen that the sweater fills a large portion

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[338] *Ibid.* p.6

[339] *Ibid.* p.6

[340] *Ibid.* p.6

[341] *Ibid.* p.6

of his field of view; and he also finds the sweater to be green when the image is made small and the observer is at a distance from the screen." [342] The conclusion from this experiment is that the absolute size of a colour patch in the observer's field of vision does materially affect the colour that they perceive.

8. The red filter is now moved from the long projector (projecting the red-filtered image) to the short projector, so the colours are reversed. "The sweater is now reddish and the hair greenish, and the lips an intense blue-green, illustrating the phenomenon of hierarchical reversal, usual, to be sure, in any color photography system but particularly important here because it demonstrates that the colors are independent of what the observer expects, and the system, in spite of use of the new "arbitrary" primaries, behaves like any system of color reproduction." [343] This experiment also showed that the effect does not depend on the viewer's "expectation" or of what the colour of a particular object should be ("memory colour").
9. This experiment was designed to eliminate any potential bias that the colours which are traditionally associated with objects would have on the colours that are reported to be perceived. "A slide is shown in which there are twelve coloured objects photographed against a gray background divided into twelve numbered squares. It is pointed out that, except for the orange on square No. 2, each object could appropriately be any color, so that there can be no prior association between the name of the object and the name of the color of the object; thus one would not know that the telephone is red, the paper stapler gray, or the design on the teacup, on square No. 12, dark blue. It is pointed out that this slide had been used to interrogate naïve observers and that, except for the color-blind, marked consistency was found in their reporting of the colour names." [344] See Figure 9.
10. In this experiment the relative intensities of the long (red) and short (green) records are changed. The subject was then asked to "indicate the two extremes at which color first appears". "It is pointed out that when color does appear at both extremes it appears at the same time for all the subjects on the slide. It is demonstrated that the ratio of stimuli can be varied enormously – with some pairs of stimuli by ratios as high as 100 to 1 – without altering the color name given to each one of the objects." [345] This experiment further showed that the colours in the image depended upon one another – none appeared before the others.

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[342] *Ibid.* p.7
[343] *Ibid.* p.7
[344] *Ibid.* p.7
[345] *Ibid.* p.8

11. "In this experiment a duplicate of the short record is superimposed on the short record already in the projector, thus doubling its contrast. A single long record is used, so that it has the original contrast of the previous experiments. Thus for the short record in places where, in the previous experiments, a fifth of the light was transmitted, the slide now transmits a twenty-fifth; in places where a tenth was transmitted, the slide now transmits a hundredth … It follows, therefore, that for each object on the slide there is now a new ratio of long to short stimulus, and it would be expected classically that each object would be a new colour. Actually, the objects retain their original color names, demonstrating the stability of the colors of an image with respect to the contrast of its component images, and illustrating further that color is independent of the quality of the stimulus defined locally." [346] This experiment was a strong demonstration of the phenomenon of colour constancy – as the reader will recall from Chapter Two, this is the phenomenon that colours of objects remain stable despite vast changes in lighting conditions.

The next experiments, "Experiments 12, 13, 14, and 15 [were] designed to demonstrate further that color at a point in an image is independent of the wave-length composition of the radiation coming from that point." [347] These are a series of experiments with a variety of different filters in different combinations.

In Experiment 16, Land showed that a yellow filter can either be used as the short or the long record: "It is demonstrated to the audience that the filter Wratten No. 73 which passes a narrow band of yellow may be used as a shorter member of a wave-length pair, and as a longer member of a wave-length pair, depending on what is picked to go with it." [348] This experiment showed that the exact colour of the two filters used in the experiment is not significant – what is important is that two filters are chosen with different (enough) wavelengths. The green and red filters chosen in the earliest experiment are just one combination among many which could elicit the effect.

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[346] *Ibid.* p.8
[347] *Ibid.* p.8
[348] *Ibid.* p.8-9

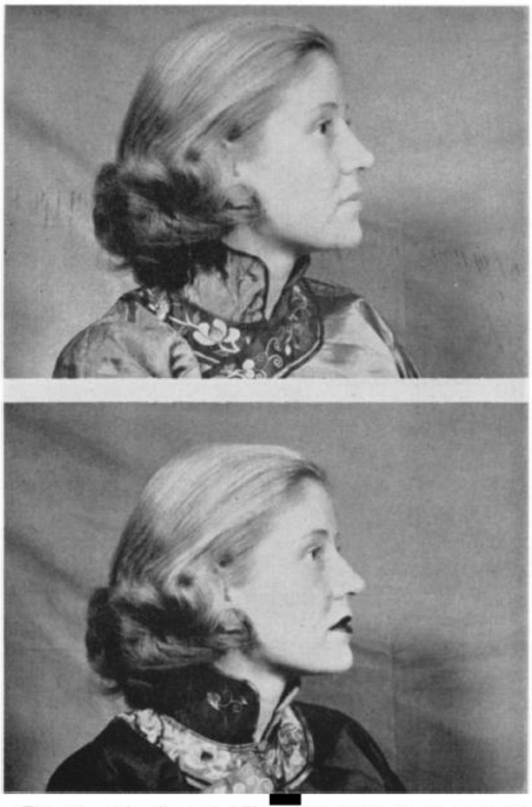

FIG. 3.—Blonde girl (Experiments 2, 3, 4, and 5). Upper image projected with longer wave-length stimulus; lower image with shorter wave-length stimulus. This applies also to Figures 4, 5, 6, 7, 12, and 13.

Figure 8: Two black and white images (in this case a side profile of a woman) shown – one taken through red filter and one taken through green.[349]

"Color Vision and the Natural Image Part II" was published in April 1959 in the *Proceedings of the National Academy of Sciences*. In this paper Land and colleagues produced charts of what colours could be achieved in images by varying the wavelengths of the long and short records. They were also interested to find out how far apart the two records have to be (in terms of wavelength) in order to create the apparent colours. As the reader can see from Figure 10**,** if the wavelengths of the two records are too similar then no colours are produced. In the graph this is represented by the "achromatic wash" around the x = y line.

It is important to note that when Land referred to long (e.g. "red") filters and short (e.g. "green") filters, these are do not filter just one specific wavelength of light, but rather a range within a limit. As Land noted, "red" and "green" as colours in themselves are irrelevant for producing the effect. All that matters is that the two images be taken with different wavelength bands:

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[349] *Ibid.* p.6

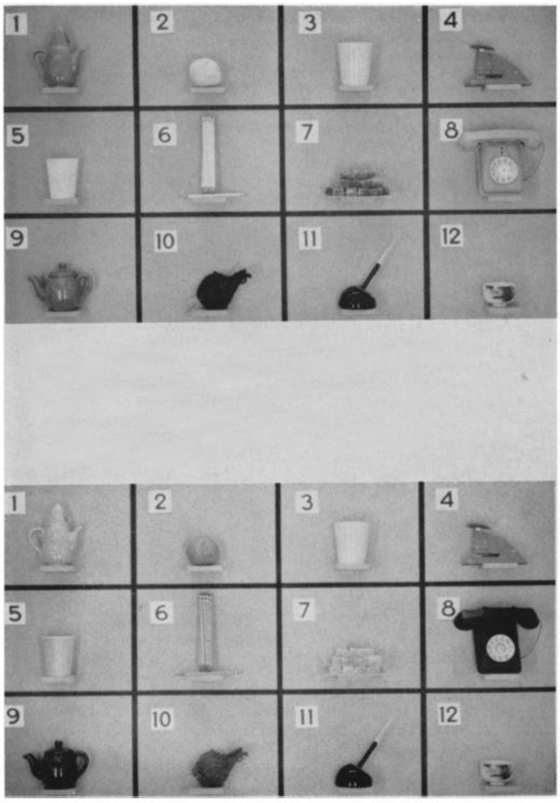

FIG. 5.—Numbered board of standard objects (Experiments 9, 10, and 11)

Figure 9: Experiment 9, designed to eliminate any potential bias that the colours which are traditionally associated with objects would have on the colours that are reported to be perceived.[350]

> When we work with filters, we are not using single wavelengths, but rather bands of wavelengths; the bands have more or less width depending on the characteristics of each filter. It turns out that the width of the band makes little difference. The only requirement is that the long-wavelength photograph, or, as we call it, the "long record," should be illuminated by the longer band and the "short record" by the shorter band. Indeed, one of the bands may be as wide as the entire visible spectrum.[351]

Land was clear that the overall conclusion to be drawn from these experiments was as follows:

> In this experiment we are forced to the astonishing conclusion that the rays are not in themselves color-making. Rather they are bearers of information that the eye uses to assign appropriate colors to various objects in an image.[352]
> …
>
> It appears, therefore, that colors in images arise not from the choice of wavelength but from the interplay of longer and shorter wavelengths over the entire scene.[353]

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[350] *Ibid.* p.7

[351] Land, Edwin. H. (1959). "Experiments in Color Vision" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.21

[352] *Ibid.* p.19

[353] *Ibid.* p.21

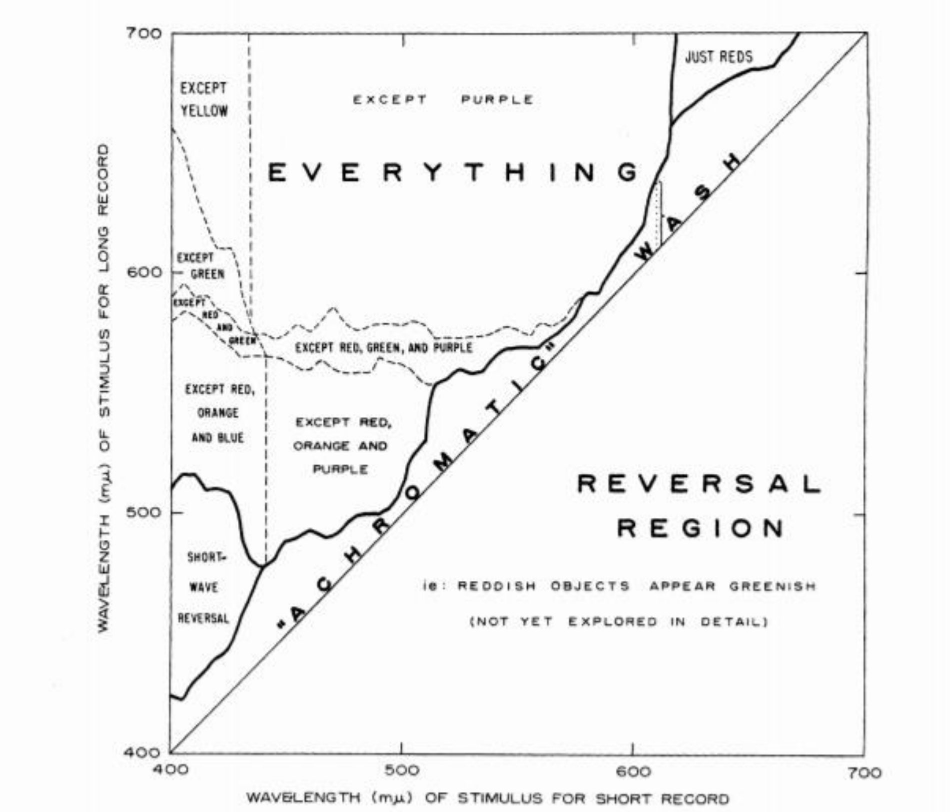

Figure 10: "Range of colors produced by different pairs of wavelengths. "Everything" is used to mean red, orange, yellow, green, blue, purple, brown, black, white and gray. Broken lines are used to define subdivisions in which the range of colors obtained differs only slightly from the gamut in the larger area."[354]

Land had concluded that colours at a point are not completely determined by the wavelength of light coming from that point. They are determined by a comparison between the wavelength at that point, compared to other points over the entire scene. Finding exactly how this spatially comparative mechanism works was a question that would occupy him for the following three decades.

"EXPERIMENTS IN COLOR VISION" PAPER, 1959

This paper – the most famous in the series – caused the biggest "stir" in the established field of colour science. Neither the content of the proposals nor the experiments had changed since

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[354] Land, Edwin. H. (1959). "Color Vision and the Natural Image Part II" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.13

"Colour Vision and the Natural Image". Simply rather, it gained a much larger audience, due to its publication in the May 1959 edition of the *Scientific American*.[355]

After a brief introduction to the experiments, the first section of this paper, entitled, "The Old Theory" explicitly presented a state of affairs in the history of science that Land felt he had overthrown:

> This conclusion is diametrically opposed to the main line of development of color theory, which flows from Newton's experiments. He and his successors, notably Thomas Young, James Clerk Maxwell and Hermann von Helmholtz, were fascinated by the problem of simple colors and the sensations that could be produced by compounding them.
> …
>
> In trying to match colors by mixing spectral stimuli Maxwell and Helmholtz found that three different wavelengths were enough to effect all matches, and that those wavelengths had to be chosen from the red, green, and blue bands of the spectrum. Accordingly, red, green and blue came to be called the primary colors. On the basis of this evidence, they proposed a three-color theory of color vision.
> …
>
> Now, as we have seen in our modification of Newton's experiment, the light at any point on the screen was composed of only two "yellow" wavelengths, yet the image was fully colored. And, as we shall see later, the colors in images will be remarkably stable even when the over-all relative strengths or intensities of the two wavelengths are varied.

What he refers to here as the "main line" of development of colour theory is what I have referred to as the "physical school" of colour, in which the *colour atomism hypothesis* was crucial element.

It is important to appreciate that Land did not have a problem with the idea that there are three kinds of colour receptors in the retina. However, he did have a problem with the idea that colour at a particular point in the visual field is completely and exclusively determined by the responses of the three receptors at that point:

> If one asserts only that there are three kinds of receptors, as Young did, there is little or no experimental evidence against that single property of the Young-Helmholtz theory. If one asserts, as Young and Helmholtz did, that these three receptors work as a simple triplet at a point in the retina, there are a number of experiments that contradict this concept.[356] If one asserts, as Helmholtz did, that the color sensation depends on the relative amounts of red, green and blue light at a point, then a particular red, green, blue ratio must correspond to a particular sensation. There are innumerable experiments from Chevreul in 1837 to the present that show that the relative amounts of red, green and blue light do not uniquely determine color sensations. The proper significance of the red and white experiments, combined with my later three-color experiments is that they show that it is

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[355] Land, Edwin. H. (1959). "Experiments in Color Vision". *Scientific American, Vol. 200, pp. 84-94, 96-99, May 1959.*

[356] Here Land references: G. Westheimer, Spatial interaction in human cone vision, *J. Physiol.* 190, 139 (1967); M. Alpern and W. A. H. Rushton, The specificity of the cone interaction in the after-flash effect, *J. Physiol.* 176, 473 (1965); S.P. McKee and G. Westheimer, Specificity of cone mechanisms in lateral interaction *J. Physiol.* 206, 117 (1970).

