Renzo Shamey
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Pioneers of Color Science

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◀ Cover Page Collage

The cover collage (by R. Shamey) depicts historical progress in the general domain of science including some of the important pioneers in the field of color science. The majority of images are available in the public domain. A brief description of the images from top left to bottom right is given below.

Top Row

1. The famous "School of Athens" by Raphael, painted between 1510–1511 CE, depicting all of the major philosophers of antiquity with Plato and Aristotle at the center (Vatican Museums, Rome).
2. Abd al-Rahman III and his court receiving the ambassador in Medina Alzahara, by Dionisio Baixeras Verdaguer (1862–1943)—University of Barcelona Virtual Museum.
3. Dar Al-Hikmah, The Museum of Science and Technology in Islam, Istanbul. Picture from Nikos Niotis.
4. The color order system according to Nasir al-din Tusi (1201–1274), Persian scientist.
5. Portrait of Ibn Sina (Avicenna) circa 980–1037, Persian polymath.

Middle Row

1. Galileo Galilei showing the Doge of Venice how to use the telescope, by Giuseppe Bertini (1825–1898).
2. Landscape with clerks studying astronomy and geometry, showing an armillary sphere, square, compasses, etc., La Vraye Histoire du Bon Roy Alixandre (The Alexander Romance in Old French prose) by Pseudo-Callisthenes, early fifteenth century.
3. Portrait of Sir Isaac Newton (1643–1727), English polymath, by Jean-Leon Huens (1921–1984).
4. Reading of Voltaire's L'Orphelin de la Chine (a tragedy about Ghengis Khan and his sons, published in 1755), in the salon of Madame Geoffrin (Malmaison, 1812), by Anicet Charles Gabriel Lemonnier (1743–1824).

Bottom Row

1. Portrait of Thomas Young (1773–1829), English physicist, From Life of Thomas Young (1855), George Peacock—frontispiece.
2. Michel-Eugène Chevreul (1786–1889), French chemist, taken in 1889.
3. James Clerk Maxwell (1831–1879), Scottish physicist. Circa 1875, Photograph by Stefano Bianchetti/Corbis Historical (1900).
4. Hermann Ludwig von Helmholtz (1821–1894), German physiologist.
5. Karl Ewald Konstantin Hering (1834–1918), German physiologist.
6. Albert Henry Munsell (1858–1918), American artist.
7. Photograph of a CIE Meeting (from left to right: Ernst Ganz, David MacAdam, Alan Robertson, Gunter Wyszecki), by Fred Billmeyer.
8. CIE chromaticity diagram.

Nanos gigantum humeris insidentes

Dedicated to my son Sean Araz Luca Shamey

Preface

Color plays an important role in our daily lives. Among our sensory qualities, color has historically attracted the greatest level of interest. The idea behind this book was conceived several years ago based on experiences gained from teaching color science and technology to undergraduate and graduate students. In the course of teaching, it was increasingly felt important to provide students with an opportunity to relate to the individuals behind discoveries. Thus, whenever a discovery or invention was mentioned, a brief description of the achievements together with a depiction (whenever possible) of the individual(s) was shown to introduce the scientist and signify their contribution in the field. The idea to generate a list of pioneers in the field was thus formed. Through conversations and consultations with colleagues, an initial list was created. A survey was then placed on social media sites to collect opinions from those interested in the domain, and a "final" list was generated.

In the meantime, the authors were placed in charge of the "People" section of the *Encyclopedia of Color Science and Technology* (Luo, 2016). There seemed to be a strong synergy between the two activities, and it became evident that many of the pioneers selected for the book could also be included in the reference encyclopedia. A number of expert individuals were invited to contribute manuscripts to the encyclopedia. When appropriate, the authors were asked for permission to incorporate their modified manuscripts in this book. These contributions enriched the book and enhanced the quality of this project. This work provided the authors with an opportunity to (re)discover some facts and interesting information about many of the pioneers listed which are now shared with the reader. The lives and works of pioneers generally reflect the ambition of man to discover unknowns and address the challenges associated with visual perception in general and color specifically. As might be expected, the journey included controversies and heated debates.

The book contains a brief description of lives and scientific discoveries of 93 pioneers in the field of color science. It is arranged in five parts according to the following plan.

Part I covers ancient Greece which in the Western World was the source of thinking about color. Essays include discussions and views from Plato, Aristotle, and Ptolemy.

Part II involves scientific contributions in the field during the Islamic Golden Age which extended from Spain to the Far East through Persia. Major discoveries included advances in optics, vision, and categorization of color by scientists such as Alhazen, al-Tusi, Avicenna, al-Farisi, among others.

Part III is a short essay on discussions pertaining to color in the Middle Ages leading to the Renaissance. Only two notable individuals, Bacon and Dietrich von Freiberg, are recorded to have made significant contributions to this domain over the period.

Part IV covers a significant period of advancement in science including color formation and visual perception, a time period from about the sixteenth to the eighteenth centuries which provided a significant range of discoveries encompassing many domains that may fall under the general umbrella of color science. In "The age of enlightenment," many scientists laid the foundations for important discoveries in the nineteenth and twentieth centuries. This chapter addresses the works of nineteen pioneers including Newton, Goethe, Young, and Chevreul.

Part V is the largest section of the book and covers the most recent discoveries and contributions from pioneers born after 1800 and includes over 60 essays. Among them are Nobel laureates, renowned vision scientists including Helmholtz and Hering, and many other notable color pioneers such as Munsell and Land.

With respect to the academic disciplines and the fields of activity, the majority of pioneers were physicists or psychologists, but the group also includes chemists, mathematicians, optical engineers, physiologists, entrepreneurs, and a few artists, demonstrating the truly multi-disciplinary nature of activity in the field.

We have strived to incorporate, in this first edition, the most notable individuals from as many different disciplines as possible. Without a doubt, the story of lives and labors of the pioneers is one of inspirations. Their trials and tribulations is a reflection of humanity's desire to comprehend the world. The story of color is largely the story of humans, and it will continue to inspire, awe, and fascinate us. We found this journey captivating and hope the reader will find it of interest.

Raleigh, USA

Renzo Shamey
Rolf G. Kuehni

Acknowledging Contributions

This book includes several modified articles that were included in the first edition of the *Encyclopedia of Color Science and Technology* as well as a few articles which are planned to appear in the second edition of the encyclopedia. We have listed contributions from authors or co-authors of these articles in the following section. It has been an honor and a privilege to collaborate with these colleagues who dedicated time to contribute articles to the encyclopedia and graciously agreed to have them incorporated in this book. The biographies in the following section are shown in an alphabetical order.

In addition to those listed below, two other colleagues helped with the preparation of the material, who are duly acknowledged. Hugh Fairman assisted Michael Brill in writing the article for Hugh Davidson, and David Briggs assisted Stephen Westland in the preparation of the entry for Johannes Itten. A brief summary of their biographies is given below.

Hugh S. Fairman is a 1958 graduate of Princeton University, majoring in analytical chemistry. Currently, he is engaged in the development of third-party software for spectrophotometric analysis and computer color matching. He is a past President (1990–1992) of the Inter-Society Color Council and an active member of ASTM International Committee E-12 on Appearance.

David J.C. Briggs obtained a Ph.D. in Science at the University of Queensland in 1990. He has been teaching drawing and color theory at Sydney's Julian Ashton Art School since 1996 and has been a lecturer and instructor at the National Art School, Sydney, since 2009. Since April 2015, he has been Chairperson of the New South Wales Division of the Colour Society of Australia.

Finally, we are also grateful to Robert Hirschler for providing several photographs, from his personal collection, of some of the Pioneers who appear in this book.

Seyed Hossein Amirshahi was born in Qazvin, Iran, on June 22, 1957. He received a Bachelor of Science degree in Textile Engineering from Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran, in 1983, and a Master of Science in Textile Engineering from the same university, in 1987. He was awarded a Ph.D. in 1994, from the University of New South Wales, Sydney, Australia.

In 1987, he joined the Department of Textile Engineering of Isfahan University of Technology, Isfahan, Iran, as a lecturer and was promoted to assistant professor (1995) and associate professor (1999). Since September 2001, he has been with the Department of Textile Engineering, Amirkabir University of Technology (Tehran Polytechnic), where he became a professor of color science in 2006. His current research interests include computational color science, spectral and colorimetric data processing, analysis of near to one-dimensional colorimetric data (such as blacks and whites), and metamerism. He has supervised several masters and Ph.D. students in the field of color science and taught graduate courses in this area. He was an invited guest professor at Gjovik University College, Norway. He is the co-author of the following articles:

- Al-Tusi, Nasir al-Din
- Al- Farisi, Kamal al-Din
- Inb Sina
- Ibn Sahl

Michael Henry Brill is the Director of Research at Datacolor in Lawrenceville, NJ, where he has been Principal Color Scientist since 2003. He was born in Bay Shore, NY, on January 26, 1949, graduated from Case Western Reserve University in June 1969, and was granted an MS and a Ph.D. in physics in Syracuse University in January 1971 and June 1976, respectively. Via research positions at M.I.T., Jaycor, Science Applications International Corporation, Sarnoff Corporation, and (most recently) Datacolor, he has carried out extensive theoretical research in color in human and computer vision, in geometric/photometric invariance, in underwater acoustics, and in physics-based vision. He is co-inventor of the Emmy-Award-Winning

Sarnoff vision model. Dr. Brill is also a Past President of the Inter-Society Color Council, and author of more than 80 refereed technical publications, 16 US patents, numerous national standards, and a SID test pattern. He has acted as a referee for more than 40 technical journals. He chaired or co-chaired six conferences on color technology, vision, and digital display. In addition, he obtained the 1996 ISCC Macbeth Award for his work on color constancy, and the 2010 ISCC Nickerson Service Award. Dr. Brill is an associate editor of *Color Research and Application*, chairs ASTM Subcommittee E12.04 (Color and Appearance Analysis), and edits and writes for the *ISCC News* column, “Hue Angles.”

Michael H. Brill is the author (or co-author) of the entries for the following Pioneers of Color Science:

- Hemmendinger, Henry
- Davidson, Hugh
- Kubelka, Paul
- Judd, Deane Brewster
- MacAdam, David
- McCamy, Calvin
- Schrödinger, Erwin
- Stanziola, Ralph

Ellen Campbell Carter is the editor of the journal Color Research and Application and a color science consultant. She received a B.A. in chemistry from Manhattanville College in Purchase, NY, and a Ph.D. in chemistry from Rensselaer Polytechnic Institute in Troy, NY. Her doctoral thesis, “The Application of Turbid Medium Theory to Metallic Paint Systems,” was supervised by Prof. Fred W. Billmeyer, Jr. After graduation, she worked in industry and education. She was a Senior Color Scientist for the Sherwin-Williams Company and later Minolta (now Konica Minolta) Corporation. Currently, Dr. Carter is the Associate Director for Color in Division 1 (Vision and Color) of the International Commission on Illumination (CIE). She is also a member of ASTM International—currently serving as Vice-Chair of Committee E12 on Color and Appearance, the Inter-Society Color Council (ISCC)—where she served on the Board of Directors and as President, the Committee for Graphic Arts Technology Standards (CGATS), the Detroit Colour

Council (DCC), the Society for Imaging Science and Technology (IS&T), the Illuminating Engineering Society (IES), US National Committee of the CIE (CIE/USA), Sigma Xi: The Scientific Research Society, and a Senior member the Optical Society of America (OSA) and the American Association of Textile Chemists and Colorists (AATCC). She received the ISCC Nickerson Service Award in 2003 and the ASTM E-12 Fred W. Billmeyer, Jr. Award in 2009.

Ellen C. Carter is the author of the entries for the following Pioneers of Color Science:

- Billmeyer, Jr., Fred Wallace
- Saltzmann, Max

Mark D. Fairchild is a Professor and Associate Dean of Research and Graduate Education of RIT's College of Science and Director of the Program of Color Science and Munsell Color Science Laboratory. He received his B.S. and M.S. degrees in Imaging Science from RIT and Ph.D. in Vision Science from the University of Rochester. Mark was presented with the 1995 Bartleson Award by the Colour Group (Great Britain) and the 2002 Macbeth Award by the Inter-Society Color Council for his research work in color appearance and other areas of color science. He is author of over 300 technical publications and the book, Color Appearance Models, 3rd Ed., which serves as a reference to the fundamentals of color appearance and the formulation of specific models. He served as Color Imaging Editor for IS&T's Journal of Imaging Science and Technology for 3 years and was named a Fellow of IS&T (the Society for Imaging Science and Technology) in 2003 for his contributions to digital color imaging. In 2007, Mark was presented with the Davies Medal by the Royal Photographic Society for his contributions to photography in the digital field of imaging science. He received the 2008 IS&T Raymond C. Bowman award for excellence in education and was named a Fellow of the Optical Society of America in 2012 for his contributions to research and education in color and imaging sciences. He was chair of CIE Technical Committee 1–34 on color appearance models and is currently a member of several other CIE technical committees dealing with color appearance and image technology issues. Mark is an active member of IS&T, ISCC, CORM, CIE-USNC, OSA, SID, AAAS, and ACM-SIGGRAPH.