> absurd to rely on second order correction factors, as Helmholtz did to explain lack of correspondence between color sensations and the ratio of red to green to blue.[357]

These "absurd second order correction factors" Land refers to here are Helmholtz's theory that the eye somehow "knows" about the properties of the light that are illuminating the scene, and then takes these properties into account to maintain colour constancy – "discounts the illuminant" (as discussed in Chapter Two). Land is clear that the eye does not simply "know" the properties of the light illuminating a scene through "memory colour", as Helmholtz asserted – the eye must work it out, somehow.

In this paper Land explicitly distanced himself from the colour atomism hypothesis:

> Is something "wrong" with classical theory? This long line of great investigators cannot have been mistaken. The answer is that their work had very little to do with color as we normally see it. They dealt with spots of light, and particularly with pairs of spots, trying to match one another. The conclusions they reached were then tacitly assumed to apply to all of color sensation. This assumption runs very deep, and has permeated all our teaching, except for that of a few investigators like E. Hering, C. Hess and the contemporary workers Dorothea Jameson and Leo M. Hurvich (who have studied the effect produced on a colored spot by a colored surround).

In mentioning these last names, Land acknowledged the work of practitioners of what I have called the "phenomenological" science of colour. Later in an appendix to the same paper Land elaborated further exactly what he drew from this "inductive" school (as he called it):

> From the middle of the 17th century to the middle of the 20th there are endless chronicles of amazement about colored shadows, and a variety of speculations about the reality of these colors so remote from the color associated with the wavelengths or wavelength mixtures of the stimuli. The speculations of Guericke, Buffon, Priestley, Rumford, Goethe and Meyer led in this first phase to a solid and extended study by A. Kirschmann in 1890, and to a set of laws embodied in E. B. Titchener's text in 1901, which read as follows:
>
> "(1.) The contrast-effect is always in the direction of greatest qualitative opposition. (2.) The more saturated the inducing colour, the greater is the contrast effect. (3.) The nearer together the contrasting surfaces, the greater is the contrast-effect. (4.) Colour contrast is at its maximum when brightness contrast is eliminated. (5.) The contrast effect is enhanced by the elimination of contours."
>
> Now some of these laws survive in the image situation, but many of them do not. None of them is in any sense a quantitative guide. We simply do not understand how anyone can suggest that these vague statements, largely inaccurate for images, having no quantitative components whatsoever, can be combined with the simple, rigorous, meticulous rules of color-mixing to produce a new arithmetic for predicting color in images.

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[357] Land, Edwin H. (1972). "On Edwin H. Land's Retinex Theory" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.93

> We believe that the reason induction did not develop into a science is that those who explored it tended to use what we regard as greatly oversimplified situations.[358]

Land's speculation as to why the "inductive"/ "phenomenological" school did not "develop into a science" is interesting. As we saw in Chapter Two, the phenomenological school was really just a collection of individual practitioners, spread over approximately two centuries, who observed phenomena which called into question the colour atomism hypothesis of the "physical" school. We can see from passages like this that Land had a particular vision of what constituted a "science".[359]

CONTEMPORARY RESPONSE – JUDD

Turner (1994) described Land's experiments as raising "furor" among colour science specialists in the early 1960s.[360] Among these specialists was the eminent colorimetrist Deane B. Judd (1900-1972), who responded to Land's 1959 *Scientific American* article with an article published in the *Journal of the Optical Science of America* :

> An analysis of the results of Land's experiments with two-primary color projections has been carried out in terms of the known phenomena of object-color perception. It is shown that no new theory is required for the prediction of Land's result that two-primary color projections can produce object-color perceptions of all hues; nor for his result that many choices of pairs of primaries yield substantially the same object-color perceptions. Land's hypothesis that when the colors of the patches of light making up a scene are restricted to a one-dimensional variation of any sort, the observer usually perceives the objects in that scene as essentially without hue, is new; several special cases of it are supported by previous work as well as Land's. This hypothesis deserves the serious attention of research workers in object-color perception.
>
> …
>
> It is nevertheless remarkable that in a few years of intensive study Land, and his associates, should have been able to rediscover independently so large a fraction of the known phenomena of object-color perception, and it is not too surprising that he should have been led by them to the false hypothesis that color in images cannot be described in terms of wavelength.[361]

Judd seemingly dismissed much of Land's work as merely a "rediscovery" of the known phenomena of colour vision. In Land's response to this critique, published in the *Journal of the*

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[358] Land, Edwin. H. (1959). "Experiments in Color Vision" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), pp.33-34

[359] I direct the reader to *Volume II* of Edwin Land's Essays, for a greater insight of how Land saw his own discipline: *Edwin Land's Essays. Volume II. Science, Education and Industry.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993)

[360] Turner, R. S. (1994), p.297

[361] Judd, Deane. B. (1960). "Appraisal of Land's Work on Two-Primary Color Projections". Journal of the Optical Society of America. Vol. 50, Issue 3, pp. 254-268 (1960), p.254

Optical Society of America in March 1960, Land claimed that Judd had interpreted his experiments in terms of irrelevant already-discovered phenomena:

> … the references which Dr. Judd cites, when read carefully, will be found to deal chiefly with phenomena such as after-images, successive contrast, retinal adaption, and eye motion. Our experiments have shown such phenomena to be of no importance in the initial and primary operation of the color forming mechanism.[362]

Indeed, as we have seen, Land showed that after-images and retinal adaption play no part in creating the apparent colours of his two-colour experiments (see Experiment 4 above).

Later – in 1962 – Land published a further paper which directly addressed Judd's criticisms. The experiments in this paper were designed to disprove the idea that the colours in the original red-white projection experiments came about as a result of retinal fatigue, which is of course a *time dependent* phenomenon. Land concluded that:

> … the field phenomena which, in our opinion, produce and determine color are activated instantaneously and do not depend on fatigue and adaption. The mechanism which produces the greens, blues, browns, blacks, grays, and oranges in a picture projected with only red and white stimulation is ready, waiting to act immediately after it is stimulated. It does not depend on some previous stimulation to change its state before it can operate to produce all this. It does not adapt; it simply acts.[363]

As we have seen in Experiment 4 above, Land and colleagues were sure that the mechanism that acts to discount the illuminant – and achieve colour constancy – acts instantaneously.

However, Land did seem to concede to one point of Judd's criticism. As we have seen, Judd criticised Land's statement that "color at a point in an image is independent of the wave-length composition of the radiation coming from that point" [364], maintaining that it is a "false hypothesis that color in images cannot be described in terms of wavelength".[365] In response, Land moderated the *absolute* language of his statement, maintaining that "the colors at each point in the projection of a pair of images are *largely* independent" of wavelength.[366] What he had meant, he maintained – although perhaps he had not expressed it very well – was that colour is not *completely* determined by the wave-length composition of the radiation coming from a point in the visual field.

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[362] Land, Edwin. H. (1960). "Some Comments on Dr. Judd's Paper" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.35

[363] Land, Edwin. H. (1962). "Colors Seen in a Flash of Light" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.47

[364] Land, Edwin. H. (1959). "Color Vision and the Natural Image Part I" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.8

[365] Judd, Deane. B. (1960). "Appraisal of Land's Work on Two-Primary Color Projections". Journal of the Optical Society of America. Vol. 50, Issue 3, pp. 254-268 (1960), p.254

[366] Land, Edwin. H. (1960). "Some Comments on Dr. Judd's Paper" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.35

DEVELOPMENT OF RETINEX THEORY

TWO OR THREE RECEPTOR SYSTEMS?

We can see from the *Experiments in Color Vision* paper of 1959 that at this stage Land and his colleagues were working with the hypothesis that colour at a local point was determined by comparing "long" and "short" bands of wavelengths.

> If the eye perceives color by comparing longer and shorter wavelengths, it must establish a balance point or fulcrum somewhere in between, so that all wavelengths on one side of it are taken as long and all on the other side as short.
>
> …
>
> From the dual-image experiments we learn that what the eye needs to see color is information about the long and short wavelengths in the scene it is viewing. It makes little difference on what particular bands the messages come in. The situation is somewhat similar to that in broadcasting: The same information can be conveyed by any number of different stations, using different carrier frequencies. But a radio must be tuned to the right frequency. Our eyes are always ready to receive at any frequency in the visible spectrum. And they have the miraculous ability to distinguish the longer record from the shorter, whatever the frequencies of the band-widths. Somehow they establish a fulcrum and divide the incoming carrier waves into longs and shorts around that point.[367]

As we saw in Chapter One, the pioneers of the trichromatic theory had come to the conclusion that there must be three "particles" which determine the colour at a single point on the retina. In this paper Land and his colleagues seemed to question this idea:

> In our experiments we provide a single photograph averaging all the long wavelengths and a single photograph averaging all the short. What happens in the real world, where the eyes receive a continuous band of wavelengths? We are speculating about the possibility that these wavelengths register on the retina as a large number of individual color-separation "photographs," far more than the three that Maxwell thought necessary and far more than the two that we have shown can do so well. The eye-brain computer establishes a fulcrum wavelength; then it averages together all the photographs on the long side of the fulcrum and all those on the short side. The two averaged pictures are compared, as real photographic images are compared in accordance with our coordinate system.[368]
>
> … it should be the burden of the classical color-triangle to predict the color at each point on the basis of the ratio of these three stimuli. But the composite colors that we actually see have no theoretical home until we introduce an idea that Thomas Young thought relevant: Extended areas of the retina are significant in determining the sensation for each point in the image. Thus far no theoretical rationale has been available to take us from the color triangle and its arithmetic to a description of the sensations produced in an image consisting of two packages of information.[369]

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[367] Land, Edwin. H. (1959). "Experiments in Color Vision" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.29

[368] *Ibid.* p.29

[369] *Ibid.* p.32

We must appreciate that at this point the "trichromatic theory", although the dominant model for physically mixing light, was not completely established as the *physiological* basis for human colour vision. As we saw in Chapter One, it was only in 1956 that Gunnar Svaetichin identified three kinds of cone cells with peak sensitivities to "red", "green" and "blue". It would be a while before this discovery became "textbook-worthy" scientific canon material. Indeed, at this stage Land seemed not to understand the necessity for a third system:

> We have demonstrated that the eye can do almost anything it needs to do with these two packages. The significance of what a third package will add is far from obvious. We are building a triple imaging-illuminating mono-chromator to find out.[370]

However, he was still open at this point to speculating what this third package could do:

> A third picture may provide better information at the photographic level or an additional and useful interaction with the stimuli from two images. However, there is not a very big gap in the sensation scale to be filled by the third picture. In a given image a particular combination of two stimuli might not provide an electrically intense blue or a delicately yellowish green, but it is still likely to provide more than enough for the animal to live with. Nevertheless we do expect the richness of many colors will be increased by the interplay of a third stimulus. Whatever we learn by adding a third picture, the visual process will remain an amazing one from the evolutionary point of view. Why has a system that can work so well with two packages of information evolved to work better with three? And who knows whether it will not work better still with four, or five or more?
>
> What does the eye itself do in the everyday world of the full spectrum? Does it make only two averages? Or does it put to better use the new ability to distinguish sharply between images at closely spaced wavelengths? Perhaps it creates many sets of averages instead of just two or three.
>
> Even if more than two information channels are used, we feel that the big jump is obviously from one to two. Most of the capability of our eyes comes into play here. And whatever may be added by more channels, the basic concept will remain. Color in the natural image depends on the random interplay of longer and shorter wavelengths over the total visual field.[371]

There are two interesting points to draw from this passage. First is the use of language in the last sentence – "color in the natural image depends on the *random* interplay of longer and shorter wavelengths over the total visual field." Such imprecision would disappear after Land addressed criticisms of his article from the likes of Deane B. Judd, and later when he developed the retinex theory.

Second, this passage is the key to understanding the rationale for why a third system may be required. Land stated two systems were "still likely to provide more than enough for the animal to live with", but this begged the question – what does a particular animal need to survive in its

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[370] *Ibid.* p.29
[371] *Ibid.* p.30

particular environment? There are human dichromats – "colour-blind" people – who live perfectly full and unhindered lives. Some even go their whole lives without ever noticing that they are "colour-blind". Distinguishing between "red" and "green", for example, may be crucial to the survival of some animals, but not to others. We can see here that Land's work raised a further question in another field – evolutionary biology – namely the question of why humans evolved from dichromats to trichromats.

THE THREE CHANNEL RETINEX

The term "retinex" (a compound of "retina" and "cortex") was first coined in Land's RESA William Proctor Prize address in Cleveland, Ohio, on December 30, 1963. A paper based on this address was published in the *American Scientist* in 1964 entitled "The Retinex". In this paper Land introduced a three-channel model to explain the results of his original red-white projection experiments. He started with a reference to the history of the three-channel model:

> We began by accepting the kind of ideas which were initiated by Thomas Young and carried on through the work of Helmholtz and Hering to such present day studies as those of DeValois, Hubel, Wiesel, Rushton, and MacNichols. All of these experimenters concluded that the retina contains receptors having peak sensitivities in different portions of the visible spectrum. In general they hypothesized that there were peaks in the regions of approximately 600, 550, and 470 mμ and that the response curves for these receptors overlapped each other widely. Some of the later experimenters proposed that there were also what are called "opponent-type" receptors, namely, sensitive end-organs connected to cells which simultaneously give an affirmative response to the presence of energy at certain wavelengths and a denial response to its absence at other wavelengths. There is so much reason and logic in these attitudes towards the visual system, that it seems certainly desirable to accept them.[372]

We can see then that the basis for Land's movement towards a three channel system was the combination of (1) the fact that a slightly greater depth of colours could be produced by three pictures (see last section), and (2) the fact that the physiological evidence pointed to the existence of three response curves.