Mark Fairchild is the author or co-author of the following entries:

- Fechner, Gustav
- Lippmann, Gabriel
- Stevens, Stanley
- von Kries, Johannes
- Lovibond, Joseph

Robert William Gainer Hunt was born at Sidcup, Kent, England, on July 28, 1923, and passed away on October 23, 2018, in Salisbury, England, before the completion of this project. He was awarded a B.Sc. (Bachelor of Science) with first-class honors, an ARCS (Associate of the Royal College of Science), in physics, 1940–1943, and a DIC (Diploma of Imperial College) in Technical Optics, 1946–47, all from the Imperial College of Science and Technology, University of London. He was also awarded a Ph.D. (Doctor of Philosophy), 1953, and a D.Sc. (Doctor of Science), 1968, from the University of London. He worked as an Experimental Officer at the Ministry of Supply on optical sighting devices for tanks, 1943–46. He was a research scientist at the Kodak Research Laboratories, Harrow, 1946–82, where he worked on factors affecting the quality of color images, and devices for making reflection prints from both negative and positive images on film; he was finally Assistant Director of Research. Since 1982, he worked as an independent color consultant and took a leading role in the development of color appearance models. He was a Visiting Professor of Physiological Optics at the City University, London, 1967–1998, a Visiting Professor of color science at the Colour & Imaging Institute at the University of Derby, England, 1994–2004, and a Visiting professor of color science at the Department of Colour Science at the University of Leeds, 2004–2009. He was Chairman of the Colour Group of Great Britain, 1961–63; Chairman of the Colorimetry Committee of the

Commission Internationale de l'Éclairage (CIE), 1975–83; and President of the International Colour Association (AIC), 1981–85. He had over a hundred papers on color vision, color reproduction, and color measurement, and two books "The Reproduction of Colour" which had six editions, and "Measuring Colour" with four editions co-authored with Michael Pointer. His research included modeling the human system of color vision to predict colors appearance in different viewing conditions, and applying color science to practical problems in industry and in the environment. He was an Honorary Fellow of the Royal Photographic Society, Fellow of the Royal Society of Arts, Fellow of the Royal Television Society, Honorary Fellow of the British Kinematograph, Sound and Television Society, Honorary Member of the Society for Imaging Science and Technology, and Honorary Fellow of the Society of Dyers and Colourists. He was a member of the Royal Institution and served as one of its Vice-Presidents, 1985–87. He was awarded the Newton Medal of the Colour Group (Great Britain), 1974, the Progress Medal of the Royal Photographic Society, 1984, the Judd-AIC Medal of the International Colour Association, 1987, the Gold Medal of the Institute of Printing, 1989, the Johann Gutenberg Prize of the Society for Information Display, 2002, the Godlove Award of the Inter-Society Color Council (USA), 2007, and Honorary Fellowship of the Society of Dyers and Colourists, 2009. For services to the field of color science and to young people through Crusaders bible classes, he was presented by the Queen of Britain with the medal of an Officer of the British Empire (OBE) in 2009.

Robert Hunt was the author (or co-author) of the following entries:

- Bartleson, James
- Crawford, Brian Hewson
- Guild, John
- Stiles, Walter Stanley
- Wright, W. David

Eric Jacob Jan Kirchner was born on June 26, 1966. He received an M.Sc in Theoretical Physics from the University of Utrecht, the Netherlands. He was awarded a Ph.D. in 1993 in Theoretical Chemistry, at the Free University of Amsterdam. His Ph.D. thesis was focused on quantum mechanical calculations in chemistry. He worked as a researcher at the environmental state agency of the Netherlands until 1996, before starting to work as a quantum chemist at Akzo Nobel.

Since 2000, he has worked in the area of colorimetry, initially as research physicist for the Car Refinishes business unit. He became project leader and team leader of color innovation and is currently Principal Color Scientist for Performance Coatings where he investigated texture measurement and appearance. He has published several articles on the methodology for developing color difference equations, the best type of gray scales for such analysis, and the optimum design of the visual tests underlying those studies.

His current research interests include accurate representation of colors on electronic displays and their color calibration, and the history of color science in the Islamic world. Besides authoring dozens of scientific articles, he is also co-inventor in eight patent applications, and sole developer of five android apps related to color.

Eric Kirchner is the author (or co-author) of the following entries:

- Al-Biruni, Abu Rayhan
- Al-Farisi, Kamal al-Din
- Ibn al-Haytham
- Al-Tusi, Nasir al-Din
- Ibn Sina
- Ibn Sahl
- Ibn Rushd

Michal Vik is currently a Professor of Material Science at the Technical University of Liberec in Czech Republic and a research consultant for VUTS a.s.

His scientific activities are mainly in the areas of color science (color and appearance measurement, color difference formula development, quality control, development and design of instruments), textile material science (smart materials, advanced microscopy), and textile finishing (surface modification-plasma, photo-polymerization).

He has been a member of the Optical Society of America since 1999, board member of the Czech Society of Textile Chemists and Colorists (1994–2000), board member of ČNK CIE, Czech National Committee which is a national society of International Commission on Illumination, since 1999, a member of Division 1 of International Commission on Illumination (CIE) since 2003, and a member of CIE Technical Committees (TC1-55, TC1-63, TC1-72, TC2-61). Since 2010, he has been an expert member of the European Technology Platform—Textile.

Currently, he is the head of the Colorimetry Group of Czech Republic as well as leading the Color and Appearance Measurement Laboratory of the Department of Material Engineering of Technical University of Liberec. He is author or co-author of six books, five patents, about 20 scientific papers, as well as more than 150 scientific contributions on international conferences.

Michal Vik is the author or co-author of the following entries:

- Kubelka, Paul
- Purkinje, Jan Evangelista
- Mach, Ernst

Stephen Westland joined the University of Leeds in 2003 to take up a Chair in Color Science and Technology following academic posts at a School of Neuroscience (Keeled University) and a School of Engineering (Derby University). He was Head of School of Design (2006–2013) and Acting Dean of the Faculty for a semester in 2012.

He has published over 100 peer-reviewed papers, chapters, and books in the areas of color science, color imaging, and color design. In 2008, he was awarded a

Fellowship of the Society of Dyers and Colourists (SDC) and is currently the President of SDC. He was awarded the Royal Photographic Society's Davies Medal for work on color imaging.

He is also an Adjunct Senior Scientist at the Dental School of the University of Texas (USA). Since 2009, he has been a member of the International Advisory Board at the Colour and Imaging Institute at Tsinghua University (China). Since 1998, he has been a member of the International Editorial Board of the Journal of Coloration Technology and in 2006 helped to launch a new journal (as editor) Colour: Design and Creativity that was renamed in 2012 as the Journal of the International Colour Association. He is also a member of the editorial boards of Journal of Textile Science and Engineering (2011-) and the Slovene Journal for Textile Clothing Technology, Design and Marketing (2009-). He is the author of Computational Colour Science using MATLAB (published by Wiley in 2004) with a second edition published in 2012.

Stephen Westland is the author (or co-author) of the following entries:

- Rushton, William
- Dalton, John
- Itten, Johannes

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Part V Nineteenth Century to Present Day: The Industrial and Modern World

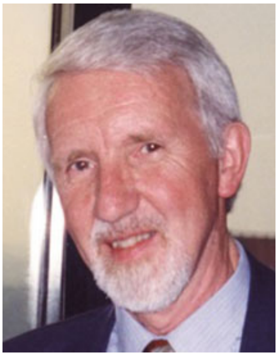
About the Authors

Renzo Shamey was born in 1967 and completed his basic and higher education in multiple locations. After receiving a Bachelor of Engineering degree in Textile & Fiber Chemistry in 1989, and a short stint in the coloration industry he obtained a Master of Science and a Ph.D. from the Colour Chemistry Department of Leeds University in England. After working on an industrial project for about a year, he joined Heriot-Watt University in Scotland as a faculty member for six years where he conducted research on color science and technology including the development of diagnostic expert systems. He then joined North Carolina State University (NCSU) in 2003, where he eventually became a professor in 2012. In 2018, he was named the CIBA Professor. He directed the Polymer and Color Chemistry (B.S.) and Textile Chemistry (M.S.) programs at NCSU for about nine years and is currently the head of the Color Science and Imaging Laboratory. He was awarded a Fellowship of the Society of Dyers and Colourists in 2010, the AATCC, JW Weaver Award in 2011, and an honorary professorship from Tianjin University in China in 2012. He has authored over 100 peer-reviewed publications, including several chapters and two books. In 2017, he was elected President of the Inter-Society Color Council of America (ISCC). He served as Technical Committee Chair in AATCC (Color Measurement Test Methods; Textile Education), CIE (TC1-76, co-chair), and serves on the editorial board of multiple Journals including Color Research & Application, and Coloration Technology. He is the current Editor in

Chief of the Encyclopedia of Color Science and Technology.

He has authored (or co-authored) the following articles:

- Plato
- Ptolemy
- Biruni, Abu Rayhan
- Al-Farisi, Kamal al-Din
- Ibn al-Haytham
- Al-Tusi, Nasir al-Din
- Ibn Sina
- Descartes, Rene Du Perron
- Newton, Isaac
- Maxwell, James Clark
- Chevrerul, Michel-Eugene
- Young, Thomas
- Mach, Ernst
- Purkyně, Jan Evangelista,
- Rood, Ogden
- Abney, William
- Lovibond, Joseph
- Albers, Josef
- Birren, Faber
- Adams, Elliot
- Hardy, Arthur Cobb
- Helson, Harry
- Hunter, Richard
- Stiles, Walter Stanley
- Luckiesh, Mathew
- Macbeth, Norman
- Nayatani, Yoshinobu



Rolf G. Kuehni was born and basically educated in Switzerland. He earned a degree in textile chemistry at the Textilingenieurschule in Krefeld, Germany. Kuehni moved to the USA in 1963, where he eventually became a dual citizen. Being involved in color matching of textiles, he became interested in color technology. In 1965, he joined Verona Dyestuffs, owned by Bayer Corp., as Manager of Development and Color Physics and became a member of the Inter-Society Color Council in 1967. He advanced to Vice President, Marketing/Textile Products for Bayer Corp. in the USA, and also was a Vice President in the successor company Dystar Corp. from which he retired in 2001. During these years, he maintained an interest in color science, being active in ISCC and in research committees of the American Association of Textile Chemists and Colorists. In 2002, he was invited to become an Adjunct Professor in color science at North Carolina State University in Raleigh, NC. From 1987–89, Kuehni was the editor of the journal Color Research and Application. He authored over 80 peer-reviewed scientific and technical papers and encyclopedia articles on color science and technology and is the author and co-author of six books on color. He is the recipient of the Armin J. Bruning Award in 1986 from the Federation of Societies for Coatings Technology, the Godlove Award in 2003 from the Inter-Society Color Council, the Olney Medal in 2005 from the American Association of Textile Chemists and Colorists, the ISCC Nickerson Service Award in 2015, and the ISCC Munsell Centennial Award for Science in 2018.

He is the author or co-author of the entries for the following pioneers:

- Aristotle
- Bacon, Roger
- Theodoric of Freiberg
- Forsius, Aron Sigfrid
- D-Aguilon, Francios
- Boyle, Robert
- Godlove, Isaac
- Harris, Moses
- von Bezold, Johann Friedrich Wilhelm
- von Goethe, Johann Wolfgang
- Grassmann, Hermann Gunther
- Helmholtz, Hermann Ludwig von
- Hering, Karl Ewald Konstantin
- Katz, David
- Kohlrausch, Rudolf Hermann Arndt
- Koenig, Arthur Peter
- Lambert, Johann Heinrich
- Le Blon, Jacob Christoph
- Luther, Thomas Diedrich Robert
- Mayer, Tobias
- Palmer, George
- Runge, Philipp Otto
- Schiffermuller, Ignaz

- Schopenhauer, Arthur
- Allen, Eugene M.
- Cohen, Jozef B.
- Evans, Ralph Merrill
- Hurvich, Leo Maurice
- Ives, Frederic Eugene
- Jameson, Dorothea
- Ladd Franklin, Christine
- Land, Edwin Herbert
- Munsell, Albert Henry
- Nickerson, Dorothy
- Ostwald, Wilhelm
- Priest, Irwin G
- Richter, Manfred
- Wyszecki, Gunter
- Hubel, David Hunter
- Indow, Tarow

Part I
The Classical Greek Period and Beyond

Contents

Abstract The first Part covers a brief introduction of philosophical discussions pertaining to color in ancient Greece and in particular three main philosophers who contributed to the advancement of science in general. Indeed a coverage of the history of science in many domains would not be complete without mentioning contributions from at least one of these philosophers. It is not therefore, any stretch of the imagination to include the great Greek philosophers Plato and Aristotle among the pioneers in the field of *Color Science*. Indeed, they may be regarded among the beacons of enlightenment in the Classical Greek period and among the first recorded individuals who significantly contributed to discussions pertaining to color formation and visual perception. While several other Greek philosophers also contributed to these discussions, as briefly discussed in the following introduction, it would be nearly four hundred years later when Ptolemy provided a revised and improved explanation that addressed the interaction of light with matter, which greatly influenced Islamic scientists over the next several centuries. This part lays the groundwork for important initial discoveries pertaining to the science of color both from a physical point of view and from a visual perception perspective. It is indeed on the shoulders of these giants that our current understanding of light and object interaction and a view of the externally perceived world continues to stand.