As we can see from the passage above, Land acknowledged the logic of the idea that there is an "opponent" system which could explain the phenomena of colour constancy and simultaneous colour contrast. However, he believed that the results of his whole field visual experiments would

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[372] Land, Edwin. H. (1964). "The Retinex" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.53

be better explained if there were three sets of *whole field* receptor systems, rather than localised colour opponency as Ewald Hering had advocated:

> We have found it fruitful, however, to go somewhat beyond these ideas and would like at this time to suggest that these receptor systems exist in sets. We would propose that all of the receptors with maximum sensitivity to the long waves in the spectrum, for example, operate as a unit to form a complete record of long-wavelength stimuli from objects being observed. (For convenience of reference let us call this suggested retinal-cerebral system a "retinex.") For us, having made this one assumption, many of the problems of colour vision were enormously simplified. It then became possible to predict color in a way which formerly had been impossible. Even more important, we wish to show that, on this new basis, an entirely different rationale comes into the understanding of color vision. Curiously, color vision itself becomes such a "simple" phenomenon that the mystery and wonder of it is shifted to another domain: the domain of the perception of lightness. Much of what we will discuss in this paper, then, will be the subject of lightness, after which we will show how simply the concept of color vision is arrived at through the hypothesis that these receptor systems exist separately.[373]

Land's concept of lightness is that the eye takes three "pictures" of a scene – three "retinexes". One picture with the long wave ("red") cone system, one picture with the middle wave ("green") cone system, and one picture with the short wave ("blue") cone system. Every point (or in modern terms, "pixel") in the visual field will thus have a lightness value for long, middle, and short waves respectively. For example, the lightness value for the long ("red") record at a point in the scene is determined by the intensity (or "reflectance") of red light coming from that point relative to the intensity of red over the entire scene.

> When, instead of looking at a black and white picture, we look at the world of color around us, the image produced by each of the proposed retinexes differs in terms of lightness from the image on each of the other retinexes, as we exemplified when we looked at the world through the succession of narrow band filters. Each retinex system will form an image in terms of lightness corresponding geometrically to the optical (i.e., physical) image on the retina. Thus, there will come into being the analogue of superposition of the optical images: somewhere in the retinal-cerebral system there will exist three images in terms of lightness which have a relationship that corresponds to having three optical images on top of each other.
>
> …
>
> These three positions are established quite independently: what happens on one retinex has nothing to do with what happens on another retinex (in the extreme pedagogical statement of the issue.) The position in lightness, or what we will refer to as the "rank order," which the given object occupies on a particular retinex is determined by the rank order of all the other objects on that retinex. And all of the positions of rank order for that retinex are determined mathematically by the interaction of the spectral absorption curve of the receptors for that retinex with the spectral absorption curves for all the objects in

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[373] *Ibid.* p.53

> the field of view. Thus, the very meaning of lightness for our given object is the interplay of all the stimuli and all the sensations for that retinex.[374]

Once the three lightness values have been calculated for a point, a colour can be assigned to it. A three-dimensional colour space is defined by the three lightness values:

> Essentially, our hypothesis is first, that the retinexes exist; second, that they draw their conclusions independently; and third, that it is the comparison of these three separate conclusions for the single object that gives the sense of color. Color is the correlation number for several rank orders of lightness. If we assign a number, for example, to each lightness position in each image on each of the retinexes, then the color of an object can be stated in terms of three digits, each of which expresses the lightness of a given object on its respective retinex.
>
> …
>
> At first, this hypothesis does not seem remarkably different from that which would be classically expected from the elementary Young-Helmholtz approaches to color. It is only when one examines the extraordinary stability of the lightness scale for each of the retinexes, that one comes to realize how this idea diverges entirely from the classical point-by-point study of color vision. In classical studies, one is concerned with the mixing of energies at various wave lengths. In this approach, one is concerned not with mixing energies, but with correlating lightnesses – whatever their associated energies happen to be.[375,376]

It is also in this paper that Land introduced his famous “Mondrian” demonstrations. They were so named because the test boards of colours resembled the paintings of the Dutch artist Piet Mondrian (1872-1944) (See Figure 11). Land used such “Mondrians” in public demonstrations to show how two different patches of colour (for example green and brown) could be made to reflect exactly the same ratios of light wavelengths (the same relative amounts of red, green, and blue light), and yet appear to the eye to retain their respective colours. When the patches of colour were isolated however (by blocking the other colour patches in the surround), the patches *did* appear to be the same colour.[377] The Mondrian experiment is a simple and effective demonstration of colour constancy, and highlights that the ratio of wavelengths at a point is not relevant for determining colour. It is the three lightness values, *not* the ratio wavelengths which determine colour at a point.

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[374] *Ibid.* p.54

[375] *Ibid.* p.54

[376] It is interesting that Land referred to the colour atomism hypothesis as the “classical” theory of colour vision. In physics, “classical physics” refers to physics which does not involve quantum physics and the theory of relativity – i.e. Newtonian mechanics. It suggests that Land (rather modestly) saw his step as big a change in vision science as the transition from “classical” to “modern” physics.

[377] This is analogous to Count Rumford’s “coloured shadow” experiments in Chapter Two. Rumford had used a darkened tube to isolate the “coloured shadows” and reveal that a “blue” coloured shadow was actually “grey” upon closer examination.

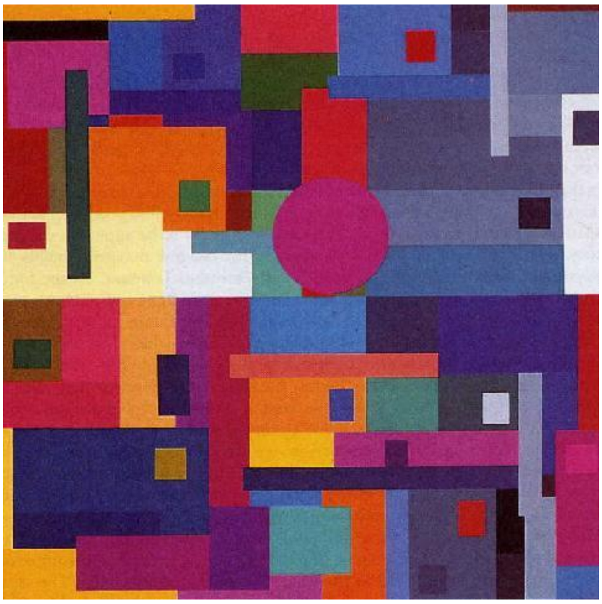

Figure 11: "Now suppose we replace the "Mondrian" made of grey strips with a board made with coloured papers. (I recommend papers for which the reflection density for either component is not greater than 1.0. They still give plenty of colour, and it keeps one from being involved in the problems of surface light.) Using such papers, with matt finishes, we made up a "Mondrian" comprising yellows, reds, greens, browns, blues, whites, pinks, in a gorgeous display which one may recommend to any pedagogue because it will hold the class's attention even if the lecture does not." [378] Image: "Mondrian" test slide from Land's experiments.[379]

In a 1970 paper Land gave another clarification of the concept of lightness:

> Lightness is the family of sensations from white to black that a person sees. Lightness is the output of a biological system. It is a sensation. There is no physical definition for lightness because it is not necessarily related to a physical quantity of light from a point, either in radiometric terms or photometric terms.[380]

Lightness is simply a value that is calculated for a point for each of the three retinexes. When we have three values for lightness at a point for all three retinexes, the colour to be perceived at that point can be determined. Land illustrated this by constructing three-dimensional colour-solids:

> Color can be arranged in the lightness solid with long-, middle- and short-wave axes of lightness. All visible colors reside in this solid independent of flux. each color having a unique position given by the three axial values of lightness. It should be remembered that the reality of color lies in this solid. When the color Mondrian is nonuniformly illuminated.

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[378] Land, Edwin. H. (1965). "The Retinex – Ciba Foundation Symposium on Color Vision" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.62

[379] Campbell, F.W. (1994). "Theory of color vision". < https://www2.rowland.harvard.edu/book/theory-color-vision > accessed 15 July 2020.

[380] McCann, John J., Land, Edwin H., and Tatnall, Samuel M. (1970). "A Technique for Comparing Human Visual Responses with a Mathematical Model for Lightness" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.85

> photographed and measured, reflectance in the photograph no longer correlates with the color but the lightness does. The three sets of ratios of integrals at edges and the product of these integrals within a set emerge as the physical determinants in the partnership between the biological system and areas in the external world.[381]

As we have seen, the lightness value at a particular point for a particular retinex is determined by the reflectance at that point "relative to the entire scene". Land and colleagues' next venture was to determine how this spatial comparative mechanism operated.

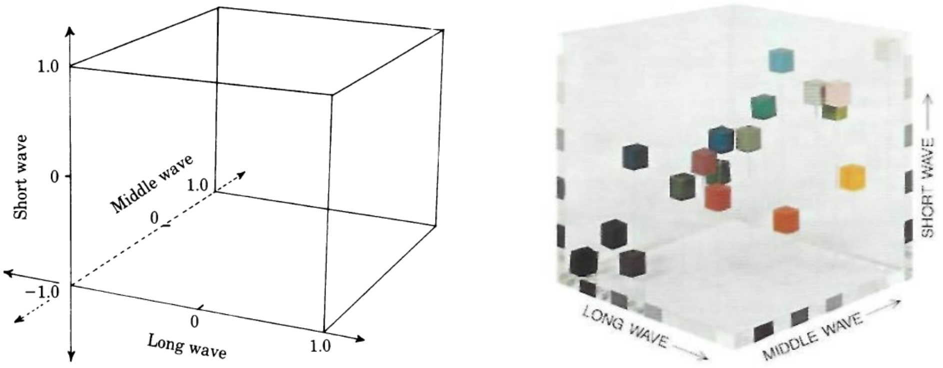

Figure 12: A simple early "color solid" shows the location of all perceivable colours, including white and black, in a three-dimensional colour space constructed according to Land's retinex theory. [382]

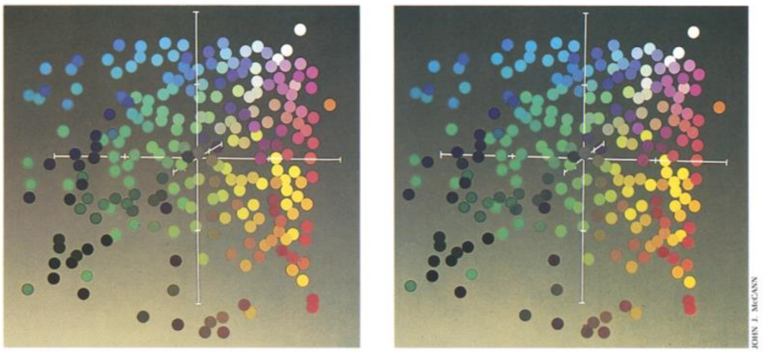

Figure 13: "The color three-space. Stereoscopic pair representing the left-eye view (Left) and the right-eye view (Right) of the color three-space populated, as indicated by designator theory, with dots of Color-Aid papers." [383] Note that black, grays, and white fall on a diagonal running from lower left to upper right.

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[381] Land, Edwin. H. (1977). "The Retinex Theory of Color Vision" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.141

[382] *Ibid.* p.139

[383] Land, Edwin. H. (1983). "Recent Advances in Retinex Theory and some Implications for Cortical Computations: Color Vision and the Natural Image" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.163

A MACHINE TO IMITATE NATURE

As we have seen, the original experiments detailed in the "Color Vision and the Natural Image" paper of 1959 produced results which were incommensurable with the colour atomism hypothesis. Land's original project had been to try and explain the discrepancy between the colour atomism hypothesis these observed phenomena.

Between the publication of this paper and the "Retinex" paper of 1964, Land and his colleagues started to think of colour vision as an engineering problem. As we saw in the section above entitled "Two or Three Receptor Systems?", this project was to build up a model from first principles to explain how the eye and brain achieves colour constancy. At first it seemed that two "retinexes" (dichromacy) would suffice for the practical needs of an animal, then Land saw the advantages of having three retinexes. This was a "bottom up", engineer's approach to the problem – once a theoretical solution had been reached that seemed elegant and efficient, it was put to the test to see if the theoretical solution had been the same one used by "nature's engineer".

The following passage from the 1971 paper "Lightness and Retinex Theory" is characteristic of this way of thinking:

> Most of us assume that, subject to a variety of compensatory factors, we see in terms of the amount of the light coming from objects to our eye; we think that in a particular scene there is more light coming from white objects than from black objects; we think there is more long-wave light (so-called red light) coming from red objects than from blue objects. Yet, when we measure the amounts of light in the world around us, or when we create artificial worlds in the laboratory, we find that there is no predictable relationship between flux at various wavelengths and the color sensations associated with objects. Accordingly, we believe that the eye must have evolved a system which, though using light as the communication medium with the world, has become as nearly independent of energy as is biophysically possible. In short, color sensations must be dependent on some as yet undefined characteristic of the field of view, a characteristic that can be communicated to us by the light with which we see, even though the amount and composition of the light are everywhere variable and unpredictable; the eye must have evolved around such a permanent characteristic of the field of view. This paper describes our search for that characteristic.
>
> As every photographer knows, the sun and sky produce every conceivable combination of sunlight and skylight. Even less uniform illumination is provided by artificial light because the distance from the light source drastically affects the illumination falling on any point. We are then left with the circular logical problem that, because the light coming to our eye is the product of the reflectance and illuminance, our eye could not determine reflectance unless the illuminance is uniform and the eye could not determine illuminance unless the reflectance is uniform.[384]

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[384] Land, Edwin. H. and McCann, John J. (1971). "Lightness and Retinex Theory" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.73

To highlight the need for "nature's engineer" to come up with a solution, Land imagined perceiving the world without the benefit of a colour constancy mechanism:

> The experience of seeing objects cannot depend on the quantity and composition of the radiation scattered by them to our eyes because objects would then vary in appearance as the radiation changed. An object could not have a permanent colour; its colour would be always changing, so that an apple might be the colour of blueberries at one moment and of oranges at another.[385]

Colour constancy brings order to an otherwise chaotic visual world. Without colour constancy, the perceived colours of objects would constantly change as the illumination changed. Land explicitly acknowledged that retinex theory was a "machine" designed to solve this problem:

> My view of evolution is that biological systems do not solve problems but rather evolve in a way such that problems do not arise. The eye-brain system must have evolved in such a way that illumination and its unpredictability do not enter into its determination of lightness. How does the eye-brain do it? In trying to understand how, let us follow Einstein's programme: To understand a natural phenomenon keep inventing a series of machines until you arrive at one with properties that match those of the particular natural domain. Explanation in science can be regarded as the successful search for such a machine – a machine which will serve as a model until it is displaced by requirements imposed by further knowledge. We can invent for the machine a procedure which determines reflectance without ever knowing or involving the value of illumination, a procedure which permits the illumination to be unknown and unknowable.[386]

This is very interesting from a philosophy of science perspective. For Land the job of a scientist was to invent "machines" which imitate nature. The closer your machine is to producing the same result as nature, the more likely the mechanism of your machine is to be a true reflection of the "machinery" of nature. In this view, "science" was a form of engineering. This is the exact opposite to the common adage that engineering is "applied science".