Chapter 1
Introduction

1.1 Color Theory in Antiquity

In the Western world, thinking about color began in antiquity in Greece. However, what the early Greek philosophers thought about color is uncertain for a number of reasons. The primary one is that original documents in which the philosophers personally describe their views no longer exist. What is available often dates from decades or even centuries later and is at times hearsay. Another issue is that the meaning of color names used by the original authors is not certain and can lead to confusion.

One of the earliest Greek philosophers was Pythagoras of Samos (ca. 540–ca. 495 BCE). He is perhaps best known for his theory about musical harmony. He is also considered to be the originator of the theory of extramission, the outflow of a kind of radiation from the eyes into the surroundings, resulting in information about form and color. A related question of the reality of what we see and experience was addressed by Parmenides of Elea (ca. 515–ca. 450 BCE). He described a goddess telling him that he must distinguish between the real world and the perceptions of form and color, which she described to him as being just appearances.

> Wherefore all these things are but names which mortals have given, believing them to be true—coming into being and passing away, being and not being, change of place and alteration of bright color. [1]

Another early philosopher concerning himself with color was Empedocles of Acragas (Sicily, Italy) (ca. 490–435 BCE), a follower of Pythagoras. He is presumed to be the first proponent of four basic elements of the universe: earth, water, air, and fire. As reported by an unidentified author in the fifth century CE:

> Empedocles declared that colors are what fit into the pores of the eyes. The differences in color derive from variations in mixture of the elements. There are four colors, exactly the same as the number of elements: white (leukon), black (melan), red (erythron) and yellow-green (ochron). [2]

R. Shamey and R. G. Kuehni, *Pioneers of Color Science*,
https://doi.org/10.1007/978-3-319-30811-1_1

The next important (in regard to color) Greek philosopher was Democritus of Abdera (ca. 460–370 BCE). He and his teacher Leucippus are considered the founders of the atomic theory of the universe. Democritus is the author of the statement

> By convention there is color, by convention sweetness and bitterness, but in reality only atoms and void. [3]

Democritus and his teacher considered the universe to consist of two elements: the solid and the empty. Solids are constructed from atoms. They differ in shape, size, and their components. Some of them result in harder substances than others. Between atoms is the void. As Aristotle reported, Democritus believed there are no real colors; they are generated by the movements of atoms. The Greek philosopher Theophrastus (ca. 371–287 BCE) described Democritus' view on primary colors as follows:

> According to Democritus there are four primary colors. White (leukon) is the smooth or slippery. All that is not rough and full of shadows is bright. … Black (melan) consists of opposite forms, rough, bumpy and uneven, resulting in more or less shadow. … Red (erythron) consists of similar if larger forms than heat. The larger the forms the more intense the redness. … The [green] (chloron) color is a mixture in equal parts of the hard and the empty. All other colors are mixtures of the four primary colors. [4]

Plato's views on color are presumably expressed in his description of a dialog between the philosophers Socrates and Timaeus [5]. To what extent these dialogs represent the supposed participant's ideas, and to what extent Plato's is not known. In paragraphs 67 and 68 of the dialog, Timaeus states:

> Colors are a flame which emanates from every sort of body and have particles corresponding to the sense of sight. … White [is] that which dilates the visual ray and the opposite is black. … Red, when mingled with black and white, becomes purple, but it becomes umber when the colors are burned as well as mingled. Flame color (purron) is produced by a mixture of auburn (orange-brown) and dun (phaion), dun by an admixture of black and white, and pale yellow (ochron) by an admixture of white and auburn. White and bright … falling upon a full black become dark blue (kuanoun) and when dark blue mingles with white, a light blue color (glaukon) is formed, as flame color with black makes leek-green (prasinon).

Somewhat later, a clearer theory of colors was offered by Aristotle who developed (for the time) a broad concept of natural science, which reaches into the present. The contributions of Plato and Aristotle to color are briefly discussed in the following sections.

With the Greek empire being taken over by the Romans, there was a general decay of philosophical and scientific activity in Greece, with the center of activity moving to Alexandria in Egypt. It was there that the mathematician, astronomer, and geographer Claudius Ptolemy (ca. 90–168 CE) wrote an extended text on optics in Greek, most of which is surviving in Arabic translations, which was later translated into Latin. Ptolemy discussed color in some detail. A significant new contribution was his mentioning of disk color mixture using a potter's wheel for rotation and by viewing small color stimuli differing in color from a distance [6]. In book V of his text on optics, he also offers an extended discussion with experimental results of light diffraction. However, these discussions are limited to water as the diffracting medium. Ptolemy is the final pioneer who is covered in greater detail in this chapter.

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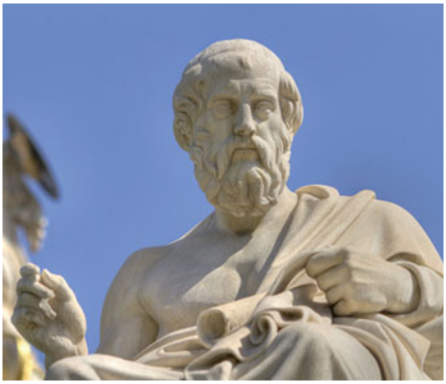
Chapter 2
Plato 427 or 424–347 BC



Statue of Plato at the Academy in Athens

The philosopher and mathematician known as Plato lived in Classical Greece and was an influential figure of the Classical Greek period.

Primary sources available from the period are rare, and thus our understanding of Plato's life is based on constructions by historians and scholars from scant sources that are available. It is estimated that Plato was born sometime between 427 and 424 BC. His parents came from the Greek aristocracy and his father, Ariston, was a descendent of the kings of Athens and Messenia, while his mother, Perictione, was likely related to the Greek statesman Solon. Plato's father died when he was young. The second marriage of Plato's mother was to her uncle, Pyrilampes, a Greek politician and ambassador to Persia.

Similar to children of his social class, Plato was likely taught by Athens' best educators. The curriculum would have featured the doctrines of metaphysics (the study of nature) and epistemology (the study of knowledge).

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Plato experienced two major events that significantly influenced his life: One was meeting the great Greek philosopher Socrates, and the other the Peloponnesian War between Athens and Sparta, in which Plato served for a brief time between 409 and 404 BC. Meeting Socrates impressed Plato to such an extent that he became a close associate and dedicated his life to the question of virtue. The defeat of Athens, the associated loss of individual freedoms, and the subsequent restoration of democracy resulted in Plato briefly considering a career in politics. However, when Socrates was executed in 399 BC Plato dedicated his life to study and philosophy.

After Socrates's death, Plato traveled for several years throughout the Mediterranean region, studying mathematics, geometry, geology, astronomy, and religion and began his extensive writings. Plato's writings include central ideals of justice, courage, wisdom, and moderation of the individual and society. He wrote "The Republic" which explored just government ruled by philosopher kings. Plato also deliberated on metaphysical ideas and the role of art, architecture, ethics, and morality in society. In the Theory of Forms, Plato proposes that ideas are constant while perceptions through senses are deceptive and changeable. He began a unique perspective on abstract objects, which led to a school of thought known as Platonism. Sometime around 385 BC, Plato founded a school of learning, known as the Academy, with curricula that included astronomy, biology, mathematics, political theory, and philosophy. The Academy in Athens was the first institution of higher learning in the Western world and helped shape the Western philosophy and science. One of Plato's most well-known students was Aristotle who is considered to be one of the pillars of science in the Western civilization. The circumstances surrounding Plato's death are somewhat clouded, though it is fairly certain that he died in Athens around 348 BC, when he was approximately 82 years old.

2.1 Plato's Chronicles on Color

Color in the Classical Greek period was of philosophical interest since it raised metaphysical issues, concerning the nature both of physical reality and of the mind. In the Classical Greece, direct consideration of human vision was used to describe color. The subject of colors appears more or less directly in three dialogs between Socrates and other philosophers as reported by Plato. In the dialog "Parmenides," Plato describes a discussion between Parmenides of Elea (born approximately 510 BCE) and a much younger Socrates about forms. Parmenides used the terms "light" and "night" to explain the fundamental dichotomy of the world that others interpreted as "light and dark," with all colors being derived from them.

In another dialog, "Meno" (76 C), Plato presents the views of a pre-Socratic philosopher from Italy, known as Empedocles of Agrigentum (495–430 BCE), on color perception. Empedocles is reported to have identified four primary colors, white, black, red, and, depending on the interpretation, either yellow or green [1]. He connected each of the four colors to one of the four elements in nature and regarded them to be correlative. Plato describes Socrates' view on this in "Meno" as follows:

> *Socrates: You and he believe in Empedocles' theory of effluences, do you not?*
>
> *Meno: Wholeheartedly.*
>
> *Socrates: And the passages to which and through which the effluences make their way?*
>
> *Meno: Yes.*
>
> *Socrates: Some of the effluences fit into some of the passages whereas others are too coarse or too fine.*
>
> *Meno: That is right.*

Plato's personal views on this topic cannot be gleaned from this conversation, although it may be argued that he appears to have followed this perspective since he does not oppose it. The most detailed discussion on color reported in Plato's dialogs is related to a philosopher from Greater Greece, the Italian Timaeus of Locri (life dates unknown). Most of the reported text is an extended presentation by Timaeus on his views about the universe. Plato quotes Timaeus describing colors as follows (67e–68d):

> We ought to term white that which dilates the visual ray, and the opposition of this black … In the eye the fire, mingling with the ray of the moisture, produces a color like blood, to which we give the name red. A bright hue [τὸ λαμπρόν] mingled with red and white gives the color auburn [xandon]. The law of proportion, however, according to which the several colors are formed, even if a man knew he would be foolish in telling, for he could not give any necessary reason, nor indeed any tolerable or probable explanation of them. Again, red when mingled with black and white, becomes purple, but it becomes umber [orphninon] when the colors are burned as well as mingled and the black is more thoroughly mixed with them. Flame color [pyrron] is produced by a union of auburn and dun [phaion], dun by an admixture of black and white, and pale yellow [ochron] by an admixture of white and auburn. White and bright meeting and falling upon a full black, become dark blue [kyanoyn] and when the dark blue mingles with white a light blue [glaykon] color is formed as flame color with black makes leek green [prasion]. There will be no difficulty in seeing how and by what mixtures the colors derived from these are made according to the rules of probability.

Thus according to the quote affiliated to Timaeus', elemental (primary) colors form a set of secondary and then tertiary, and quaternary mixtures of colors as schematically shown in Fig. 2.1. Additional colors could presumably be generated from further mixture. In addition, lightness seems to be present in the arrangement of colors as indicated by statements like "auburn plus white makes light yellow" and "dark blue plus white makes light blue"; however, there is no indication of a systematic arrangement of colors according to lightness in this description.

It is not known to what extent Plato agreed (or disagreed) with the claims of Parmenides, Empedocles, and Timaeus as no texts in which he expressed his own views are known. It appears that the philosophers of the time considered colors not objects on an artist's palette but energy forms of the objects themselves. In fact, according to this tenet the artists' colors are not objects. Colors are not pigmentary mixtures but theoretical conceptions, and the color bright is a symbol of idealism:

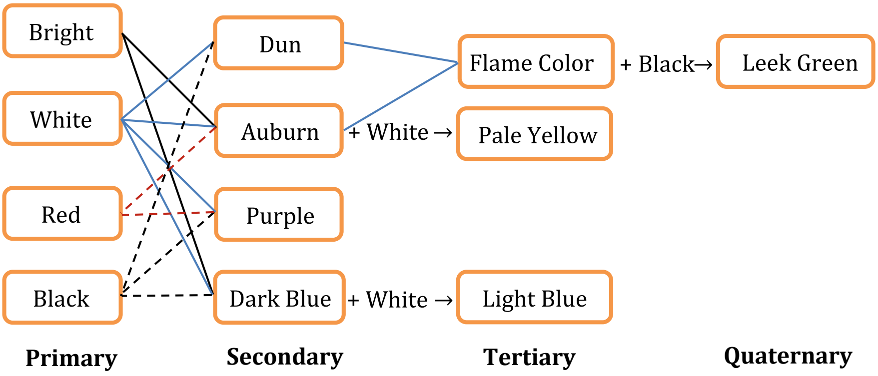

Fig. 2.1 A schematic representation of elemental colors and their admixture according to Timaeus [2]

the lifting of the human being above his level. The prevailing view pertaining to perception at the time was that objects' rays meet and mingle with the pure fire (rays) placed in all human eyes by the gods. Thus, the very act of seeing (or not seeing) is dependent on the size, strength, and speed of the rays originating from the objects. A scale represents the interaction between the energy forms and the eye, which starts from lambron, and extends from erython (red), to leukon (white), and ends with melan (black). Black represents a reaction weaker than that of white that fails to reach the eye. A system of fire (light) reactions was used to produce colors, whereby the most potent of these, lambron, overwhelmed the fire of the eye and expelled it. Therefore, some have argued that color intensity was more important than hue.