Land made a specific analogy with colour photography in this respect. The eye must account for the illuminant automatically in the way that a skilled photographer knows which film (which specific white balance) to use to accurately reproduce the colours in a scene:

> Paradoxically the modern technology of color photography has reinforced the belief that the colors discerned by Newton in the spectrum are, with minor qualifications, the colors of the world around us. We know, for example, that if we use daylight color film when we take a picture in the light shed by an ordinary tungsten-filament lamp, the picture will turn out to have a strong reddish cast. That, we say, is because the rays from the tungsten filament are too "red." never asking how we ourselves can move constantly in and out of tungsten-lit worlds without experiencing any change in the color of familiar objects: apples,

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[385] Land, Edwin H. (1974). "The Retinex Theory of Colour Vision" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.95

[386] *Ibid.* p.99

> lemons, strawberries, bread, human faces (the tones of which are so hard to get right on a television screen).[387]

As Land stated here, we understand that the white balance of a camera must be adjusted depending on the illumination of the scene. In the same way, the "white balance" of the human eye must be adjusted depending on the illumination of the scene. Land's retinex algorithm was the first attempt to understand how the human eye automatically chooses the correct white balance for every scene. In this way, Land argued, we should see the retinex algorithm as a "machine" that was constructed to solve the same problem that the human eye has to solve.

THE IMPORTANCE OF EDGES

After establishing the idea of the retinex in the 1964 paper, the next issue for Land would be to understand how the spatial comparative mechanism worked – i.e. how lightness values were calculated at a particular point for the three retinexes.

In the 1964 paper Land did not exclude the idea that Hering-style opponent mechanisms could form part of each retinex:

> We are not urging that the retinal elements with the same peak sensitivity have to be directly connected to each other, but rather that, in the retinal-cerebral liaison, those elements with the same peak sensitivity cooperate to form a mechanism that has the capacity to establish an image. (Incidentally, this theory does not imply that "opponent-type" receptors are not utilized; to the contrary, the presence within our proposed sets of receptors of denial responses as well as of affirmative responses would only serve to strengthen the suggested reaction of these systems.) [388]

In fact, by 1971 Land and colleagues had come to realise that edges between adjacent patches of colour were crucial in computing the correct lightness value:

> Given a procedure for determining the ratio of reflectances between adjacent areas, the next problem is to obtain the ratio of reflectances between any two widely separated areas in an entire scene. We solve the problem in the following way: Find the ratio of luminances at the edge between a first and a second area, and multiply this by the ratio of luminances at the edge between the second and a third area. This product of sequential ratios approaches the ratio of reflectances between the first and third areas, regardless of the distribution of illumination. Similarly, we can obtain the ratio of reflectances of any two areas in an image, however remote they are from each other, by multiplying the ratios at all the boundaries between the starting area and the remote area. We can also establish the

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[387] Land, Edwin H. (1977). "The Retinex Theory of Colour Vision" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.125

[388] Land, Edwin. H. (1964). "The Retinex" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), pp.53-4

> ratio of the reflectance of any area on the path to the reflectance of the first area by tapping off the sequential product at that area.[389]

An illustration of this can be seen in Figure 14.

We can see now how an algorithm could be developed for computing the ratio of reflectances for any particular patch of colour. Land and colleagues developed a mouse tool called a "bridge photometer" – much like a modern computer mouse but with a photometer instead of a sensor – with which they could trace a path through an image, detect reflectance values, and calculate the ratio of reflectances for the patch at the end of the path. After a number of paths (usually 20 or more) had been drawn through the Mondrian, starting at different random patches, and ending at the same patch, a lightness value could be calculated for that patch by averaging the ratio of reflectances obtained for all the paths. Once the three lightness values were calculated for a particular patch of colour, the colour perceived at that point could be predicted (with remarkable accuracy and reliability) by using the lightness values as coordinates in Land's 3-D colour space.

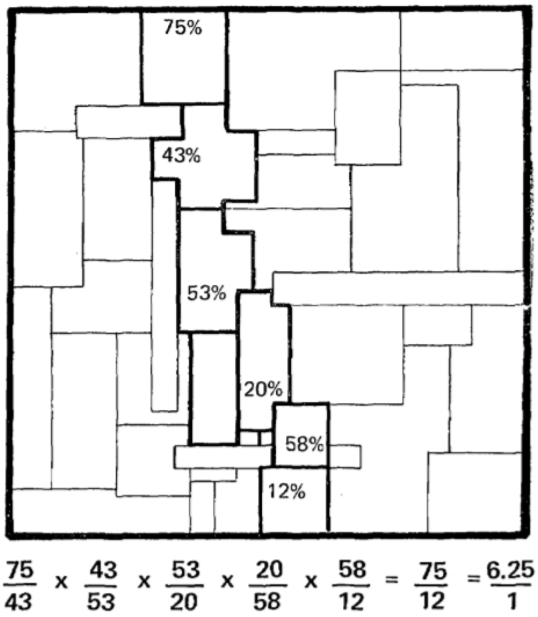

Figure 14: "Reflectance along one path between the top and the bottom of a black-and-white Mondrian. The numbers at the bottom indicate the ratios of reflectances at adjacent edges along the path." [390]

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[389] Land, Edwin. H. and McCann, John J. (1971). "Lightness and Retinex Theory" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.77

[390] *Ibid.* p.77

Land and colleagues acknowledged the limitations of the bridge photometer as a tool. Of course, the real visual world is not made up of discreet patches of uniform colour as represented in the model in Figure 14. Real world visual scenes are populated by gradations of colour change.

> The actual biological path, however, must be reading ratios not only across edges between areas of markedly different reflectances, but also as it traverses areas in which the change from point to point is only the small change due to graded illumination. These small changes must not be summated and incorporated in the sequential product since this would raise and lower the lightness of the various areas in response to the vagaries of variable illumination. All of the derivations you will see tonight are based on the presumed availability of biological detectors which cannot read gradients smaller than some threshold value. The bridge photometer cannot detect the small differences caused by gradual changes in illumination. The net result is that the sequential product of bridge photometer ratios for each area is the same as the sequential product of the bridge reading which would have been taken only at the edge.
>
> It must be kept in mind that these operations are the properties of a machine model of the visual system and that such a model is distinct from the actual visual system.[391]

The bridge photometer and the algorithm above was a simple model which worked for predicting colour in a simple simulated world. As Land acknowledged here, the human visual system of course has even more complex retinex algorithms, adapted to a complex visual world.

The Mondrian slides and the bridge photometer were a proof of principle. The next task of the retinex research program was to create more complex algorithms which could predict colour in more complex visual scenes, especially those involving gradations of colour. This is a task which continues to this day.[392]

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[391] Land, Edwin H. (1974). "The Retinex Theory of Colour Vision" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.101

[392] McCann, John J., Rizzi, Alessandro. (2011). *The Art and Science of HDR Imaging.* (John Wiley & Sons).

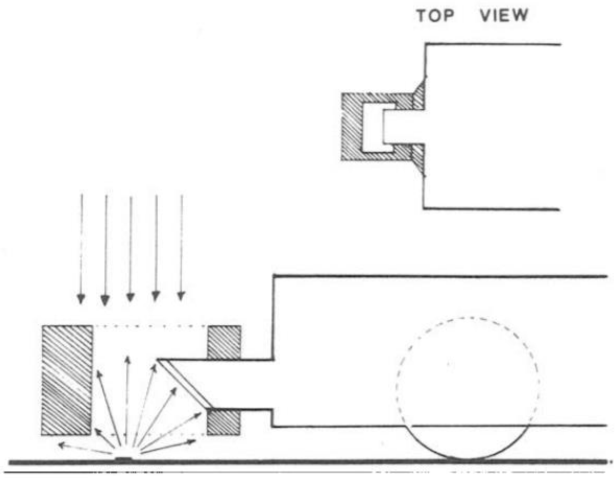

Figure 15: "Diagram of an optical mouse. The rectangular aperture in top view (right) rests on the surface of the collage or screen. The projected radiation passes through the aperture to the surface where it is scattered back toward the (sloping) photosensitive element. A large number of rapid readings are integrated and read into the minicomputer every third of an inch of travel".[393]

RETINA OR CORTEX?

By the 1980s, retinex theory had captured the attention of practitioners outside the narrow field of colour science. In 1983 Land published a paper in collaboration with the Nobel-prize winning neurophysiologist David H. Hubel (1926 – 2013). Hubel had won the Nobel Prize in Physiology or Medicine alongside his colleague Torsten Wiesel in 1981 for the discovery of "ocular dominance columns" and visual cortex neurons which acted as edge detectors, motion detectors, colour detectors, and stereoscopic depth detectors.

This paper attempted to pinpoint the location of the retinex processing mechanism. With the help of the neurologist Norman Geschwind, the researchers obtained a subject whose corpus callosum had previously been severed in a surgical procedure.[394] As we know from basic neuroanatomy, the left side of the visual field (for both eyes) is relayed to the visual cortex of the right cerebral hemisphere, and the right side of the visual field (for both eyes) is relayed to the visual cortex of the left cerebral hemisphere. The researchers' hypothesis was that "if the site of the computation is indeed cortical, events in one visual half-field should have no influence on the appearance of objects in the other half-field. If an influence is found, the computation responsible for that must

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[393] Land, Edwin H. (1986). "Recent Advances in Retinex Theory" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.176

[394] The corpus callosum is the neural "bridge" which connects the left and right cerebral hemispheres. It is the only way the two hemispheres can communicate.

be retinal".[395] This is because in this subject, the only neuro-anatomically possible opportunity for one half of the visual field to influence the other would be at the retinal level, before the two halves of the visual field diverge at the optic chiasm. The researchers found that:

> Since J.W. gave normal responses when the Mondrian was in his right visual field, his visual system is clearly capable of generating the long-range interactions that occur in a normal observer. What he failed to do was to transfer the information which would enable him to make a computation based on the whole field of view across the vertical midline. Therefore the calculation could not have occurred solely or largely in the retina and must have occurred in the cortex, where regions representing the two halves of the visual field are joined by the corpus callosum.[396]

The conclusion was that the retinex operation occurs at a cortical level – thus "retinex" should be read as more "cortex" than "retina". This conclusion was backed up by neurophysiological experiments carried out by Semir Zeki (1940 –) at University College London on cells in the primary visual cortex of the rhesus monkey.[397]

THE LIMITATIONS OF RETINEX THEORY

In 1982 Land was forced out of Polaroid by the company's board of directors, largely due to the disastrous losses the company incurred investing in its unsuccessful "Polavision" home video system. He paid for the construction of a new laboratory in Cambridge Massachusetts which he named the Rowland Institute, and for the last decade of his life dedicated much of his time there to enhancing the retinex model.

There are certain limitations to Land's original retinex algorithm which have been addressed in the years since. We have seen that the retinex algorithm works well for predicting colours in scenes populated with a large variety of different wavelength reflectances. However, there are obvious questions that come to mind – for example, how is it that we still see the Grand Canyon as coloured "red" when we go down deep inside, when nothing else is in our visual field?

It seems that Land's original retinex algorithm works for the limited case where we have scenes populated with great variety.[398] Some other moderating mechanism must come into play in scenes

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[395] Land, Edwin. H., Hubel, David H., Livingstone, M. et al. (1983). "Colour-Generating Interactions Across the Corpus Callosum" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.155

[396] *Ibid.* p.158

[397] Land, Edwin H. (1983). "Recent Advances in Retinex Theory and some Implications for Cortical Computations" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.166

[398] Brainard, David H. and Wandell, Brian A. (1986). "Analysis of the retinex theory of color vision," J. Opt. Soc. Am. A **3**, 1651-1661 (1986)

without great variety. Maloney and Wandell's research suggested that Land's insistence that the three retinexes work *completely* independently of one another, at all times, may be unfounded.[399] In addition, the spatial extent over which a colour in the scene affects the appearance of others seems to be more variable than Land's original algorithm suggested, and may operate on multiple levels of spatial resolution.[400] Despite its limitations, the retinex model was – as the seminal textbook *The Science of Colour* describes – "the first computational model of colour constancy to attract widespread attention".[401] Research on computational models of colour constancy continues to the present day.

RETINEX AND THE PHENOMENOLOGICAL SCHOOL

AFTERIMAGES

As we have seen, Land's original retinex algorithm held up well for the case of scenes populated with a sufficient variety of wavelength distributions. Retinex theory is a powerful explanatory tool for shining light on hitherto mysterious observations of the "phenomenological" science of colour.

We saw in Chapter Two that Buffon noticed that coloured afterimages always appear to be the "complementary" colour to the colour that induced them. Following Helmholtz, afterimages have traditionally been explained as a consequence of "retinal fatigue". If this is true, then the colour of afterimages must be the complementary colour to the absolute wavelength value of the colours that caused them. This would be the colour atomism hypothesis model of colour afterimages.

In the context of retinex theory, we may therefore ask the question – are the colours of afterimages caused by the absolute wavelength value of the colours that induce them (as per the colour atomism hypothesis), or are they determined by the same spatial comparative mechanism that operates in normal colour vision? Semir Zeki and colleagues found that the latter seems to be correct:

> We undertook psychophysical experiments to determine whether the color of the after-image produced by viewing a colored patch which is part of a complex multi-colored scene depends on the wavelength-energy composition of the light reflected from that patch. Our results show that it does not. The after-image, just like the color itself, depends on the ratio of light of different wavebands reflected from it and its surrounds. Hence, traditional

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[399] Maloney, Laurence T. and Wandell, Brian A. (1986). "Color constancy: a method for recovering surface spectral reflectance," J. Opt. Soc. Am. A **3**, 29-33

[400] McCann, John J. (1999). "Lessons Learned from Mondrians Applied to Real Images and Color Gamuts", Proc. IS&T/SID
Seventh Color Imaging Conference, pp. 1-8

[401] Shevell, Steven K. (ed.). (2003). *The Science of Color.* (Elsevier), p.185

> accounts of after-images as being the result of retinal adaptation or the perceptual result of physiological opponency, are inadequate. We propose instead that the color of after-images is generated after colors themselves are generated in the visual brain.[402]

If the conclusions of this study are correct, it seems that afterimages are not caused by "retinal fatigue", as Helmholtz believed. Afterimages are of a cortical nature. Colour is generated by the retinex process first, after there is a stimulus at a point in the visual field, and the retinex scheme compensates for this stimulus. Subsequently depriving the scene of this stimulus means that all the viewer is left with is the compensation of the retinex scheme (which is appears as the complementary colour). The retinex process then takes time to remove this overcompensation as it takes in other cues from the visual environment, which accounts for the duration of colour afterimages.