One may argue that the prevailing philosophical view on color at the time, including that of Plato, was that perception did not just result in colorful sensations but also created the qualitative character of our perceived world.

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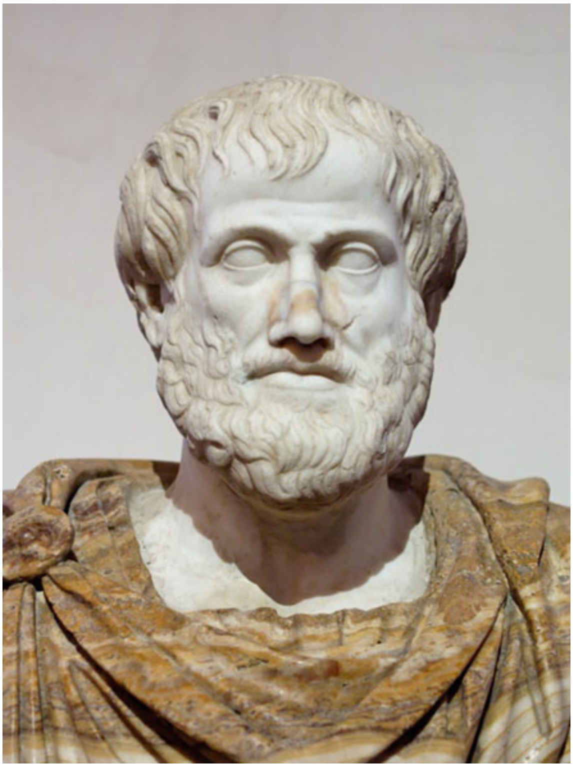
Chapter 3
Aristotle 384–322 BC



Roman marble copy of bronze bust by Lysippus, ca. 330 BCE

The classic Greek philosopher known as Aristotle was born in Stagira in northern Greece to a father who was the physician to the local king. At 18 years of age, he joined philosopher Plato's Academy in Athens where he stayed until Plato's death

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in 347 BCE. At that time, the ruler of Greece, Philip II of Macedon, requested him to tutor his son Alexander the Great, which he did for 33 years. Aristotle is often recognized as the World's first scientist. Tutoring Alexander provided various opportunities for Aristotle one of which was to set up in 335 BCE the Lyceum and its library in Athens, the leading educational facility of the time, where he taught until 323 BCE. Here, he is believed to have authored most of his written works.

It is generally assumed that only about one-third of his written works survived into the present. They consist of 47 essays, of which a few may actually have been written by followers as representing his views. The range of subjects is very wide, indicating how broad Aristotle's thinking and interests ranged. The subjects include several categories, including analytics, logic, physics, the universe and heavens, soul, senses, memory, sleep, animals, plants, ethics, morals, politics, rhetoric, poetry, and many more. The subject of color was of considerable interest to him. He covered it briefly in *Meteorologia*, more detailed in *Sense and Sensibility,* and at some length in the essay *On Colors* usually taken to have been written as representing Aristotle's views by Theophrastus, one of his followers [1].

3.1 Aristotle and Color

Known thinking about color in ancient Greece ranges back to Pythagoras in the sixth century BCE. He is said to have named the basic color species white, black, red, and yellow. These categories became influential and were related to the four elements of nature of the time: air, fire, water, and earth. A related important and controversial subject was the idea that eyes are sending out radiation that is reflected back from objects and reveals their colors (the emission or extramission theory), introduced by Empedocles. Aristotle, unlike Plato, was not a supporter. Aristotle expanded the list of basic color categories to seven. In *Meteorologia,* he briefly discussed the rainbow and attributed three colors to it: red, green, and purple. "These are almost the only colors which painters cannot manufacture; for there are colors which they create by mixing, but no mixing will give red, green or purple. These are the colors of the rainbow, though between the red and the green an orange color is often seen."

Aristotle did not relate colors to the elements and believed in the intromission of radiation into the eyes for the purpose of seeing. In *Sense and Sensibility,* he described his idea that five kinds of basic chromatic colors are generated by mixtures of white and black in simple ratios (3:2 or 3:4, for example). There are five such basic categories; he identified as yellow, crimson, violet, green and blue, "and from these, all others are derived by mixture." Aristotle was aware that divisibility into many ratios implied an infinity of possible colors.

In *On Colors,* his ideas are presented in more detail: "We must not proceed in this inquiry by blending pigments as painters do, but rather by comparing the rays reflected from the known colors, this being the best way of investigating the true nature of color-blends. Verification from experience and observation of similarities are necessary if we are to arrive at clear conclusions about the origin of different colors …." This brief excerpt provides insight into the breadth of his thinking on colors and his insistence on a scientific approach. His approach to problems was one of empiricism.

These texts, handed down through multiple paths of translation, have been read and commented on by many people over the past 2300 years. The ideas monopolized Western thinking on color into the sixteenth century and continue to have an impact today.

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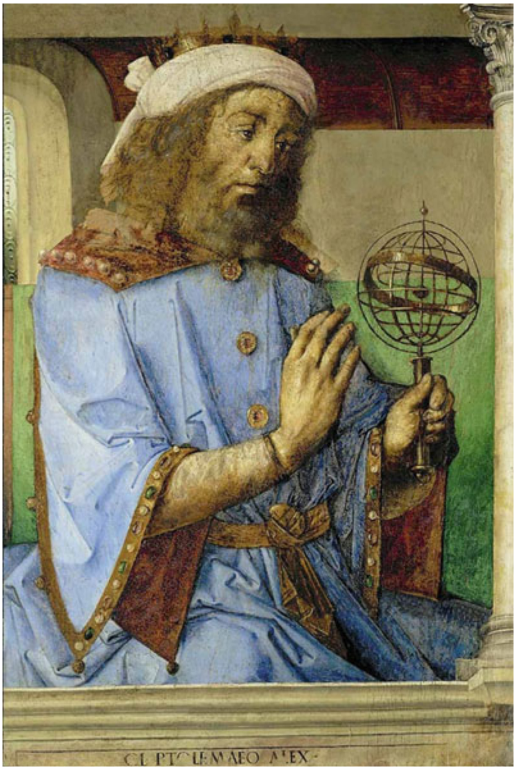
Chapter 4
Ptolemy, Claudius Ca. 87–100 to 161–180 AD



Ptolemy with an armillary sphere model, circa 1476, attributed to Pedro Berruguete and Justus le Gand, public domain via Wikimedia Commons

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Claudius Ptolemy, known in Arabic as Batlamyus, بطلميوس, was one of the most influential scientists of his time who made significant contributions to several fields including mathematics, geography, astronomy, astrology, and literature. His name is a mixture of the Greek Egyptian "Ptolemy" and the Roman "Claudius." The name Claudius indicates he lived under the Roman rule in Egypt, likely with the privileges and political rights of Roman citizenship. The name would have been taken by the first in Ptolemy's ancestry whom was granted citizenship, or himself, and if as was common, this was the Roman emperor Claudius, and it would be dated between AD 41 and 68 [1].

According to various sources, Claudius Ptolemy was born ca. 100 AD in Egypt [1]. He lived in or near Alexandria most of his life and died ca. 170 AD, also in Alexandria, Egypt [1, 2]. His recorded observations in Almagest, his astronomical treatise, can be traced back to the 11th Year of Hadrian's rule (127 AD) and Pius' reign (141 AD). If accounts related to him surviving until the rule of Marcus Aurelius are correct, then he may have lived to his eighties [2]. However, very little is known of Ptolemy's personal life including information pertaining to his ancestry or any significant relationships. Some scholars believe that Ptolemy was ethnically Greek [3], and some suggest he was a Hellenized Egyptian [4] and others, in Arabic sources, have referred to him as "the Upper Egyptian" [5]. The ninth-century Persian astronomer Abu Ma'shar Balkhi ابو معشر بلخى, also listed Ptolemy as a member of Egypt's royal lineage [6], although this has been disputed.

Ptolemy was the author of several scientific treatises, and his major works have fortunately survived. In general, he followed Aristotle philosophically; however, he regarded Aristotle's division of science into theoretical, productive, and practical science with far greater reverence. He wrote in Greek and utilized Babylonian astronomical data. His work was translated to Arabic and then to Latin [7]. His three major contributions that influenced Byzantine, Islamic, and European science are Almagest, Geography, and Astrological Treatise.

Almagest is the astronomical treatise discussing planetary theory and was originally entitled the "*Mathematical Treatise,*" also known as the "*Great Treatise.*" It was in use from the second century up to the late Renaissance [8]. This is thought to be Ptolemy's greatest contribution, providing, at the time, a satisfactory theoretical model to explain the rather complicated motions of the planets. Ptolemy wrote of his observations of solstices and equinoxes, and based on these observations, he determined the lengths of the seasons. He used geometric models to predict the positions of the sun, moon, and planets, using combinations of circular motion known as epicycles and then provided a model for the orbit of the sun, and the motion of the moon, as well as a theory of eclipses. Ptolemy then created a sophisticated mathematical model to fit observational data. His geocentric theory prevailed for nearly 1400 years until Copernicus offered a new one. In Geography, in eight books, Ptolemy attempted to map the known Greco-Roman world by giving latitude and longitude coordinates of the major locations. However, the maps drawn by Ptolemy were quite inaccurate because he was relying on data collected by questionable sources [9]. One of these maps was used by Christopher Columbus on his westward-bound trip to Asia, in which he discovered the Americas.

In Astrological Treatise, Ptolemy attempted to adapt horoscopic astrology to the Aristotelian natural philosophy of his day. Ptolemy claimed that while the Almagest calculates the positions of the heavenly bodies, his astrology book was a companion work describing the effects of the heavenly bodies on people's lives. This work is sometimes known as the Apotelesmatika but more commonly known as the Tetrabiblos or the "*Four Books.*"

4.1 Optics

Ptolemy's *Optica* represents an advanced stage in Ptolemy's intellectual development and consists of five books. The only surviving text of Ptolemy's Optics is a badly mangled, twelfth-century Latin version of an Arabic translation in about twenty manuscripts, which was translated by Eugenius of Palermo (c. 1154) [10]. Lacking any trace of the original, it is very difficult to reconstruct the Optics' early textual history with certainty. In Optics, Ptolemy writes about properties of light, the study of color, reflection (katoptrica), refraction (dioptrica), and mirrors of various shapes. The first chapter of the book deals with light, the visual rays, and color, which were unfortunately lost. One of its most striking features is believed to be the establishment of theory by experiment, frequently supported by the construction of special apparatus. There is a debate, however, whether the subject matter was derived or original. Nonetheless, it is an impressive example of the development of a mathematical science using physical data.

Ptolemy's work shaped part of the early history of optics [11] and influenced the more famous eleventh-century "*Book of Optics*" by Alhazen (Ibn al-Haytham). It contains the earliest surviving table of refraction from air to water and to glass. The refraction values (with the exception of the 60° angle of incidence) appear to have been obtained from an arithmetic progression [12]. Ibn al-Haytham devoted several studies to Ptolemy's Optics and wrote a critique, "*Doubts on Ptolemy,*" including a point-by-point discussion of Ptolemy's tenets. Ptolemy also differentiated seven colors in the rainbow, but his explanation of the phenomena was no different than that of Aristotle.

Optics is an important contribution to the early history of perception. Ptolemy's view on vision was based on an extramission–intromission theory, whereby the rays (or flux) travel from the eye and form a cone. The extramission was in line with the earlier model proposed by Euclid (c. 300 BC), and also Galen (130–200 AD), that shaped all geometrical optics [13]. The vertex of the vision cone would thus be within the eye, and the base would define the visual field. Ptolemy believed that the rays were sensitive and conveyed information back to the observer's intellect about the distance and orientation of surfaces. His ideas about perception were similar to those of Aristotle. He believed that color is what is seen and that spatial characteristics of the scene, i.e., information pertaining to size, shape, position, and movement, were not specific for sight. The final stage of the visual process according to Ptolemy was the judgment phase when sensation becomes perception [12].

An important aspect of this model was the relationship between size and shape of the object according to the visual angle subtended at the eye combined with perceived distance and orientation. The relationship between the distance of objects and size was not well defined until this point and Ptolemy provided an early model that related perceptual size to distance and thus shape constancy, and this view was supported by the Stoics [14].