COLOURED SHADOWS

In Chapter Two we saw that Land acknowledged the priority of Otto von Guericke's observation of coloured shadows in 1672:

> Perhaps the first observation pointedly relevant to the mechanism of color formation in images is not Newton's spectrum but the phenomenon of colored shadows, described in 1672 by Otto von Guericke.[403]

In a 1977 paper Land proceeded to reconstruct Guericke's observations and analyse them in terms of lightness and retinex theory:

> "This is how it happens." he wrote, "that in the early morning twilight a clear blue shadow can be produced upon a white piece of paper [by holding] a finger or other object... between a lighted candle and the paper beneath." This important experiment, we now know, depicts an elementary example of generating three different lightnesses on the three receptor systems. A diagram of this experiment with longwave ("red") light and white light appears below. Here the color of the shadow is blue-green. The diagram shows that the triplet of lightnesses in the shadow corresponds to the blue-green color one would predict for it from its position in lightness-color space.[404]

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[402] Zeki, S., Cheadle, S., Pepper, J., & Mylonas, D. (2017). The Constancy of Colored After-Images. *Frontiers in human neuroscience*, *11*, 229. https://doi.org/10.3389/fnhum.2017.00229

[403] Land, Edwin. H. (1977). "The Retinex Theory of Color Vision" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.138

[404] *Ibid.* p.138-140

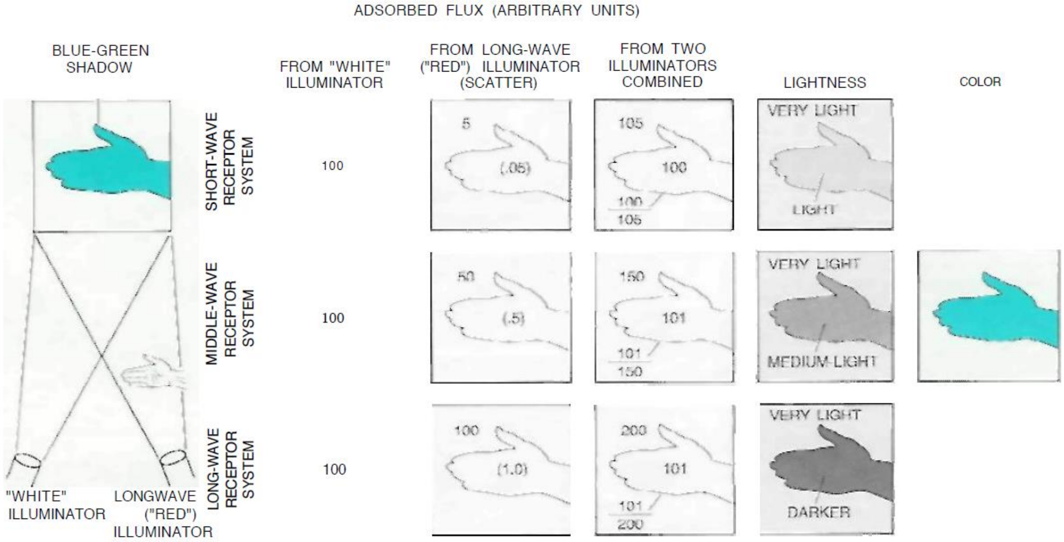

Figure 16: A "Blue-Green Colored Shadow is seen when a hand or some other object is placed in the beam of a projector that is sending longwave ("red") light to a screen while the screen is illuminated by a beam of white light. The author regards Otto von Guericke's description in 1672 of seeing colored shadows made by candlelight as the first observation pointedly relevant to the mechanism of image and color formation. In the analysis at the right it is assumed that one projector sends white light to the screen. The other projector, equipped with a red filter, sends only long wavelengths to the screen. Assume that the white light contributes 100 arbitrary units of flux to each of the short-, middle- and long-wave receptors. The long-wave flux is absorbed by the three receptor systems in different proportions: 100 units are absorbed by the long-wave system, SO by the middle-wave system and five by the short-wave system. (A small amount of scattered longwave light also appears in the shadow.) The third column of boxes shows the combined amounts of flux from both sources absorbed by each receptor system. The fractions represent the ratio at edges of the flux from within the shadow divided by the flux from outside. The fourth column shows the lightness on each receptor system. The lightness of the lightest place in the scene for each receptor system will be near the top of the lightness scale, being determined by the flux of radiant energy in the same way that a spot has its lightness determined by flux. Triplet of lightnesses within the shadow falls in the region of color space that the eye perceives as being blue-green."[405]

As we can see from Figure 16, retinex theory makes the coloured shadow phenomenon simple to explain – even simpler than the Mondrian, since there are only two coloured "panels" to compare. We can also see from this that the "apparent" colours elicited in Land's original two-colour experiments were effectively an elaborate array of coloured shadows.

Thus, another consequence of Land's studies is that the distinction between "apparent" (or "accidental") colours and "real" colours disappears. Both are produced through the same mechanism. If we find the blue colour of a shadow "surprising" then it is only because we are entrenched both in the Newtonian way of viewing light and colour – the idea that shadows are an

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[405] *Ibid.* p.140

absence of light – and the "colour atomism hypothesis" which dictates that the colour perceived at a point cannot be affected by colours in the surround.

As I noted in Chapter Two, the only practitioners who were "amazed" by the phenomenon of coloured shadows were those who had subscribed to Newtonian views of light and colour. Painters such as Leonardo da Vinci, for example, had known that shadows could (and should) be coloured to depict a visual scene accurately.

THE IMPORTANCE OF COLOUR CONSTANCY

To say that an organism has colour vision, it is necessary that it is capable of two things. Firstly, it must have an additional capability that differentiates itself from monochrome vision. For example, dichromats can distinguish (broadly) "yellow" and (broadly) "blue", in addition to distinguishing white light and darkness. In addition to these abilities, trichromats can distinguish all three of (broadly) "red", "green" and "blue" from one another.

Secondly, in order for this colour vision to have any use at all, this organism must have colour constancy. Without it, colour itself would be useless.

> Such a scheme would be an evolutionary failure because the moment-to-moment and place-to-place variations in the composition of illumination in the world around us would change the moment-to-moment wavelength composition of the radiation reaching the retina from the object – and hence would lead to complete unpredictability of the color names characterizing the surfaces of the objects around us.[406]

In other words, the concept of colour would not have a meaningful existence if the colours of objects in the world did not remain constant with changes in illumination. This is clear from the meaning of "colour" in our language. We learn colour terms e.g. "red", "blue", "green", "yellow" etc. as children when our parents/guardians point to objects in the world and say these colour terms, in various contexts. We then learn that the collective term for "red", "yellow", "green" and "blue" etc. is "colours".

Let us imagine a scenario – let's call this Scenario #1 – in which a person is born without colour constancy. As we have seen, for such a person, the colours of objects in the world would constantly change with the illumination of a scene. It would be impossible to learn colour terms, and thus impossible to learn the concept of what a "colour" is.

Let us consider another scenario – Scenario #2 – in which a person lives with colour constancy, learns the concept of colour as normal, and then subsequently loses colour constancy. They would not necessarily lose the concept of colour – just as someone who turns blind does not necessarily forget what it was like to see – but they would lose the practical ability to make use of colour, and identify objects by their colour.

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[406] Land, Edwin. H. (1978). "Our Polar Partnership with the World Around Us" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.152

From Scenarios #1 and #2 we can see that colour constancy is *practically* constitutive of colour vision. Without colour constancy the "language game" of colour would be impossible to play.[407]

At some point we have all wondered about the question: "do I see the same colours as you?", "is my red your blue?" etc. The subjective colour "labels" that our minds apply to the sense data coming from the external world are, of course, arbitrary. As Ludwig Wittgenstein (1889-1951) explained in his private language argument, we will still use the same words to describe these shared sensations, even if at the subjective level, they are completely different.[408] What is important is the practical use if colour – colour discrimination – not the subjective labels applied to it.

Colour constancy exists in order for us to identify stable visual properties of objects, and to discriminate differences in surface reflectance properties, despite changes in illumination. This view can be found even in the etymology of the word "colour". Pythagoras defined colour as the surface – χρωμός ("chromos") – of a body.[409]

Davies (2012) has rightly argued that colour constancy is the ability to discriminate differences in surface reflectance properties despite changes in illumination, and not simply the apparent property of colours remaining stable.[410] The reason his argument is successful is precisely because colour constancy is a practical tool, evolved to solve a problem, and not just a passive feature of the world.

In this sense then, colour constancy is definitive of colour vision. We could go so far as to say that in the practical sense, colour constancy *is* colour vision.

COLOUR AS A "POLAR PARTNERSHIP" WITH THE OUTSIDE WORLD

As we saw in Chapter One, the "physical" school – adherents of the colour atomism hypothesis – saw colour as out there, in the world. The colour perceived at a point in the visual field was completely determined by the physical properties of the light rays entering the retina at that point. In Chapter Two we saw that the "phenomenological" school observed phenomena incommensurable with the colour atomism hypothesis. The conclusion was that the mind must contribute in some way to the construction of colour.

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[407] Wittgenstein, Ludwig. (1953). *Philosophische Untersuchungen* [Philosophical Investigations]. Translated by G.E.M. Anscombe. (Basil Blackwell – Oxford), §2 onwards

[408] *Ibid.* §256 onwards

[409] Kuehni, Rolf G. (1996). *Color – An Introduction to Practice and Principles*. (Wiley), p.18

[410] Davies, W. (2012). Essays on the perception, representation, and categorisation of colour [PhD thesis]. Oxford University, UK.

In Chapter Three we saw that Edwin Land and colleagues were able to reconcile these two schools. They did this by expanding out from examining colour only at a single point, and instead looking at how colour is perceived over a wide visual field. They appreciated that colour vision is an evolutionary solution to a problem – the problem of keeping the colours of objects constant despite changes in illumination.

Colour vision evolved in what Edwin Land called a "polar-partnership" with the outside world:

> Ordinarily when we talk about the human as the most advanced product of evolution and the mind as being the *most* advanced product if evolution, there is an implication that we are advanced out of and away from the structure of the exterior world in which we have evolved, as if a separate product had been packaged, wrapped up, and delivered from a production line. The view I am presenting proposes a mechanism more and more interlocked with the totality of the exterior. [411]
>
> …
>
> The reason for the painfulness of all philosophy is that in the past, in its necessary ignorance of the unbelievable domains of partnership that have evolved in the relationship between ourselves and the world around us, it dealt with what would indeed have been tragic separation and isolation. What meaning is mind-by-itself-without-the-world? That is tragic. Of what meaning is the world without mind? That question cannot exist.[412]

Colour was only confusing to us because it was a peculiarity of the world. It seemed superficial, superfluous – as if its benefit was simply the ornamentation of an otherwise dull, monochrome world – the world "coloured in". We did not understand that it was there for a reason. With the work of Land and the research program he engendered, colour ceased to be a passive peculiarity of the world, and became an *active* purposeful tool for survival in the world.

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[411] Land, Edwin. H. (1978). "Our Polar Partnership with the World Around Us" in *Edwin Land's Essays. Volume III. Color Vision.* (Society for Imaging Science and Technology – ed. Mary McCann, 1993), p.154

[412] *Ibid.* p.154

COMTE DE BUFFON

SEVENTH TREATISE

OBSERVATIONS ON ACCIDENTAL COLOURS, AND ON COLOURED SHADOWS [413]

(1774)

TRANSLATED FROM THE FRENCH

Even though a great deal of attention has lately been given to the physics of colours, it seems that not much progress has been made since Newton. This is not because he exhausted the subject, but rather because most Physicists (*Physiciens*) have worked more in opposition to him, rather than to understand him, and though his principles are clear, and his experiments incontestable, there are so few individuals who have made an effort to deeply examine the entire set of his discoveries and their interrelationships, that I feel that I should not speak of a new kind of colour phenomena without first presenting a clear picture of the origin of colours in general.

There are many ways to produce colours, and the first is refraction: a beam of light passes through a prism and is broken down and divided such that it produces a coloured image, composed of an infinite number of colours. Close examination of such a coloured image of the Sun has taught us that the light of this star is composed of an infinitude of differently coloured light rays, and that these rays have as many different degrees of refrangibility as they do different colours, and that the same colour always has the same degree of refrangibility. All diaphanous bodies with non-parallel surfaces produce colours by refraction. The order of the colours is invariable, and their number, although evidently infinite, has been reduced by some to seven principal denominations; *violet, indigo, blue, green, yellow, orange, red*. Each one of these denominations refers to an exact interval in the coloured image containing all the shades of the named colour, so that in the red interval one finds all the shades of red, in the yellow interval all the shades of yellow, etc. and in the confines of these intervals the intermediate colours which are neither yellows nor reds, etc. It is with good reason that Newton chose seven as the number of colour denominations. The coloured image of the Sun which he calls *the solar spectrum* at first only appears to have five colours; violet, blue, green,

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[413] Leclerc, Comte de Buffon. (1774). *Oeuvres complètes de M. le Cte. de Buffon ...: tome septième, Suite de la théorie de la terre, & introduction à l'histoire des minéraux*, (de l'Imprimerie Royal), p.309

yellow and red, which is a rather imperfect decomposition of light, and a confused representation of the colours. As the image is composed of an infinitude of differently coloured circles, corresponding with as many discs of the Sun, and that these circles largely overlap over one another, the middle of all these circles is the point at which there is the greatest mixture of colours, and the colours are only pure at the rectilinear sides of the image. However, since they are very weak it is difficult to distinguish them, so we must come up with another way of cleanly separating the colours. By narrowing the image of the Sun's disc, which reduces the overlapping of the coloured circles, we can thereby reduce the mixing of the colours. In this clean and homogenous light spectrum, one can easily see the seven colours. With a little perseverance one sees even more than seven, since by successively catching different parts of this purified light spectrum on a piece of white string, I have often counted as many as eighteen or twenty colours for which the differences were perceptible to my eyes. With better organs or greater attention, one could count yet more. This does not mean however that we should not fix the number of denominations at seven, no more, no less. This is all this for a good reason, since by dividing the pure light spectrum into seven intervals, and following the proportions given by Newton, each of these intervals contains colours which, when taken together, are indecomposable by the prism or by any other method, and this is why we call them *primitive colours*. If instead of dividing the spectrum into seven, we divide it into six, or five, or four, or three intervals, the colours contained in each of these intervals will be decomposable, and consequently cannot be considered pure, and should not be regarded as primitive colours. We therefore cannot reduce primitive colours into fewer than seven denominations, and we should not admit a greater number of them, because then we would be pointlessly dividing the intervals into two or many parts for which the colours would be of the same nature, and it would be inappropriate to split a single kind of colour and give different names to similar entities.