Ptolemy was probably the first to describe color mixing including the optical mixing in the eye. He used a wheel with colored sections to obtain an impression of the required time for a single observation. He also discussed the mixing of individually bright colors in a mosaic from a distance, whereby each is not individually interpreted or perceived and an optical mixture is viewed. Ptolemy offered explanations for several phenomena concerning illumination and color, size, shape, movement as well as binocular vision. His discoveries in the field of binocular vision and the explanation of the process were not far from the correct model [15]. He also divided illusions into those caused by physical or optical factors and those caused by judgmental factors. He attempted to explain the Moon illusion where the apparent size of the moon or the sun on the horizon is enlarged and attributed this to the difficulty of looking upwards; this is considered to be somewhat abstruse [16, 17].

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Part II
Eighth to Thirteenth Century: The Islamic Golden Age

Contents

Abstract The second Part covers an important period of development in scientific discovery in an era known as the Islamic Golden Age. This period covers the 8th century to about the 13th century, and may be extended to around 14–16th Centuries. During this period, much of the historically Islamic world was ruled by various caliphates, and science, economic development and cultural works flourished. The land covered by the Islamic world extended from the Far East to Spain and

Africa. A love of knowledge was evident in many of the important cities of the time including Baghdad, Nishapur, Cairo, Samarkand, Tabriz and Isfahan. Scholars, philosophers, doctors, and other thinkers all gathered in these centers of trade and cultural development and it was not uncommon for academics to make long arduous journeys in pursuit of knowledge. Academics—many of them fluent in Persian, Greek, Arabic and Turkic languages—exchanged ideas and translated texts into the official scientific language of the time, Arabic. Baghdad replaced and overshadowed Damascus as the capital city of the empire. The Abbasids built Baghdad from scratch while maintaining the network of roads and trade routes the Persians had established. Abbasid Caliphs established a House of Wisdom in Baghdad—a dedicated space for scholarship. The House of Wisdom increased in use and prestige, from 813 to 833 and a special effort was made to recruit famous scholars. During the Golden Age of Islam, Arab and Persian scholars—as well as scholars from other countries—were able to build on the information they translated from the Greeks and others and forged new advances in many fields. The work of many of these scholars on color involved assessing gemstones, plants and the rainbow and led to the advancement of optics and astronomy. Ibn al-Haytham is listed among the first to have used a camera obscura in his studies of light and object interaction. He was also able to form an explanation of how the eye sees. Doctor and philosopher Avicenna wrote the *Canon of Medicine*, and the *Cure* [of ignorance] and also examined color order. Biruni, in his *Kitab al-jamahir* used color to identify minerals and gemstones and explored ‘saturation’ to describe slight color differences between them. Ibn Rushd in Spain revived Aristotle’s works and examined the formation of colors on the rainbow. Al-Khwarizmi, invented algebra, Tusi introduced trigonometry and expanded Avicenna’s color order system and Khayyam invented analytic geometry. Farisi, developed experimental studies and accurately explained the formation of the rainbow colors. While some of these scholars’ works were never translated into Latin many were studied in important Western universities of the time and influenced the path of advancement in the Western society over the scientific revolution period.

Chapter 5
Introduction

The advancement of science, including an understanding of color formation and visual perception, experienced a major leap during a period that would come to be known as the Islamic Golden Age. This period coincided with the medieval era in Europe where scientific discussions were confined to limited locations. In contrast, in the Islamic land, which extended from Spain to the Far East through Persia, major advances in medicine, mathematics, astronomy, alchemy/chemistry, and physics were witnessed by scholars and philosophers.

The works of Aristotle, discussed in Chapter I, were the focal point of many of the subsequent scholars who worked on vision and visual/color perception leading up to the Renaissance. The philosopher and mathematician Farabi, فارابی (d. 872) also known as the Second Teacher after Aristotle, and philosopher Suhrawardi, سهروردی, (d. 1191) as well as Ibn Rushd, ابن رشد, (d. 1198) were among those who promoted the Aristotelian views, including those on the formation of colors. According to this model, combinations of brightness and darkness, in varying proportions, result in formation of various colors. While Aristotle's approach to color theory was mainly philosophical, the corresponding developments by Islamic scholars were often more empirical. A good example of the empirical nature of investigations in this period is color mixing. Among important scholars, faithful to Aristotelian view, in some regards, is the scientist Ibn al-Haytham, ابن الهیثم, also known as Alhazen (d. 1039). Using a spinning top, he theorized color mixing and ascertained the need for a minimum length of time to observer individual colors. Fakhr al-Din al-Razi, فخرالدین رازی, (d. 1209), explained the color mixing on a millstone as follows:

> If we draw on a millstone from the center to the edge many lines of different colors, close to each other, and if the mill stone rotates fast, then we see only one color, which is evenly mixed from all these colors [1, 2].

Nasir al-Din al-Tusi, نصیرالدین طوسی, (d. 1274), Qutb al-Din al-Shirazi, قطب الدین شیرازی, (d. 1311), and Kamal al-Din al-Farisi, کمال الدین فارسی, (d. 1318) also examined this experiment and provided commentary.

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Aristotle's view on the formation of the rainbow and its number of colors, which was expanded by Ptolemy and others, was also favorably considered by several Islamic scientists. A good summary of the historical advance and understanding of the rainbow can be found elsewhere [3, 4]. At the time, no distinction was made between the rainbow primaries and pigments used by painters. On the number of colors present in the rainbow, the Islamic scholars showed their ability to break with the Aristotelian theories and their views often appear more logical to the modern reader compared with similar texts from the ancient Greeks. However, the distinction between colorimetric attributes lightness and hue was not made. Aristotle had believed that all colors have a natural, one-dimensional order. Most of the Islamic scholars took what turned out to be a midway position between Aristotle's view and that of Newton. Abu Ali Ibn Sina, ابو على ابن سينا, (d. 1037), better known as Avicenna, devoted an entire chapter to color in his *Kitab al-Shifa* and was among the first to brake away from the Aristotelian color ordering [5]. Ibn Sina identified three different paths in color space that lead from white to black and proposed a two-dimensional ordering. His works would become very influential both in the East and in the West. In the translation of his *Kitab al-Shifa* [Liber de Anima], it is stated:

> Moreover, if whiteness does not exist without light and blackness not in ways already discussed then whiteness and blackness cannot only be joined in one manner. A manifestation of this is the fact that white gradually passes to black by three paths. The first is via pale (light [yellow-green]) and its progression is pure: it will indeed be of pure progression, at first it progresses to pale (light [yellow-green]), from there to grey (yellow-green), and continuing in this manner until black is obtained, because thus proceeding to its limit it does not veer from gradually stretching towards blackness, until it becomes pure black. There is also another path proceeding [from whiteness] toward red (light red), and from there to red brown (red), thereafter to black. The third path is the one going to green (blue-green), from there to indigo, thereafter to blackness. And in these ways not all color diversity can exist, neither can they be the source of the diversity of [Aristotelian] median colors [5].

Al-Tusi was among those who chose to ignore the rainbow altogether in the description of color mixing and ignored the Aristotelian doctrine. Tusi, in a response to a letter from his student al-Katibi, الكتيبى, (d. 1276) who had asked a question about the color theory proposed by Ibn Sina, wrote that when yellow and blue colors are seen together, a green color is produced [6]. Al-Tusi recognized five different paths between black and white and stated:

> Regarding the production of colors from black and white there are numerous paths, from which one gradually walks from white to black. The path through yellow belongs there: First by the mixing of dense and fire, both in small amount, the strawyellow is produced, then the lemon-yellow, then the saffron-yellow, then the orange-yellow, then the grenade-yellow, then in it the tendency towards black increases, according to the increase in the number of dense particles and the decrease of fire, until it becomes black. Another path goes through red. First, it becomes rosy, then like evening-red, then blood-colored, then purple, then violet, violet-colored. One path goes through green. It becomes pistachio-colored, then leek-colored, then verdigris-colored, then egg-plant green, then naphta-colored. One path goes through blue. It becomes sky-blue, then Turkish blue, then lazur blue, then indigo-blue, then like kohl. One path goes through turbidity/dirt. It

> becomes grey, then darkish/dirt-colored, then dark etc. This all occurs according to the differences of particles in transparency, opacity (density), light and darkness. Now and then one sees a color together with another, and a different color is produced, such as green from yellow and blue, verdigris from green and white. There are infinitely many of such arrangements, and some are often found in small particles of plants and animals. Anyone who observes them is surprised by their number [7].

Several Persian scientists can be credited for their work on description of a limited hue scale. Abu Rayhan al-Biruni, ابوریحان بیرونی, (d. 1048) wrote a book entitled the *Kitab al-jamahir fi ma'rrifat al jawahir* (the book of the multitude of knowledge of precious stones) and discussed the colors of gemstones. Al-Jawahari al-Nishaburi, الجواهری نیشاپوری, (d. 1196), also wrote a series of works on minerals and gemstones. Al-Tusi and later Aboulghasem Abdollah Kashani, ابوالقاسم عبدالله کاشانئ, (d. 1300) used and expanded these texts and were the first to describe a hue scale [7]. Nishaburi, for instance, mentions that by mixing blue and yellow pigments in different proportions, colors are produced that change gradually from blue, via green, to yellow.

Some of the Islamic scholars also rejected the Aristotelian view from other aspects. Al-Kindi (d. 873), الکندی, for instance, redefined the role of the medium in color vision and argued that color is produced by dense objects that block the sight [8, 9]:

> vision does not see the transparent medium, but it sees the object on the far side of it.

In this regard, Ibn al-Haytham and Qutb al-Din al-Shirazi [10] also followed al-Kindi's view. Abu Rayhan al-Biruni is another important scientist that differed from Aristotle in the role of light on color vision. He stated changes in the light result in changes of the appearance of the object and that the position of the eye and the amount of light affect the perceived color [11].

> Often it changes with the incident light, so the water lily appears grey in sun light but red in candle light.

In his very influential work *Kitab al-Manazir*, Alhazen described how the perceived color of objects changes depending on the intensity of incident light [12]:

> We find further, that for dense objects with bright colors, purple, blue etc., when they are located in weak light and similar places, then the colors appear turbid. When they are in strong light, they become bright.

He also observed that color differences appear to be larger when light intensity is larger and concluded [13]:

> …This behavior indicates that the eye observes the colors of colored objects only according to the colors that fall on them.

Farisi (d. 1318) added that the same colored object is seen in a certain color in sun light, but in a different color in moon light and, yet in another color in the light of fire. Apart from that, colors also change when the illumination becomes weaker.

> When a colored body is illuminated and its color is observed, and if one slightly weakens the light, then one sees a different color, that tends to pale/achromatic. If one weakens further, then one observes yet another color, tending to darkness. It continues like this, until the light disappears. Many colors are observed in this way, that are ordered in a regular series based on the weakness from the first until the disappearance [12].

Having examined various aspects of color theory and color mixing during the Islamic period, it is not difficult to suggest that the early Western investigators of color, such as Grosseteste, Bacon, and even Newton, either directly or indirectly were influenced by the developments made by Islamic scholars more than what is currently assumed. Chapter III includes a few Western scholars who examined color over the period of 13–15 centuries.

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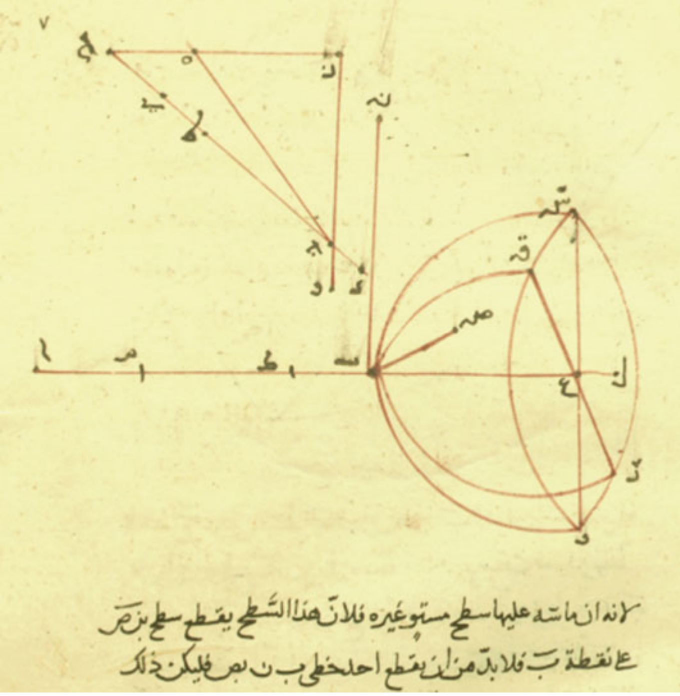
Chapter 6
Ibn Sahl Ca. 940–1000



لانه ان ماسه عليها سطح مستوٍ غيره فلان هذا السطح يقطع سطح ب ن ص
على نقطة ب فلا بد من ان يقطع احد خطي ب ن ب ص فليكن ذلك

With the triangles in this diagram, Ibn Sahl illustrated the law that is currently known as Snell's law. ©Iranian National Library, Tehran. Manuscript MS 687

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Abu Sa'd al-'Ala' ibn Sahl, ابن سهل, (c. 940–1000 AD) lived and worked as a geometer at the Abbasid court in Baghdad. The exact details of his biography and ancestry are unknown. He wrote important works on geometric optics, mathematics, and astronomy [1].

While investigating the transparency of the heavenly spheres that occur in Aristotelian cosmology, Ibn Sahl decided to study Ptolemy's classical work *Optics*, written in the second century AD. Thus, Ibn Sahl was the first of the Arabic sources to have read and correctly understood Ptolemy's theory of refraction [1]. Ibn Sahl utilized this theory in an entirely original way for constructing burning instruments such as lenses and glass spheres by means of refraction.

6.1 On Burning Mirrors and Lenses

In the year 984 AD, Ibn Sahl wrote the treatise *On Burning mirrors and lenses*. In this work, he investigated the optimum (non-spherical) shape of lenses and mirrors to focus light at a given distance. Ibn Sahl "appears to be the first in history to engage in research on burning lenses" [2]. He subsequently treated the parabolic mirror, the ellipsoidal mirror, the plano-convex lens, and the biconvex lens. His calculations on geometric aberration predate similar calculations done by Descartes in the 1620s, as discussed in Part IV. Ibn Sahl carried out these calculations both for light sources at an (almost) infinite distance such as the sun, but also for light sources at finite distances [3]. In these calculations, Ibn Sahl needed a law of refraction. Intriguingly, for this he used a law that is geometrically equivalent to Snell's law that would be re-discovered in 1602 by Thomas Harriot and in 1621 by Willebrord Snellius. The sine law of refraction was thus discovered by Ibn Sahl [4, 5].

The illustration shown at the beginning of this entry is taken from a page of Ibn Sahl's manuscript. In the top part of the figure, two overlapping triangles are shown. The hypotenuse of the external triangle represents the direction of incident light, while the hypotenuse of the internal triangle represents the direction of refracted light inside a transparent medium. By demanding that these two direction vectors intersect in one point, constructing the direction of refracted light with this figure is geometrically equivalent to keeping the ratio of sines of incident and refracted angles constant. This is known as Snell's law of refraction.

Ibn Sahl used this law of refraction several times in the treatise, but without explicitly stating it as a law [4, 5]. Indeed, the concept of natural law did not exist at the time. Ibn Sahl used his law as if it was a mathematical relation that was well known. He repeatedly applied this relation, utilizing the fact that the ratio between the sinuses of incoming and refracted angles is constant. He made no reference to the fact that this constant depends on material dependent properties, i.e., what is now known as their refractive index.

Ibn Sahl's treatise was later used by Ibn al-Haytham in his investigations of refraction. Interestingly, Ibn al-Haytham apparently did not recognize the law of refraction as used by Ibn Sahl. Instead, Ibn al-Haytham started his own experimental investigation into finding a law of refraction. While Ibn Sahl examined the refraction of light, his writing does not include a reference to vision [1].

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Chapter 7
Ibn al-Haytham (Alhazen) 965–1040

Ibn al-Haytham, alongside Galileo, in polish astronomer Johannes Hevelius's work on the Moon, Selenographia, published in 1647. Image from book's title page (*Source* Houghton Library, Harvard University)

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Abu Ali al-Hasan Ibn al-Haytham, ابن الهيثم (Latinized name: Alhazen), was born in Basra (in current Iraq) in 965 AD, but details of his ancestry remain uncertain. He made important discoveries in astronomy, mathematics, and optics. He died in Cairo in 1040.

Caliph al-Hakim of Cairo, impressed by Ibn al-Haytham's claim that he could regulate the flow of the Nile, persuaded him to come to Egypt. However, Ibn al-Haytham soon found out that he was not up to the task. He fell in disgrace and was placed under house arrest for many years. This proved to be beneficent for continuing his studies in mathematics, astronomy, and optics.

According to Aristotle, the light was a manifestation of a change of the state of the medium from opaque to transparent. Ptolemy had considered vision to be the result of visual rays, spreading out from the eye, that were reflected or refracted by surfaces of objects. Ibn al-Haytham (as well as Ibn Rushd) proposed an alternative view that light has a much more active role in color vision. It is light which is seen, according to Ibn al-Haytham [1]. Moreover, light is directed toward the eye instead of spreading from it. Ibn al-Haytham was the first to consider light as an entity by itself, traveling from visible objects to the eye, according to mathematical laws originally proposed by Euclid [2]. Regarding the role of the medium for color vision, Ibn al-Haytham adopted the view from al-Kindi, الكندى (d. 873), that the medium plays a passive role in color vision in the sense that it should not block vision.

In Ibn al-Haytham's theory, color is a distinct property of material bodies. He stated that color and light are distinct, but that colors behave exactly as light does in transmission, reflectance, and refraction. Therefore, Ibn al-Haytham's theory of light is at the same time a theory of color [3]. However, apart from formulating these theories, Ibn al-Haytham went further and designed many experiments by which he verified the proposal step-by-step and afterward subjected the results to thorough mathematical analysis [4, 5]. Nevertheless, Ibn al-Haytham also explored some more philosophical treatments of color and light [4].

7.1 Alhazen's Optics

His *Kitab al-Manazir,* كتاب المناظر (Book on Optics), made the works from Aristotle, Ptolemy, and Euclid obsolete. He merged their classical theories, combining the mathematical, physical, and physiological aspects into one unified optical theory. The *Kitab al-Manazir* also introduced the distinction between optics and physiology/psychology that is a cornerstone of modern optics and colorimetry.

In his work, Ibn al-Haytham attempted to show how illumination, hue, and saturation combine together into color perception. Although he was not able to establish a complete system of color attributes, his account is largely consistent.

In terms of scope, details and comprehensiveness of treatment, Ibn al-Haytham's observations on the subject of color perception are unequalled in any single writer before him. Vol. 2, p.43 of Ref. [5].

The *Kitab al-Manazir* would be the dominant text on optics for several centuries to come, both in the East and West. Latin translations appeared from 1200 until 1572 (*Perspectiva, De aspectibus, Opticae Thesaurus*), and in Italian around 1350 (*Prospettiva*). Basing themselves on what they read in this book, Kamal al-Din al-Farisi and Theodoric of Freiberg around 1300 discovered the correct explanation for the colors of the rainbow. Kepler also formulated the theory of the retinal image in 1604 using this book, and Willebrord Snellius discovered a few years later what is now known as Snellius' law of refraction. In the East, Ibn al-Haytham's work survived through its thorough treatment and further elaboration by Kamal al-Din al-Farisi (d. 1318).

Ibn al-Haytham's view of the active role of light in color vision made him investigate many crucial aspects of color vision. He described how changing the type and intensity of light affects the color appearance of objects, and how a stronger light intensity increased perceived color differences [6, 7]. Thus, Ibn al-Haytham came close to what has been called a key notion in colorimetry that color is the product of the eye, the light, and the object. In the words of Ibn al-Haytham:

> This behavior indicates that the eye observes the colors of colored objects only according to the colors that fall on them [6, 7].

Ibn al-Haytham was one of the first to use the word saturation as describing an aspect of color in his *Kitab al-Manazir*. Generally, it refers to the sensation one feels after a copious meal, indeed analogous to the modern English word saturation. In modern Arabic, the same word is still used for color saturation [8]. About this and other words related to color that appear in the *Kitab al-Manazir*, see Vol. 2, p. 43 in Ref. [5].

In other aspects, Ibn al-Haytham followed classical traditions. He supported the Aristotelian view that the colors of the rainbow are the result of mixing light and darkness, and the Ptolemaic interpretation that color mixing in the spinning top is a visual illusion.

Alhazen is among the few pioneers of color science who appears on a banknote. Figure 7.1 shows a copy of the banknote from the National Bank of Iraq.

Fig. 7.1 Al-Hazen's image in a 10 Dinar National Bank of Iraq note. (Wikimedia, this work was first published in Iraq and is now in the public domain because its copyright protection has expired by virtue of the Law No. 3 of 1971 on copyright, amended 2004 by Order No. 83, amendment to the copyright law)

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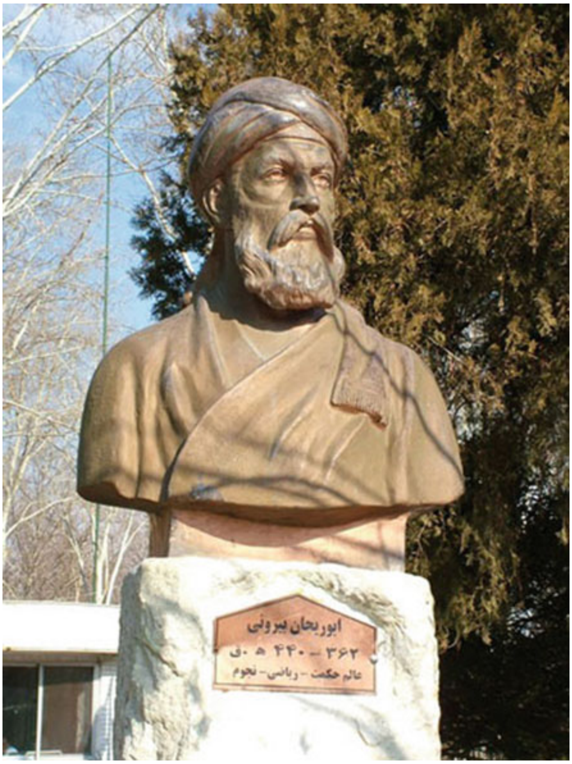
Chapter 8
Al-Biruni, Abu Rayhan 973–1048



Statue, Abu Rayhan Biruni, http://img8.irna.ir/1395/13950613/82214874/82214874-70988258.jpg

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Abu-Rayhan al-Biruni, ابوریحان بیرونی, was a Muslim scholar and a Persian polymath. He was born in the outer district of Kath, the capital of the Afrighid dynasty of Khwarezm (modern-day Uzbekistan) in 973. Details of his ancestry remain uncertain. He died in Ghazni (modern-day Afghanistan) in 1048 and is buried there.

He was well versed in physics, mathematics, chemistry, medicine, philosophy, and pharmacology and is considered the father of anthropology, founder of experimental mechanics and astronomy, and a pioneer of experimental psychology. He was conversant in Khwarezmian, Persian, Arabic, Sanskrit, and also knew Greek, Hebrew, and Syriac. Leaving his homeland, he left for Bukhara, and there he corresponded with his fellow scholar and philosopher Avicenna, who was also a well-respected Persian polymath and scholar. In 1017, Mahmud of Ghazni took the city Rey, currently on the outskirts of Tehran. Most scholars, including al-Biruni, were taken to Ghazna, the capital of the Ghaznavid dynasty. Biruni was made court astrologer and accompanied Sultan Mahmud on his invasions into India, living there for a few years. Biruni thus became acquainted with many things related to India.

8.1 Kitab al Jamahir

During Biruni’s travel in India, he not only taught Greek science, but in exchange he became acquainted with Indian science. This made him a strong promoter of this science in the Islamic world. At the court of sultan Mas’ud, al-Biruni wrote an important work on minerals and gemstones, called the *Kitab al-jamahir fi ma’rrifat al jawahir,* كتاب الجماهر فی معرفته الجواهر (The book of the multitude of knowledge of precious stones) [1–3]. In this lapidary, al-Biruni gives a detailed description of the colors of many minerals and gemstones. Color is used as a clear way to identify minerals and gemstones. He discusses extensively the slight color differences between minerals originating from different mines or having different degrees of purity, relating them to the effect this may have on their financial value.

The *Kitab al-jamahir* does not contain a separate chapter on color itself, or on color ordering. Nonetheless, taken together, many descriptions of color variations that appear in this book while discussing different types of minerals and gemstones do form a large body of scientific knowledge on color. Two centuries after al-Biruni, another Persian scientist by the name of al-Tusi would indeed collect many of al-Biruni’s findings and formulate an impressive color ordering scheme by combining them with other sources [4].

An example of this part of al-Biruni’s scientific legacy is found in his description of different types of rubies. According to al-Biruni, the colors of rubies range from sky blue via lapis lazuli and indigo-blue to kohl-black. Almost exactly the same color series is found in the grand color scheme of al-Tusi, with only the color turquoise having been added. In a similar way, not only many color words in al-Tusi’s grand color scheme already occur in al-Biruni’s work, but the latter also provided several partial color orderings.

Another interesting aspect of al-Biruni’s description of color is that he is one of the first to verbally describe one of the color dimensions. After having described the color series from sky blue, via lapis lazuli and indigo-blue to kohl-black, al-Biruni characterizes this gradual color change by the word *shab’a,* شبع (p.72 in Ref. [1], Vol. 2, p.42 in Ref. [5]). Originally, this word is used for describing the feeling one has after a copious meal, and it is best translated as saturation. In classical Arabic literature and in modern Arabic, the same word became the common word for color saturation (p.701 in Ref. [6]). Although the color sequence mentioned above shows

Fig. 8.1 Some of the stamps commemorating Biruni from top left to bottom right: Egypt, Soviet Union, Afghanistan, and Iran (Images obtained from public domain)

that the colors in this series do not change only with respect to color saturation in the modern definition of this word, al-Biruni's text is one of the first to relate this term to color [7].