By a unique coincidence, the relative proportions of these seven intervals of colours correspond rather well with the relative proportions of the seven tones of the musical scale, although this is a coincidence which we should not give serious attention to. These two results are independent of one another, and one would have to blindly invest oneself in this hypothesis to pretend that by virtue of such a fortuitous coincidence we should construct common scientific laws for the workings of the eye and the ear, and treat one of these organs as if it conformed to the laws of the other, and imagine that it be possible to play a concert to the eyes or to perceive a landscape with the ears.

These seven colours, produced by refraction, are inalterable, and contain all the colours and shades of the world. The colours of the prism, as well as those of diamonds, those of the rainbow, and those of halos, all depend on refraction, and strictly follow the laws of refraction.

Nevertheless, refraction is not the only way to produce colours. In addition to its refrangible qualities, light has other properties, which although being dependent on the same general cause, produce different effects. In the same way that light is broken down and divides into colours by passing from one medium to another transparent medium, it is also broken down by passing by the surfaces of opaque bodies : this kind of refraction, which takes place within the same medium, is called *inflexion* [414]*,* and the colours that it produces are the same as those produced by ordinary refraction. The violet rays which are the most refrangible, are also the most flexible, and the fringe coloured by the inflexion of the light differs only in shape from the coloured spectrum produced by refraction. Even if the intensity of the colours is different, their order is the same, all their properties the same, their number equal, and they all share a primitive quality, as inflexion is effectively just another kind of refraction.

Nevertheless, still the most powerful means that Nature has to produce colours is refraction [A]; all the material colours depend on it – vermillion is only red because it abundantly reflects red light rays, and absorbs the others; the sea only appears blue because it strongly reflects blue rays, and because it absorbs, through its pores, all the other rays which lose themselves deep inside. It is the same for the other colours of opaque and transparent bodies. A body's transparency depends on the uniformity of its density; when the component parts of a body are of equal density, whatever shape these parts are, the body will always be transparent. If we reduce the thickness of a transparent body to an extremely thin film, it will produce colours, the order and principal appearances of which will be very different from the phenomena of the spectrum and from the aforementioned coloured fringe. Furthermore, it is not by refraction that these colours are produced, rather by reflection; the thin films of transparent bodies, bubbles of soap, birds feathers, etc. seem coloured because they reflect certain rays and let through or absorb the others. These colours have their laws and depend on the thickness of the thin film; a certain thickness consistently produces a certain colour which no other thickness can produce. If we reduce the thickness infinitely, so that the thin, transparent film has only one smooth surface on an opaque body, this surface – which can be regarded as the first degree of transparency – also produces colours by reflection, which obey yet different laws; since when we shine a beam of light on a metallic mirror, the entire beam of light does not completely reflect with the same angle, and a

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[414] Modern physicists call this diffraction

part is dispersed which produces colours of which the phenomena, like those of thin films, have not yet been observed in enough detail.

> Footnote A:
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> I admit here that I do not completely see eye to eye with Newton on the subject of the reflexibility of different rays of light. His definition of reflexibility is not general enough to be satisfying, as it is certain that there is a correlation between ease of reflection and ease of reflexibility, and this greater ease should be generalised for all cases. Yet, how can one presume that the violet ray is most easily reflected in all cases just because in one particular case it bends more in glass than the other rays? The reflection of light follows the same mechanical laws as all elastic bodies; from that we must conclude that the particles of light are elastic, and consequently that the reflexibility of light will always be proportional to its spring, and from there that the most reflectable rays will be those with the most spring. This is a difficult quality to measure in the substance of light, since one can only measure the strength of a spring by the speed that it rebounds. Thus, before it would be possible to conduct an experiment to test this, it would first be necessary that the satellites of Jupiter be illuminated by all the colours of the prism successively, so that we may see by their eclipses if the violet light moved at a higher or lower speed than the red light; it is only by the comparison of these two different rays that we can know if one has a greater spring than the other, or a greater reflexibility. However it has never been observed that the satellites, at the moment of their appearance, first appeared violet, and then coloured successively with all the colours of the prism, and therefore it must be presumed that the rays of light all have more or less the same spring, and consequently the same reflexibility. Incidentally, violet only seems to be most reflectable in the case of refraction, and not in the case of reflection, and this is easy to demonstrate. Newton demonstrated beyond doubt that different rays are differently refrangible, and of these that red is the least refrangible and violet the most. It is not therefore surprising that at a certain angle the violet ray, which exits the surface of the prism at a greater angle than all the other rays, is the first to be seized by the attraction of the glass, and is constrained enough for it to re-enter the glass, while the other rays, for which the refraction angle is lesser, continue on their path without being attracted enough to be forced to re-enter the glass. This is not therefore, as Newton supposes, a real reflection, but only a result of the refraction. It seems to me that he should not assume that the most refrangible rays are the necessarily the most reflectable. This can only seem true when we mistake the result of a refraction as a reflection, since it is obvious that a light ray which shines on a mirror and which reflects with an angle of reflection equal to the angle of incidence, is a very different case to a light ray which exits the surface of a glass so obliquely that it is forced to re-enter it. These two phenomena do not have anything in common, and cannot, in my opinion, be attributed to the same cause.

All the colours I have just been discussing are natural and depend uniquely on the properties of light. Yet there are other colours which seem to me to be accidental, and which depend as much on our sense organ, as on the action of the light itself. When the eye is struck or pressed, one sees colours in the dark, and when this organ is fatigued or debilitated, one sees colours again. It is these kinds of colours that I thought I should call *accidental colours*, to distinguish them from natural colours, and because they effectively never appear unless the organ is forced or has been impressed too vigorously.

Nobody before Dr. Jurin[B] had made the slightest mention of this kind of colours, and yet they conform to the phenomena of the natural colours in many respects. I myself have discovered a unique set of phenomena on this subject, which I will report here in the most succinct manner I can.

> Footnote B:
>
> Essai, *Upon distinct and indistinct vision, pag. 115,* des notes sur l'Optique de Smith, *tome II,* imprimé à Cambridge en 1738.

When one fixes one's gaze for a long period on a mark or on a red figure on a white background, for example a small square of red paper on a white sheet of paper, one sees a sort of crown of a weak green colour appear around the small red square. Ceasing to look at the red square and turning one's gaze to the white paper, one sees, very distinctly, a square of a pale green colour, approaching blue in hue. This appearance subsists for quite some time, depending on how strong the impression of the red colour had been. The size of the imaginary green square is the same as that of the real red square, and the green only vanishes after the eye has been reassured by gazing successively at many other objects whose images destroy the overbearing impression caused by the red.

By gazing fixedly and for a long period at a yellow mark on a white background, one sees a crown of a pale blue colour appearing around the mark, and on ceasing to look at the yellow mark and turning one's gaze to another white background, one sees a distinct blue mark of the same shape and size as the yellow mark, and this appearance endures at least as long as the appearance of green produced by the red. It appears to me, after having repeated this experiment myself and with others who have better, stronger eyes than my own, that the impression induced by the yellow was stronger than that of the red, and that the blue colour that it produced faded with more difficulty and subsisted longer than the green colour produced by the red. This seems to prove what Newton suspected; that yellow is, of all colours, the most tiring to our eyes.

If one gazes fixedly at a green mark on a white background for a long period, one sees an off-white colour appear around the green mark, which is coloured with the slightest tint of purple, but upon ceasing to look at the green mark and turning the eye to another white background, one sees a distinct mark of a pale purple colour, similar to the colour of a pale amethyst. This appearance is weaker and does not endure anywhere near as long as the blue and green colours produced by the yellow and by the red.

Likewise, while gazing fixedly at a blue mark on a white background for a long period, one sees an off-white crown with a slight red tint appear around the blue mark, and upon ceasing to look at the blue mark and turning the eye towards the white background, one sees a pale red mark, still the same shape and size as the blue mark, and this appearance does not endure any longer than the purple appearance produced by the green mark.

Looking with the same attention at a black mark on a white background, one sees a crown of bright white appear around the black mark, and ceasing to look at the black mark and turning the eye towards another white background, one sees an exact copy of the shape of the mark, in a much brighter white than the background. It is not a matte white, rather a brilliant white similar to the intense and radiant white of the coloured rings described by Newton. In contrast, if one looks at a white mark on a black background for a long period, one sees the white mark discolour, and turning the eye towards a black background, one sees a mark of a bolder black than the background.

So there we have it – a set of accidental colours which are related to the set of natural colours. Natural red produces accidental green, yellow produces blue, green produces purple, blue produces red, black produces white, and white produces black. These accidental colours only exist in the fatigued sense organ, since another observer does not perceive them. They even have an appearance which distinguishes them from natural colours; they are subtle, brilliant, and appear to be at different distances, depending on whether one links them with neighbouring or distant objects.

All these experiments were conducted using matte colours with coloured pieces of paper or fabrics, but they are even more successful when one uses brilliant colours, as for example with brilliant, polished gold instead of or yellow paper or fabric; with brilliant silver instead of white paper; with lapis instead of blue paper, etc. the impression of these brilliant colours is more vivid and endures much longer.

Everyone knows that after looking at the Sun, one sees – sometimes for a very long time – the coloured image of this star over all objects, and the overpowering light of the Sun produces in an instant what ordinary light from bodies only produces after a minute or two of fixed gazing at colours. These coloured images of the Sun – that the dazzled and over-impressed eye carries everywhere – are colours of the same kind as those as we just described, and the explanation of their appearance depends on the same theory.

I will try not to write all the ideas which have come to me on this subject here. However sure I am of my experiments, I am not certain enough about the conclusions I should draw from them to risk speculating on a theory of these colours, and I will content myself to report other observations which confirm the previous experiments, and which will serve, without doubt, to elucidate this subject.

If one gazes fixedly at a square of a vivid red colour on a white background, for a very long period, one firstly sees the appearance of a thin crown of delicate green, as I have already remarked. Next, continuing to gaze fixedly at the red square, one sees the middle of the square discolour, and the sides saturate with colour, forming a frame of a red colour that is stronger and even deeper than that at the middle. Then, moving back a little, and still continuing to fix one's gaze, one sees the deep red frame divide in two in all four corners, and form a cross of at least as deep a red colour. The red square then appears as if it were a window crossed in its middle by a large grille and four white panes. Since the frame of this window image is of as strong a red colour as the grille, still continuing to gaze with perseverance, this appearance changes yet more, and the whole thing reduces itself to a red rectangle, so deep and so vivid that it is offensive to the eyes. This rectangle is of the same height as the square, but does not have even a sixth of its width. This is the last degree of fatigue that the eye can put up with, and finally when one turns one's eye away from this object, and towards another white background, one sees, instead of the real red square, the image of the imaginary red rectangle, exactly defined and of a brilliant green colour. This impression persists for a very long time, and discolours only little by little, and stays in the eye even after the eye has been closed. What I have just recounted for the case of the red square also happens when one looks at a yellow or black square for a long period, or for any other colour. One also sees the yellow or black frame, the cross and the rectangle, and the impression which stays is a blue rectangle if one has looked at yellow, and a brilliant white rectangle if one has looked at a black square, etc.

I have demonstrated the experiments I have just described to many people, and they saw, as I did, the same colours and the same appearances. One of my friends assured me on one of these occasions, that having looked at an eclipse of the Sun one day through a small hole, he had carried the coloured image of this star over all objects that met his gaze over three weeks, and that when he fixed his gaze on a brilliant yellow, as on a gilded edge, he saw a purple mark, and over a blue such as over a slate roof, a green mark. I have myself often looked at the Sun and seen the same colours, but as I feared to do harm to my eyes by looking at that star, I thought it better to continue my experiments with coloured fabrics, and I found that these accidental colours change upon mixture with natural colours, and that they follow the same rules of appearance; since when an accidental green colour, produced by a natural red, is imposed on a brilliant red background, this green colour turns yellow; if an accidental blue colour, produced by a vivid yellow, is imposed on a yellow background, it turns green. Thus, the colours which result from the mixture of these accidental colours with natural colours, follow the same rules and have the same appearances as the natural colours in their composition and in their mixture with other natural colours.

These observations could be of some use to increase knowledge of the ailments of the eyes, which probably come from the damage caused by impressions of light that are too strong. One of these ailments is to constantly see marks in front of one's eyes, and white circles or black spots that look like buzzing flies. I have known many people to have this kind of complaint, and I have read in a few medical writers, that the serene white bead one sees is always preceded by black spots. I do not know if their description is based on experience, since I have gone through it myself, and I saw black spots for more than three months and in such a large quantity they caused me a great worry. I had apparently tired out my eyes by doing and repeating the preceding experiments, and by looking at the Sun a few times, since the black spots appeared at this same time, and I had until that point in my life never seen them. Eventually they irritated me a lot, most of all when I looked at strongly illuminated objects in daylight, wherein I was forced to turn my eyes away. Most of all yellow was unbearable to me, and I was obliged to change the yellow curtains of the room which I lived in and put green ones in their place. I avoided looking at all colours that were too strong and all brilliant objects, and little by little the number of black spots diminished, and now I am no longer bothered by them. What convinced me that these black spots come from an overpowering exposure to light, was that after having looked at the Sun, I always saw a coloured image that I carried over all objects that met my gaze for quite a long time, and by closely following the different shades of this coloured image, I recognised that it discoloured little by little, and that at the end I only carried a black mark over the objects that met my gaze, which was at first quite large, but then diminished little by little, and finally reduced itself to a black spot.

At this occasion, I will report a fact that is quite remarkable, which is that I was never more irritated by these black spots than when the sky was covered with thick white clouds, and a day like this would tire me out a lot more than the light of a clear sky because when the sky is covered with thick white clouds, the quantity of light reflected by it is much greater than the quantity of light reflected by pure air. With the exception of objects which are directly illuminated by rays of sunlight, all other objects which are in shadow are much less illuminated than those which are illuminated by reflected light from a sky covered with thick white clouds.