Al-Biruni has been depicted in a number of stamps from different countries, as shown in Fig. 8.1, and a lunar crater is named after him.

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Chapter 9
Ibn Sina (Avicenna) Ca. 980–1037

Unknown artist, image obtained from public domain

Abu ‘Ali al-Husayn ibn ‘Abd Allah ibn Sina, ابوعلئ ابن سينا (Latinized name: Avicenna), was a Persian polymath and probably the most influential natural philosopher in Islamic history [1]. He was born near Bukhara (present-day Uzbekistan) in 980. His mother, Sitāra, was from Bukhara; and his father, Abdullāh, was an Ismaili scholar from Balkh (present-day Afghanistan) [2, 3]. He died in Hamadan (Iran) in 1037 at the age of fifty-eight from complications arising from colic.

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At sixteen years of age, famous physicians worked under his direction, and at the age of eighteen, Ibn Sina mastered the contemporary knowledge of the various sciences [4]. His massive *Qanun fi- 'l-tibb,* قانون الطب (Canon of Medicine), would be the main medical text in East and West until the seventeenth century [5].

The *Kitab al-Shifa,* كتاب الشفا (The cure [of ignorance]), is an equally immense four-part encyclopedia on mathematics, physics, and metaphysics [6, 7]. For several centuries, this would be the main text on natural philosophy. Here, Ibn Sina displayed his Aristotelian sympathies mainly by refuting alternative theories. For theories on light and color, this meant that Ibn Sina rejected the so-called extramission theories advocated by Ptolemy and Euclid, as described in Chapter I. Ibn Sina gave good arguments why it is absurd to assume that vision occurs by visual rays emerging from the eye. Instead, Ibn Sina explained vision in terms of Forms transmitted from the visible object to the eye (i.e., by intromission). In this respect, he followed Aristotle [8]. It would be Ibn al-Haytham, a contemporary of Ibn Sina, who would formulate an intromission theory as a successful fusion of the optical theories of Ptolemy, Euclid, Galen, and Aristotle.

9.1 Kitab al-Shifa

The *Kitab al-Shifa* contains a full chapter on color [9, 10]. In Chap. 4 Sect. 3, Ibn Sina was the first to break with the Aristotelian notion that all colors can be ordered along a one-dimensional line, writing:

> … the fact that white gradually passes to black by three paths. The first is via pale […], at first it progresses to pale, from there to grey, and continuing in this manner until black is obtained […]. There is also another path proceeding [from whiteness] toward red, and from there to red brown, thereafter to black. The third path is the one going to green, from there to indigo, thereafter to blackness [7, 10] (Depicted in Fig. 9.1).

Thus, Ibn Sina introduced what in modern terms would be called a two-dimensional color order (*cf. the illustration above*) [11]. It would become known in Christian Europe as well, for example, through its inclusion in the *Speculum majus* from Vincent de Beauvais (1244) [10]. Ibn Sina's texts on color were also widely discussed in the Islamic world. When more than two centuries after Ibn Sina's death a student of the astronomer al-Tusi formulated questions about Ibn Sina's color ordering, al-Tusi further elaborated on this theory [11].

In his commentary, Ibn Sina also criticized the Aristotelian ideas on color mixing. For example, he disagreed with the Aristotelian tradition that claimed green is composed of red and purple. According to Ibn Sina, a composition of red and purple does not produce green because from mixing red with purple, a color is

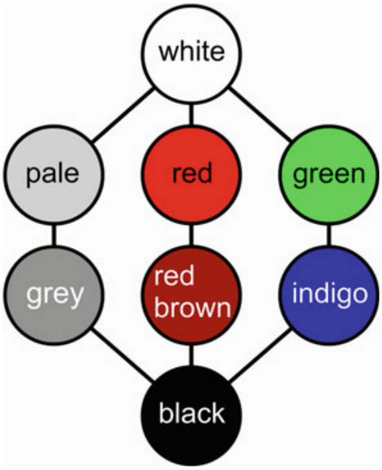

Fig. 9.1 Schematic representation of a 2D color order system according to Ibn Sina [11]

Fig. 9.2 Some stamps commemorating Ibn Sina from top left to bottom right: Germany, Mali, Poland, Comoros, and Soviet Union. (Images obtained from public domain)

Fig. 9.3 Twenty Somoni banknote from Tajikistan, which bears a portrait of Avicenna. (Wikimedia, this work is not an object of copyright according to the Law of the Republic of Tajikistan No. 726 of November 13, 1998, on Copyright and Neighboring Rights)

produced that is brighter than purple but more purple than bright red. Instead, according to Ibn Sina green is formed by a mixture of yellow, black, and indigo–blue [12]. Further, Ibn Sina made a clear distinction between the brightness of a light source (*lux*, in the Latin translation of Ibn Sina's work), and the "splendor" shining from an object (*lumen*) [13].

Finally, Ibn Sina was highly critical about what was known about the cause of the rainbow. He wrote that he was:

> not satisfied with what our friends the Peripatetics [i.e., Aristotle and his followers] have to say about the rainbow.

He continued by reporting some of his observations that cannot be explained by that theory, only to conclude that he himself also had nothing to add, except by a suggestion that the cause of these colors might be inside the eye of the observer [8].

A lunar crater and numerous monuments are named after Ibn Sina. Ibn Sina is among the few pioneers listed in this book with commemorations on stamps (Fig. 9.2), and he also appears on a banknote, as shown in Fig. 9.3.

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Chapter 10
Ibn Rushd (Averroes) 1126–1198

https://historiaespana.es/biografia/averroes

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Abu'l-Walid Muhammad bin Ahmad Ibn Rushd, ابن رشد, (Latinized name: Averroes) was born in Córdoba (Spain) to a family with a long and respected tradition of legal and public service in 1126. His father Abu al-Qasim was the chief judge of Córdoba [1]. Ibn Rushd died in Marrakech (Morocco) in the year 1198 AD, and his body was returned to Córdoba for burial [2].

His works range from philosophy, astronomy, and medicine to religion. He would be the most influential of Aristotle's medieval commentators, writing comments and corrections on all the Aristotelian works available to him [3]. Scholars in Christian Europe would refer to him as "the Commentator [of Aristotle]." The revival of Aristotelism in twelfth-century Europe was mainly based on Ibn Rushd's commentaries. However, in the Islamic world, Ibn Rushd's defense of rationalist philosophy would be less influential than the religious Asharite philosophy that emphasized divine manifestations in nature, as advocated by al-Ghazali (al-Ghazel) الغزالى.

Ibn Rushd tried to formulate a theory of light and color, as consistent with Aristotle and his followers as possible. Like Ibn Sina had done previously, Ibn Rushd provided many arguments why the so-called extramission theories from Ptolemy and Euclid were absurd, and vision cannot be caused by visual rays emerging from the eye. Similar to Ibn Sina, Ibn Rushd explained vision in terms of forms transmitted from the visible object to the eye, i.e., an intromission theory [4].

Ibn Rushd maintained that colors exist even when they are not perceived, and that light is necessary for colors to be visible [5]. In a manner similar to Ibn al-Haytham's approach, Ibn Rushd considered light as playing an active role in color vision, thus breaking with the traditional Aristotelian view. However, unlike Ibn al-Haytham, Ibn Rushd did agree with Aristotle that the medium also played an active role in color vision. Apparently, Ibn Rushd was not aware of the theory on the vision that had been proposed by Ibn al-Haytham, successfully combining the various classical theories into one mathematical–physical intromission theory of light, color, and vision.

10.1 Ibn Rushd's Color Theory

Ibn Rushd explained the different species of color as consisting of various mixtures of bodies of much or little transparency with bodies of much or little luminosity. Since every material is composed of the four elements, with only water and air being transparent and only fire being luminous, the color of a material can be attributed to the relative amounts of the elements. This explanation was later adopted by Theodoric of Freiberg (p. 172 of Ref. [6]), who explained it in terms of four principles (much or little transparency, much or little luminosity) of colors.

Ibn Rushd did not agree with Ibn Sina's criticism of the Aristotelian ideas on color mixing. In his *Jawāmi' al-āthār al-'ulwiyya*, كتاب جوامع الآثار العلوية, (Short Commentary on the Meteorology: 74, 19–76, 18), Ibn Rushd defended the Aristotelian view by arguing that it referred to color mixing in a qualitative sense,

Fig. 10.1 Stamp commemorating Ibn Rushd from Tunisia. (Image obtained from public domain)

but not in a quantitative sense [7, 8]. For example, Ibn Rushd argued that green is formed by mixing the yellow that exists in light red with the black that is in purple. From a modern point of view, this makes the approach philosophical rather than scientific. In addition, in his description of the rainbow, Ibn Rushd closely followed Aristotle: The rainbow forms by the reflection of sunlight on individual raindrops that reflect light and transmit color [6].

Ibn Rushd's ideas on color would be influential on later scholars. In his works on colors (*De coloribus*) and on the rainbow (*De iride*), Theodoric of Freiberg (d. 1318) makes clear that his theory on the formation of colors is based on Ibn Rushd's color theory (p. 47 of Ref. [9]; p.11 of [10]). Theodoric literally quotes the Latin translation of Ibn Rushd's *Tractato de* Sensu *et Sensato* (p. 35n2 of Ref. [9]) [11]. His description of the colors of the rainbow and also his four principles by which color is explained were all explicitly taken from Ibn Rushd's work.

A number of countries have issued stamps commemorating Ibn Rushd, with one example shown in Fig. 10.1.

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Chapter 11
Tusi, Nasir al-Din 1201–1274

Wikimedia, http://upload.wikimedia.org/wikipedia/commons/b/b6/Al-Tusi_Nasir.jpeg

Muhammad ibn Muhammad ibn Hasan al-Tusi, نصير الدين طوسى, usually known as Nasir al-Din al-Tusi, or Tusi, was born in Tus (today Iran) in 1201. During his life, he worked in Maragha (Iran) and Baghdad (Iraq). His influence reaches into many fields [1]. Tusi died in Baghdad (Iraq) in 1274.

He learned basic science and Arabic from his father, Wajih al-din ibn Hasan, وجيه الدين ابن حسن, who was a theologian and a scholar, and learned mathematics and logic from his uncle Noor al-din Shi'i, نورالدين شيعى. He then studied with Nasir al-din ibn Hamze, ابن حمزه, who was a well-known Shiite jurisprudent, and at his recommendation moved to Nishapur to study further. There, he studied

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Ibn Sina's work under Fakhr Razi's, فخر رازی, guidance. His work on reforming Ptolemaic theoretical astronomy would be crucial for later astronomers, including Copernicus. In mathematics, he published landmark editions of the works of Euclid and Archimedes and developed trigonometry as a discipline separate from astronomy. He wrote several works on optics [2]. Al-Tusi was born into a Twelver Shi'a family. For Shiite theology, al-Tusi wrote an important work on ethics and also authored the first systematic treatment of rationalist theology in twelve-Imam Shiism, a work still central in Shiite theological education.

Under patrons at Ismaili courts, he became a famous mathematician. When in 1256 under Mongol rule, Hulagu destroyed the Abbasid Empire; al-Tusi had taken refuge at the last Ismaili stronghold located on mount Alamut. After the Mongols destroyed also this mountain fortress, Hulagu personally saved al-Tusi's life since the ruler's interest in astrology made him respect al-Tusi's astronomical knowledge. Al-Tusi persuaded Hulagu to support building the first full-scale astronomical observatory in the world at Maragha. With al-Tusi as director, it would collect a mass of observation data for about 50 years, and it would inspire later observatories in Samarkand, India, and possibly even Tycho Brahe's observatory in Denmark.

11.1 Tusi's Color Order System

Al-Tusi thoroughly studied the works of Ibn Sina. When after teaching Ibn Sina's color theory, one of his students wanted to know more about it, al-Tusi replied in a letter:

> Regarding the production of colors from black and white there are numerous paths, from which one gradually walks from white to black. The path through yellow belongs there: First by the mixing of dense and fire, both in small amount, the straw-yellow is produced, then the lemon-yellow, then the saffron-yellow, then the orange-yellow, then the grenade-yellow, then in it the tendency towards black increases, according to the increase in the number of dense particles and the decrease of fire, until it becomes black.
>
> Another path goes through red. First, it becomes rosy, then like evening-red, then blood-colored, then purple, then violet, violet-colored. […]
>
> This all occurs according to the differences of particles in transparency, opacity (density), light and darkness. Now and then one sees a color together with another, and a different color is produced, such as green from yellow and blue, verdigris from green and white. There are infinitely many of such arrangements, and some are often found in small particles of plants and animals. Anyone who observes them is surprised by their number [3, 4].