Before concluding this treatise, I think I should announce one more observation which will perhaps seem extraordinary, but which is nonetheless certain, an observation which I am astonished that no one has made before; this is the fact that the shadows of bodies which by their essence should be black, since they are nothing but the absence of light, that these shadows, I say, are always coloured at sunrise and sunset. During the summer of the year 1743, I observed more than thirty dawns and as many dusks, and all the shadows which were cast on white surfaces, for example on white walls, were sometimes green, and more often blue, and a blue as vivid as the most beautiful azure. I showed this phenomenon to many people who were as surprised as I. The season did not have any effect on this, since it was only eight days ago (today's date being the 15th November 1743) that I saw blue shadows, and whosoever makes the effort to observe the shadow of one of their fingers cast on a piece of white paper at sunrise or sunset, will see this blue shadow as I did. I do not know any astronomer, any physicist (*Physicien*), anyone, in a word, who has spoken of this phenomenon, and I believed that in virtue of it being a novelty, one might permit me to give more precise details of this observation.

In the month of July 1743, while I was occupied with my accidental colours, and I was trying to look at the Sun – for which the eye can better cope with its light at its nadir than at any other time of day – and in order to identify the colours and the changes of these colours which are caused by this solar impression, I noted that the shadows of the trees which were cast on a white wall were green. I was in a place of relatively high altitude and the Sun was setting in a mountain gorge, so that it seemed to me to be very much below my horizon. The sky was clear, with the exception of the setting Sun, which, although free of clouds, was covered by a transparent curtain of reddish-yellow vapours, and the Sun itself was of a strong red colour, and its apparent size was at least four times that at midday. I thus saw, very distinctly, the shadows of the trees which were at 20 and 30 feet from the white wall, coloured in a delicate green that was approaching blue. The shadow of a trellis which was 3 feet from the wall, was perfectly traced on this wall, as if one had just painted it in a greenish grey. This appearance endured for around 5 minutes, after which the colour weakened with the light of the Sun, and disappeared only when the shadows did.

The next day, at sunrise, I went to look at other shadows on a white wall, but instead of finding them to be green, as I was expecting, I found them to be blue, or rather the colour of the most vivid indigo. The sky was calm, and there was only a thin curtain of yellowish vapours to the east, and the Sun rose over a hill, so that it seemed to me to have risen over my horizon, and the blue shadows only lasted for 3 minutes, after which they seemed to be black. On the same day at sunset I saw the green shadows again, as I had seen them the day before. Six days then passed without my being able to see the shadows at sunset, because the Sun was always covered with clouds. On the seventh day I saw the Sun setting, and the shadows were no longer green, but rather a beautiful azure blue, and I noted also that the vapours were not very abundant, and that the Sun, having advanced during the preceding seven days, set behind a rock which made it disappear before it was able to go under my horizon. Since this time I have observed shadows very often, both at sunrise and at sunset, and I have only seen them blue, or a few times a very vivid blue, other times a pale blue, or a deep blue, but nonetheless always blue.

This treatise was printed by the Académie Royale des Sciences, in the year 1743. The following text is what I thought I should add today, in the year 1773.

More frequent observations have made me recognise that shadows never appear green at sunrise and sunset, and only appear when the horizon is dense with red vapours. In all other cases the shadows are always blue, and even bluer than the clearest sky. This blue shadow colour is nothing other than the colour of the air, and I do not know why some physicists (*Physiciens*) have defined the air as an invisible fluid[C], odourless, and innocuous, because it is certain that the celestial azure is nothing other than the colour of the air, and that in truth a great thickness of air is needed so that our eye can perceive the colour of this element, but that nonetheless when one looks from afar at dark objects, one always sees them as more or less blue. This observation, that the physicists (*Physiciens*) have missed on shadows, and on dark objects viewed from afar, has not been missed by the most able painters, and must effectively be used as a basis for the colours of distant objects, which will all have a bluish tint which is more visible when they are more distant from the viewing point.

One could ask; how is it that this blue colour, which is only visible to our eye when there is a very great thickness of air, is nevertheless so distinct at a distance of only a few feet during sunrise and sunset? How is it possible that this colour of the air, which is hardly visible at a distance of twenty thousand yards, could give the black shadow of a trellis – which is only three feet away from the white wall – a most beautiful blue colour? The explanation of the entire phenomenon effectively depends on the solution of this question. It is certain that the small quantity of air – which only amounted to three feet between the trellis and the wall, could not have given such a strong shade of blue to the black colour of the shadow. If that had been the case, one would see blue shadows at midday and at all other times of the day, as one sees them at sunrise and sunset. Thus, this appearance does not depend uniquely on the extent of the air between the object and the shadow, but rather almost doesn't depend on it at all. However, it must be considered that at sunrise and sunset, the light of this star, being weakened by the surface of the Earth – which at this time is at the most oblique angle relative to the star – therefore the shadows are less dense, that is to say relatively less black. At the same time the Earth is only being illuminated by the weak light of the Sun which only glances off its surface, and the mass of air which is at the highest altitude, and consequently still receives the light of the Sun much less obliquely, deflects this light towards us, and illuminates us at least us much, perhaps more than the Sun itself. Yet this pure and blue air can only illuminate us by sending us a great quantity of rays of that same blue colour, and as soon as these air-reflected blue rays fall on objects like shadows that lack all other colours, they tint them with a more or less strong shade of blue, depending on how little direct sunlight there is, and how much reflected atmospheric light there is. I could add many other things which would be relevant to support this explanation, but I think that what I have just laid out is sufficient for the understanding and satisfaction of reasonable minds.

Footnote C:
Dictionnaire de Chimie, *article de l'Air*.

I think I should cite here a few facts observed by M. l'Abbé Millot, the former Grand-Vicaire of Lyon, who has had the grace to communicate them to me by his letters of 18 August 1754 and 10 February 1755, of which the following are extracts: "It is not only at sunrise and sunset the shadows become coloured. At midday, with an overcast sky, except in a few places, through one of the gaps in the clouds, I procured shadows of a strong and beautiful blue, on white paper, a few steps away from a window. When the gap in the clouds closed, the blue disappeared. I would add in passing that I saw the azure of the sky paint itself – as faithfully as from a mirror reflection – on a wall where the light shone obliquely. However, there are yet more important observations than this in my opinion. Before going into detail, I should describe the topography of my room; it is on the third floor, the window is close to the corner where the sun shines through at sunset, and the door is almost opposite this window. This door opens into a gallery, at the end of which, a couple of yards away, there is a window facing the midday position of the Sun. Whenever the light of those two windows is united, the door being open and against one of the walls, I see coloured shadows, at almost any time of day, but mostly at ten o'clock in the morning. None of the sunrays which obliquely pass through the window of the gallery, pass through the window in the bedroom and onto the wall I just mentioned. A few inches away from this wall, I place wooden chairs with perforated backrests. The shadows given by these are sometimes very vibrant.

I have seen some shadows for which, even though both were projected on the same side, one was dark green, and the other was a beautiful azure. When the light is very controlled, so that the shadows are both equally bright, the one opposite to the bedroom window is blue or violet, and the other is of a yellowish green. The latter shadow is accompanied by a kind of coloured penumbra, which is composed of a double blue border on one side, and on the other side a green or red or yellow one, depending on the intensity of the light. If I close the blinds of my bedroom window, the colours of this umbrage are even more vivid, and they disappear when I half-close the door. I should add that the phenomenon is not nearly as visible in winter. My bedroom window points towards the setting sun in summer, and I did my first experiments during this season, and during a time when the sunrays fell obliquely upon the wall which makes an angle with the wall upon which the shadows were coloured.”

We can see from the observations of M. l’Abbé Millot, that it suffices that the sunlight shines very obliquely on a surface, so that the blue of the sky, whose light always shines directly, tints and colours the shadows. However, the other phenomena he records only depend on the arrangement of the room and furniture, and other incidental circumstances.

GUILLAUME LE GENTIL

ON THE COLOURS THAT RED AND YELLOW-PAINTED OBJECTS ASSUME WHEN THEY ARE VIEWED THROUGH RED OR YELLOW-TINTED GLASSES [415]

(1791)

READ AT THE ACADÉMIE ROYALE DES SCIENCES, ON SATURDAY 24TH AND WEDNESDAY 29TH JUNE 1791

TRANSLATED FROM THE FRENCH

In 1754 I gave the Académie a Mémoire, which was printed in the volume of that same year, on the apparent diameter of the Sun, and on the way to view it with different coloured glasses, and most importantly with green-coloured glasses. To this end I made use of a very good green objective.

I had started this treatise with a Newtonian theory of colours; that is that sunlight is composed of differently refrangible rays, and that consequently the spectre or image of the Sun that formed at the focus of an objective was composed of as many coloured circles as there are differently refrangible rays.

Today I will reconsider this matter from a different point of view to that of the truth, but still conforming to the Newtonian theory of colours. It is thus here a question of whether a given colour, red, for example, or yellow, is always allied with certain kinds of rays which compose light, as Newton has said. (See *Opticks,* book 1, part 2, 10th proposition, problem V.)

During the summer of 1789, M. Monge conducted a remarkable experiment at the Académie, which seemed completely opposed to the Newtonian system. M. Monge placed a sheet of red paper against the west-facing wall of a house which was opposite the windows of the hall of the Académie, at a distance of around 15 yards more or less – the distance is not important; then having viewed the paper through a lightly tinted red glass, it appeared to be white. What's more, a red cloak which that day one of us was wearing, appeared whitish.

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[415] Le Gentil, Guillaume. (1791). « Sur la couleur qu'assedent les objects peints en rouge ou en jaune lorsqu'on les regard à travers des verres rouges ou jaunes. Annales de Chimie » 10, 225–254.

M. Monge then read a treatise to the Académie to explain this experimental fact which he believed to be have incontestably taken place; that is to say, that he posited a general theory. This *académicien* has since published his treatise in the third volume of the *Annales de Chimie*, with the title *Mémoire sur quelques phénomènes de la vision.*

However, having myself been impressed by the extraordinary nature of this fact, and having often reflected upon it, I resolved to repeat this experiment at home, in order to see if it was not the result of some optical illusion, (because in doing experiments like this we sometimes see things we should not) and if it was not a purely optical illusion to discover the real cause, if possible. It therefore seemed very interesting to occupy myself with this question; yet I must declare here that it is only the desire to elucidate this important subject that M. Monge addressed in his treatise, that has guided me in the experiments that I will now describe to the Académie. Moreover, I must suppose that some foreign scholar will not neglect to repeat such an interesting experiment. I thought it better therefore that such a work be the product of the Académie.

I must say again, to be precise in the facts, that M. l'abbé Haüy had the same idea as myself, that is to say, he began to repeat, even before myself, of M. Monge's experiment; that he procured, much before me, glasses of all colours, as well as papers painted with analogous colours to those of the glasses; and that having been questioned during a conversation – between him and myself – about the facts relating to Newton's coloured rings, I informed him of my intention to repeat M. Monge's experiment, in a manner that leaves no doubt, if possible, on this subject; that M. l'abbé Haüy announced to me that he was already busy doing the same, and that, as I seemed to him to be well-disposed to take on the entire task from him – I not at all wanting to invade the space which belonged to him by virtue of the priority of his work and experiments – he declared to me very sincerely that he would be very pleased to hand the work over to me, for which he very kindly offered me all his glasses and painted papers: I will now relate my method.

First of all, I think it imperative to cite the actual words of M. Monge. "We know, he said, that transparent coloured substances have the property of letting rays of certain colours pass through, and of intercepting all others; and that, for example, red glass gives passage to most red rays which arrive at its surface, and it stops the highest quantity of rays of all the other colours. It would seem, according to this, that knowing the kind of homogenous rays that a transparent coloured substance can transmit, one would be able to predict the changes which must take place in vision when one views objects through this substance. Suppose that through a red glass – that is to say, a glass which has the faculty to let red rays of a certain shade pass through, and to absorb or to reflect all other rays – we view a suite of objects of different colours; it seems that one could predict, for example with white bodies, that the rays of all colours emanating from their surfaces are reduced to only red rays by passing through the glass, and that the images of these bodies will be as if their surfaces were red, and the alterations caused by the interposition of the coloured glass can be reduced to, (1) a diminution in clarity induced by the suppression of intercepted rays; (2) a change in colour from white to red. Apropos red bodies of the same shade as the rays which the glass lets pass, it seems that one could be forgiven for believing that the rays sent by these bodies, having the faculty to pass through the glass, the only change to the perception of them could be a slight weakening of clarity caused by the imperfect transparency of the glass; and that otherwise their colour should appear the same whether one uses the intermediate glass or not. Regarding objects of all other colours, that is to say, those which reflect neither white rays nor red rays, it is clearly evident that of all the rays that they send to the glass, none pass through its substance, and these bodies are indistinguishable from those in perfect darkness, and they must appear to be black.

"For the first two cases, M. Monge said, precisely the contrary happens in the experiment, when we view a suite of objects of different colours through a red glass; the white bodies and the red bodies appear in truth to be of the same colour, but we do not see them as red as it would seem natural to think, but rather white.

An analogous phenomenon should take place, M. Monge continued, when we view the objects with a glass tinted with any other colour but red; that is to say, that when the glass only lets through homogenous rays of a certain kind, the bodies which only reflect the rays of the latter kind should appear to be white. I have in my hands a yellow glass, said M. Monge, through which paper tinted yellow with gamboge appears to be absolutely white".

Such were the facts reported by M. Monge; this Académicien then went on to say that it must be admitted that glasses of all other colours, for example blue, green and violet, that he had the opportunity to experiment with, did not present similar results, a fact that he believed should be attributed principally to the fact that these colours can be produced in many ways, either with homogenous rays, or with a mix of different rays; and finally M. Monge, before considering explanations of these facts which he supposed to be constant, believed he should re-emphasise that the illusion at work here (he called it so) is even more striking for the fact that when the objects that one views through a coloured glass are even brighter, the more there are of them, and when among them there is a greater number that we know to be naturally white. As for myself, I think I am able to hazard an assumption that all the experiments I have done have appeared to me to prove the contrary to these assertions, that is to say that the more that bodies are illuminated, the more white rays there are among them, the more they appear to be red when viewed through red glasses; so that the phenomena presented by red glasses when viewing white objects which are slightly illuminated, and red objects of varying redness, or different shades of red, only come, in my opinion, from the variable intensity of white or red light reflected by these bodies.

GEORG WILHELM MUNCKE

ON SUBJECTIVE COLOURS AND COLOURED SHADOWS [416]

(1820)

TRANSLATED FROM THE GERMAN

As is well known, there is hardly any subject in optics that has received more attention than the study of colour, and there has always been a great variety of opinions and theories given on it. Every contribution which has cast some light on this otherwise shady area is thus very significant, and I think it very important to draw the attention of the general public to some of the more recent discoveries which I have come across, partly through luck, partly through my own enquiry. I covered many of these in my recently published volume *Principles of Natural Science* (*"*Anfangsgründen der Naturlehre*"*), but did so in quite a brief way as part of a general course on the subject, but in the meantime I have not moved on from the subject, and I have tried to gain a firmer understanding of these phenomena, over which the various theories are still in conflict with one another, and where possible I have made experiments to test these theories. I have had lucky circumstances in that all the natural science institutes of my local university are unified together with the departments of physics and chemistry, and so have been able to avail myself of the relevant experts at relatively short notice. It takes barely half the time and effort if you only have to take a few steps from your desk and books to get to the experimental apparatus, and when undertaking physical experiments also having access to the very best of chemistry labs, not to mention those of the other sciences.

Among other things I have followed the phenomena of coloured shadows and subjective colours with great enthusiasm, and yet despite many efforts there still has not been a satisfying theory to explain them. I made the most important results of my investigations known in §133 and 134 of my *Principles.* Although these results can be understood with only a few remarks and do not need further explanation, sometimes I have not been able to stop myself, and in order to make myself fully understood this paper at times reads rather like a news bulletin.

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[416] Muncke, G. W. (1820). "Ueber subjective Farben und gefärbte Schatten," *Journal für Chemie und Physik* 30 (1820): 81

Before all else, it is important to note that the phenomenon of the coloured shadows does not exhibit any "unnatural" colours, rather they are *subjective* colours, produced in the eye through the contrast of the primary colour ("Hauptfarbe"). This claim has already been established by Rumford,[1] and this subject has already been treated to exhaustion through his interesting experiments. As proof of his claim, he observed that the colouring of the shadow disappeared when it is observed through a long pipe blackened in the interior. In the *Principles of Natural Science* I mentioned in §133 that this contradicted my own observations, and since then I really wanted to distance myself from the coloured shadows phenomenon. As time has passed however, I have found these observations to be true, although these new results were achieved with great difficulty. I took a tube so narrow that the impression of the light coming from the shadow was *completely* isolated, in fact it was almost completely dark, and it did not appear to be coloured. This was a satisfactory proof of the claim on the entire phenomenon, and dare I say, it can be completely validated by this experiment. I have performed quite a number of experiments which have completely put aside any doubts, and as it would take too much time to recount all of them here, I will have to content myself with recording only the most important results, and a few somewhat more trivial yet well-established results.

Footnote 1:

S. *Gren* Journ. d. Phys. B. II. S.58.

In general, it is very difficult to produce pure colours through the use of pigments and so-called "coloured substances", and thus to define the primary colours ("die Hauptfarben") and their corresponding complementary colours. Whatever coloured substances you take, only the colours yellow and blue can be produced very well; it doesn't work so well with red and green. Luckily there is another method you can employ, using different light sources, e.g. day and candlelight in a dark room, letting the daylight pass through coloured silk curtains, and compare the resulting coloured shadows with one another. The simplest and surest way to get to know the primary and complementary colours ("Haupt und complementairen Farben") is to produce polarised beams of light by shining light through thin paper (like you can get from the gypsies of Mont-Martre), and then rotating it 45°, swapping the two beams of light. In this way one can obtain the light in its proper purity and intensity, in order to perceive the phenomenon more accurately. While I have performed many such experiments, I have to openly admit that I am biased towards accepting 4 primary colours, namely red, yellow, green and blue, which are widely accepted, and that these colour names span a wide range in their respective parts of the spectrum. For each of these four primary colours there is a certain complementary colour; to red belongs green, to yellow belongs blue, and the complementary colour is always very much darker, the lighter the primary colour is, and vice versa. Violet has no complementary colour, apart from green, and light red, violet, and dark magenta ("dunkelpurpur oder dunkelblutroth*"*) respectively complement dark green, black-green, and light green. It almost beggars belief how sharp the gradations of distinction are. This is the case no matter if the violet is pure or whether it is produced through a mixture of dark blue and red, and no doubt there are yet further reasons for this.

The cause of the coloured shadows phenomenon is to be found inside the eye, and it is the same thing that causes the complementary colours. When a beam of light of a known colour impresses the eye, it seems to carry the corresponding complementary colour, and pastes it onto the neighbouring shadow or weakly lit object. To confirm the proposition that they arise in eye, I took some impeccable coloured glasses, red and green, and yellow and blue (although these last two were not so impeccable). Then I took the beams from two light sources and shone one of them through a coloured glass, and left the other free, and shone them on to an opaque object, for example on to a pen, caught the two resultant shadows on a piece of paper, and observed that one of them is always coloured with the complementary colour of the neighbouring shadow. Red and green glass panes are the most effective in this, because the resulting coloured shadows are more discernible from the original colour, and make a stronger impression on the eye, and prove that the root cause of the shadows is not just due to any peculiarities of my second-hand equipment (glass panes). So that is where Rumford's original experiment left us, which I wrongly doubted in my *Principles on Natural Science* Part. 1 p. 209, and which I now fully endorse. Now, if one observes the complementary coloured shadow through an adequately long and thin tube, blackened on the inside, so that only that shadow is visible, one can see that it is no longer coloured; but if the other original coloured shadow, or indeed any other coloured light enters the same field of view, the shadow becomes coloured again. In the past I did not take this last observation into account, and conducted the experiment with a tube that was too white in the interior, and so I did not achieve the same results as Rumford. One can however modify this experiment in another interesting way, when one looks at the complementary coloured shadow with both eyes together, with one of them looking through the tube, the other free, in which case in one eye it appears coloured, and in the other eye not coloured.

Through serendipity I once came into possession of a very interesting piece of apparatus, which was of use to me in a very striking way when I was pursuing this subject further, and thus gave me a final enlightenment on this matter. All in all, it was nothing more than two large thick dark green coloured glass plates. Against one of the surfaces, I placed a pen or quill, which cast a reflection on each of the surfaces, one of them green coloured, and one of them pale red. Here once again we have the primary colour ("Hauptfarbe") with its complementary colour emerging, and most peculiar and interesting of all was the fact that the colours had the same quality, and it looked as if they belonged to the reflection itself since both the image in front of and behind the glass was coloured. In order to see this you have to keep only the two images of the mirrored object in your field of vision, and concentrate on them alone, and through a turning motion of the whole apparatus or by altering the direction of the incident light you can make the red image change to a green one, and vice versa. This most interesting experiment has caught the attention of many physicists I have had the pleasure to demonstrate this to, and last autumn Herr Gilbert from Leipzig, Herr Pfaff from Kiel and myself were delighted by it when they visited.

Having laid out the facts above on the genesis of coloured shadows in the eye – i.e. when there is a stimulus of coloured light, and a complementary colour is induced adjacently if that surface is adequately illuminated – there are, on the other hand, a lot more phenomena which serve as applications of this theory, and at the same time are very interesting confirmations of it. The number of these is certainly not small, and the diligent observer often discovers more of them, which can all easily be traced back to the same fundamental phenomenon. The predictable change between red and green, and yellow and blue, with sufficient attention soon becomes striking. Most interesting of all is the observation that the atmospheric air does not have a weak blue colour, as is widely held to be the case; in the thickest layer of the atmosphere where we think the blue colour is generated, the colour is actually only subjective, being the complementary colour to the yellowish white light reflected off the earth and the objects on it. Other well-known observations seem to support this claim, namely: that neither the stars by night, nor indeed other distant objects when viewed through a telescope, have even the slightest blue tint that they should have if we were to follow the ordinary view. Furthermore, this can explain the pure dark blue of the Italian and Tropical sky, in contrast to our country where it is lighter and milkier in colour. I once thought, following the common theory, that a coloured body through the "blue" mist should appear to be darker, not lighter. However, from looking at real clouds it is evident that they only reflect white light, of course apart from instances where the light is refracted and then appears to be coloured for other reasons. The theory I have set out also explains why the blue of the sky should become much darker, the lighter the yellowish-white daylight reflected from objects is, and therefore also in the intermediate spaces between clouds the sky should appear to be darker in proportion to the brightness of the yellowish-white clouds. An analogous phenomenon occurs in winter, when we look at pure white fresh fallen snow illuminated when the sun is low, the shadows of trees and branches cast on the snow appear to have a light or dark blue colour.

To those of my readers who are not easily moved to the same theoretical conclusions, and not inclined to abandon the long-standing theory, and in order to convince them of the undoubtable truth of this new theory, I want to draw their attention to a classic experiment which will put the issue beyond all doubt. Everyone knows that the moon and the sun appear to be much larger closer to the horizon compared to at the zenith, but one can easily prove that this is merely an optical illusion by making measurements with a telescope and a micrometer during the month. A very similar experiment can reveal that the sky is actually not in the least blue-coloured, but only appears to be blue as a result of an optical illusion. If you observe the sky with one eye through a long tube blackened on the interior, and with the other eye free, the blue colour as seen the tube gradually fades, but the blue colour persists in the free eye. That the fading of the blue colour occurs only gradually, and not all of a sudden, does not at all detract from the theory, rather it provides a confirmation of it. However for a strict and complete experimental proof, one should only use one eye and look through the tube, and first of all point it at a location in the sky which is free of clouds (thus appearing white), then move it to a location which there are parts of clouds in the field of view, so the sky will then appear to be blue among these clouds. Whoever puts some effort in to doing this experiment properly will soon be convinced that it is a complete proof of these claims. Meanwhile an almost equal amount can be drawn from the known observation that icy mountain peaks appear to be emerald green in colour when the surrounding sky is red in the evenings. Another thing that interested me in this respect was the account of Captain Ross, who on his voyage of 1818 in Baffin Bay saw ice which gave off a golden shine at the same time as the sky took on a beautiful green colour. This account is important in many respects, and begs some important questions. If the surface of the ice was really yellow, in the true sense of the word, the complementary colour of the sky should have been blue. Ross described the ice as having a "golden shine", and this gold light does not only contain red light, but as Prevost discovered, a reflected "golden" light beam will take on a purplish red if a dark object is reflected from the "golden" mirrored surface, just as white light appears to be yellowish when reflected from the same surface.[2] Hereby the phenomena are linked together; thin gold leaf attached to glass lets green light through, which is perhaps explicable through the law I have outlined above, although I am unable to do so satisfactorily here.

Footnote 2:

S. Annales de chimie et de physique 1817. Fevr. p.192. See also Biot's Traité de phys. Exper. Et math. T. IV. p.119

I should not leave these investigations without discussing one more question, which has an intimate connection to our subject, and could cast some doubt upon the claims set out above. One may easily ask where the yellow colour comes from, which engenders the apparent blue colour of the sky, when it is well known that light is white. Were the experiment I detailed above not so decisive in its result, I have to confess that this argument would make me doubt the whole theory, since it is well known that blue and yellow are complementary to one another, and no other explanation is available as to why daylight reflected from objects on the earth's surface contains so much yellow. This is so much the case that, as I have shown in the experiments detailed above, objects which appear to be very red can even make the sky appear to be green, and this observation is enough to quash this objection. Naturally, part of light with the greatest intensity is the light-yellow part, and the weakest is the dark-blue part (if we abstract from Violet), and while these correspond to one another as complementary colours, they reciprocally invoke one another; this seems to be a good enough reason, that the blue of the sky is in direct proportion to the strength of the this bright though weakly yellow-tinted daylight.

Another directly related question; whether the induced complementary colour is physical, physiological, or psychological in nature, can be answered just as easily. According to the laws on the generation of subjective colours, which also govern the phenomena detailed above, one cannot doubt that there is a physiological cause, and if we did not know how to find further proof that this or that view is really the right one, we can always construct an experiment to provide a satisfactory explanation. I succeeded in finding an experiment which infallibly proves that the proximate cause is completely physiological in nature, and has nothing to do with the psychological, even though the actual physical cause of this and all other colour phenomena has not been found up to now, and perhaps can never be found. If you construct a tube, between one and a few inches wide, through which you point a mirror to produce a greater intensity of light, on whose plane the axis of the tube is directed at such an angle that the sunbeams falling onto it enter the eye of the observer, with the eye of the observer completely closing the top of the tube so that it does not receive any incident sideward light, and if the tube also stands on a hollow cube or parallelepiped, of which three sides are closed, and the fourth is open but lets the sun's rays fall freely on the mirror, and you cover this open side with a coloured glass panel, so that therefore only light coloured by the glass panel can enter the eye of the observer; and then you view this for only one or a few minutes, then take the glass plate away, you will see that the complementary colour then appears with a strength proportional to that of the original light stimulus. One of the most interesting parts of this experiment – which is quite analogous to the well-known Darwinian one – is the fact that only one eye becomes disposed to produce the complementary colour, since when you switch to looking through the tube with the eye that was not previously affected, and then back and forth with the affected eye, the complementary colour (in ever decreasing intensity) is perceived only with the affected eye, and not at all with the unaffected eye. This clearly shows that the phenomenon is not at all physical, otherwise it would not be possible for there to be such a difference between the two eyes; besides, the experiment shows us why the blue colour of the sky does not suddenly disappear when you observe it through a blackened tube, since once created the complementary colour can only gradually disappear. NB: if you want to avoid the adverse influence of reflected sunlight, you can reflect it from a white wall or shine it through some frosted glass.

When I reflect on these investigations, so it seems to me, further pursuit of them could lead to very significant discoveries in the science of vision, or at least in the science of colour. I always find it remarkable that colours which are so fundamentally different in their illuminative and chemical properties can reciprocally evoke each other as complementary colours, that the root cause of this is found only in the eye, and that it possible to predict with certainty the effect that each and every colour will have. Very pale yellow (which is almost pure white) can invoke the darkest of blues, just as pure white stands in opposition to pure black as the strength of illumination changes. The same is true for the contrast of green and red light, for which it is striking how the former colour affects the eye in such a mild and agreeable way, and yet the latter colour is not only nauseating, but can even be painful in some instances. Besides this, it would also be a significant step for colour theory if it could be decided with sufficient certainty if the colour violet, composed of red and blue light, should be one of the series of primary colours. I will abstain from making any conclusions on this matter here, but will surely pursue this line of enquiry in the future now that it has been opened up.

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CHAPTER ONE

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CHAPTER THREE

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