Thus, while Ibn Sina had specified three paths from white to black, al-Tusi described five of such paths (see Fig. 10.1). They go via yellow, red, green, blue, and gray, *as illustrated in the Figure*. Remarkably, Forsius in 1611 also described five different tint/shade scales from white to black, as described in Chap. IV. This may all be compared to the German monk Theophilus (ca. 1120), who described how to produce up to twelve grades in a tint/shade scale [5]. The text of al-Tusi shows that he must have considered color space to be two dimensional. Interestingly, at approximately the same time in Latin Europe Grosseteste had argued on theoretical grounds that color space is three dimensional [6, 7].

In his work on minerals and gemstones, the *Tansukhname-yi Ilkhani* تنسوخ نامه ایلخانی, (The book on precious stones for the Ilkhan [i.e., for Mongol ruler Hulagu]), al-Tusi also describes a color theory [3, 8]. Written primarily by Nishaburi, نیشاپوری, and largely copied by al-Tusi and Kashani, کاشانی, these texts are the first to describe a limited hue scale. It describes that by mixing blue and yellow pigments in different proportions, colors are produced that change gradually from blue, via green, to yellow. This description represents a great step forward from the Aristotelian point of view that stated that green is one of the colors painters cannot produce (Fig. 11.1).

Fig. 11.1 Color order system according to Tusi [3]

Fig. 11.2 Stamps commemorating Tusi from Iran and Azerbaijan (Wikimedia, Commemorative stamp of Nasir al-Din al-Tusi from Azerbaijan.)

Although several scholars before Nishaburi and al-Tusi had mentioned that green can be produced by mixing blue and yellow, no earlier scholar had described that depending on the mixing ratios, different hues of green are produced [7].

The common opinion among scholars since Aristotle had been that by mixing black and white, all colors can be produced. However, following Nishaburi, Tusi wrote that

> if white color and black color are mixed with each other, an incense-grey color will result.

This had been stated only twice before in history, and in much less clear wordings. Clearly this statement, which was a starting point for Newton’s optical work, was not made for the first time by Scaliger in 1557, as is generally thought [9].

Tusi has been commemorated in a number of stamps from different countries with some examples shown in Fig. 11.2.

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Chapter 12
Farisi, Kamal al-Din 1267–1319

Wikimedia

Kamal al-Din Hasan ibn Ali ibn Hasan al-Farisi, كمال الدين فارسى, was born in 1267 in Iran. The exact location of his birth is uncertain with Tabriz, Shiraz, and Isfahan listed as possible locations. It is known that he traveled to these cities and studied with a number of scholars of the time. The exact details of his ancestry, however, are also unknown. At the time, Tabriz was a center for scientific discovery, and Farsi studied at the school of Tabriz with the famous astronomer Qutb al-Din al-Shirazi, قطب الدين شيرازى, who in turn was a student of Nasir al-Din al-Tusi. Farsi died in Tabriz in 1319 [1].

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12.1 Farisi and Color

Al-Farisi felt “perplexity” when he found several inconsistencies and errors in the classical works about optics [1]. His teacher then managed to obtain a manuscript copy of the *Kitab al-Manazir* from Ibn al-Haytham, which was brought in “from a very distant land (probably Egypt).” Farisi was greatly impressed by this work and decided to write a detailed commentary on it. He discussed it in great detail and completed it by adding appendices with other optical writings. Al-Farisi also included corrections to these texts, aptly calling the resulting work *Tanqih al-Manazir,* تنقيح المناظر, (Revision of the *[Kitab] al-Manazir*) [2].

In one of al-Farisi’s comments in the *Tanqih,* he described how an object is seen in a certain color under sunlight, but in a different color under moonlight, and yet in another color in the light of fire. From this, al-Farisi concluded that colors are not really present in objects, but depend on illumination [3]. The role of incident light had therefore been changed from being a mere catalyst for color vision as in the ancient Greek theories, to being as prominent as in modern color theory [4].

Together with his teacher Qutb al-Din al-Shirazi, al-Farisi tried to find explanations why the famous experiment of Ptolemy, with a spinning top (or mill stone) having sectors painted in different colors, led to new colors [5].

Regarding the colors of the rainbow, Ibn al-Haytham had supported the Aristotelian idea that these were due to a mixture of light and darkness. Al-Farisi rejected this concept. He argued that if it was true, then the colors of the rainbow would be ordered from bright to dark. In addition, the secondary rainbow would then have the same color order. Neither is supported by observation [6].

However, Farsi would become the most famous for his experimental study of the formation of rainbow colors. Inspired by Ibn Sina’s work and by Ibn al-Haytham’s *Kitab al-Manazir* and the latter’s treatise on the burning glass sphere, he filled a glass sphere with water and considered this as a model for a droplet of rain water in the atmosphere. He then studied the resulting reflection and refraction of light in a darkroom (see illustration in Fig. 12.1). This led him to the first correct explanation of the colors of the rainbow, which he described in the *Tanqih*. Interestingly in Germany, at approximately the same time also Theodoric of Freiberg, equally inspired by the *Kitab al-Manazir*, carried out the same experiment and formulated the same conclusions.

It was recently discovered that in his *Tanqih*, Farsi included the text of Tusi on color ordering, in which five paths were proposed to go from white to black [7]. In this way, this text would become available to many later generations. Farisi also sought for an explanation of the different orderings of the colors in the primary and secondary rainbow. His darkroom experiments let him conclude that various colors of the rainbow were produced by a superposition of different images as projected after reflections and refraction in the sphere [8]. Thereby, the colors became a function of the positions and luminous intensities of the composing images [9, 10].

The *Tanqih al-Manazir* would become widely spread in the Muslim world, where it was used in academic classrooms and would be commented upon until the

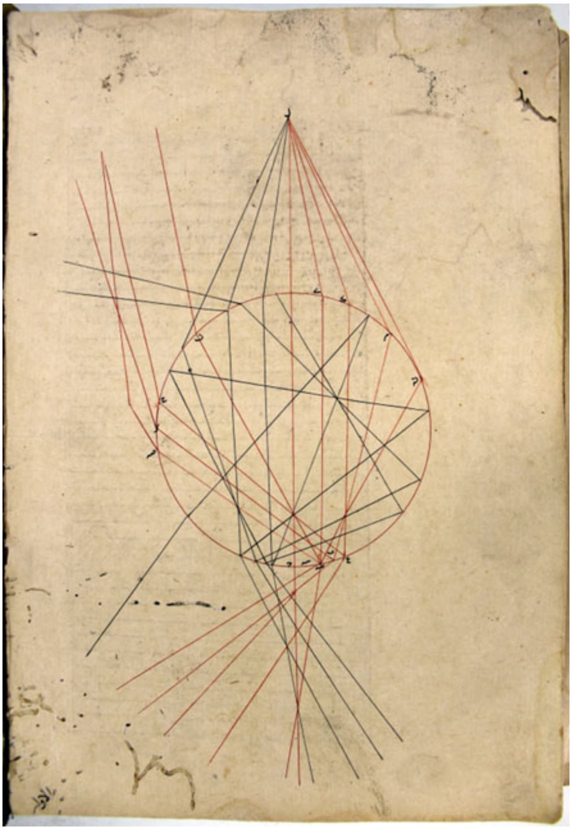

Fig. 12.1 Double refraction and single reflection in a raindrop. Simultaneously with Theodoric of Freiberg, al-Farisi was the first to give the correct explanation of the rainbow in his *Tanqih al-Manazir* (©Library of the Masjid Sepahsalar, Tehran)

sixteenth century. Therefore, in the Muslim world, this would be the main textbook on optics for more than three centuries. Since it was never translated into any Western language, its influence on European science is marginal at best.

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Part III
Thirteenth to Fifteenth Century: Middle Ages and The Renaissance

Contents

Abstract Part 3 provides a brief review of discussions pertaining to color in the Middle Ages leading to the Renaissance. As will be seen, only a few notable individuals in the Western civilization are recorded to have made significant contributions to this domain over the period. This era was the intersection of two significant and important periods in the history of developments in color science: the Islamic Golden Age, which provided considerable contributions to several domains including optics and the natural world (e.g. vision science); and the Scientific Revolution period in Europe that generated several seminal contributions including those by Newton and Young, among others. In contrast to the Islamic world's attitude towards science, which encouraged discovery and debate, the Catholic Church of the time required approval of all scientific and natural world discoveries before they could be supported. Non-compliance could often lead to confinement, financial hardship or even death. However, in concert with any other major developments there were individuals who took steady and gradual steps and dared to provide alternative explanations even in the face of hardship or incarceration. The works of the great eastern scientists Al-Hazen, Avicenna and Averroes, among others were being translated and examined in various universities in Europe over this period. One of the Western pioneers, Bacon, studied their works as well as those of Aristotle during his tenure at Oxford and Paris. He was also placed under house arrest or was incarcerated for a period by the Church. Interestingly, our other pioneer, Dietrich, was a theologian and a leader of the German Dominican Order, and arguably he made one of the most notable discoveries pertaining to color in this period. Independently from Tusi in Persia, Dietrich also examined the refraction of light by water and explained the colors of the rainbow. The relative lull in scientific discovery of this era would be more than compensated by the explosion of knowledge in the next period.

Chapter 13
Introduction

In the Middle Ages, there was an influx of translated works of later Greek philosophers such as Plato and Aristotle and the early Arab philosophers/scientists introduced into Europe as shown in the previous section. They were read by scholars and representatives of the church resulting in thinking about and experimenting in several fields, including the nature of colors. Early universities, beginning in the late eleventh century CE, such as those in Paris, Oxford, and Bologna, were founded by the Catholic Church to teach theology, medicine, law, and the arts. They usually had broad libraries of handwritten works available for study as well as the means to produce multiple copies of given works. Talented people had the opportunity to teach new students their insights and findings, often considerably influenced by classical texts.

One of the first university-related color theorists was Robert Grosseteste (ca. 1175–1253). Little is known about his early life but around 1230, he taught at Oxford University as well as at the Franciscan Convent in the same city. In 1235, he was named Bishop of Lincoln. His most important student was Roger Bacon. Before becoming a bishop, Grosseteste developed an interest in scientific work, perhaps as the result of his study of Aristotle's works. He authored several brief works on astronomy, geometry, light, the rainbow, and color. What he wrote about color is very brief and obviously influenced by Aristotle [1].

It is likely that Grosseteste was instrumental in opening his student Roger Bacon's mind in regard to science and specifically color. As his entry, in the next section, shows Bacon moved the discussion about colors forward in a significant manner.

Another English Franciscan writing about visual optics was John Pecham (ca. 1235–1292). He was for a time in Paris when also Francis Bacon was there and it is quite certain that they were in contact and the slightly older Bacon influenced Pecham's views and writing on optics in his work *Tractatus de perspectiva* [2].

Another theologian of the time with interest in science was Erasmus Witelo (ca. 1230–1300), son of a German father and a Polish mother. He studied arts in Paris and canon law in Padua. He was much influenced by the writings of the Islamic

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scientist Alhazen. Together with Alhazen's seven books on optics Witelo's main work, *Perspectiva*, a discussion of optics, was published in book form in 1572 as *Vitello's 10 books on optics* [3]. Most of it (474 printed pages) is an extended commentary on Alhazen's text. However, at the end, he discusses the rainbow and how it is generated by refraction, mentioning the reverse order of colors in the two bows that are often visible. Further, he states

> The colors of the rainbow are also generated by a hexagonal crystal placed opposite the sun (Book 10, para. 83).

Theodoric of Freiberg (ca. 1245–1320) is the youngest of these Middle Age thinkers and researchers about color vision. His biggest achievement in this field is his independent, scientifically sound explanation of the rainbow, as explained in his entry in the next section.

It was artists and art theorists of the Renaissance who initiated color discussion of their time, followed by major developments in the science of color. One of the earliest writing on the subject of color was the Italian architect and painter Leon Battista Alberti (1404–1472), the author of a manuscript entitled *Della pictura libri tre* (Three books about painting), ca. 1435 [4]. He disavowed interest in the philosophers' arguments about color, considering it only from the point of view of a painter. He stated

> Through the mixing of colors infinite other colors are born, but there are only four true colors – as there are four elements … Red is the color of fire, blue of the air, green of water and of earth [what is interpreted as a dull yellow] … There are four color genera, and these make their species according to the addition of dark and light, black or white. They are thus almost innumerable.

One of the most important painters of the time was Leonardo da Vinci (1452–1519). In addition to being a renowned painter, he was also an engineer and a scientist. He kept extensive notebooks on many subjects, later sorted into themes. One of these was named *Trattato della pittura* (Treatise on painting, da Vinci, 1956) [5]. In his most extensive note on color, he related chromatic colors to the four elements in essentially the same fashion as Alberti had and wrote:

> The simple colors are six of which the first is white … yellow the second, green the third, blue is the fourth, red the fifth and black the sixth.

As will be shown, in the next two centuries, progress in the field of color was mainly made in regard to optics, as optical equipment became more and more sophisticated, while color itself remained largely a matter of speculation.

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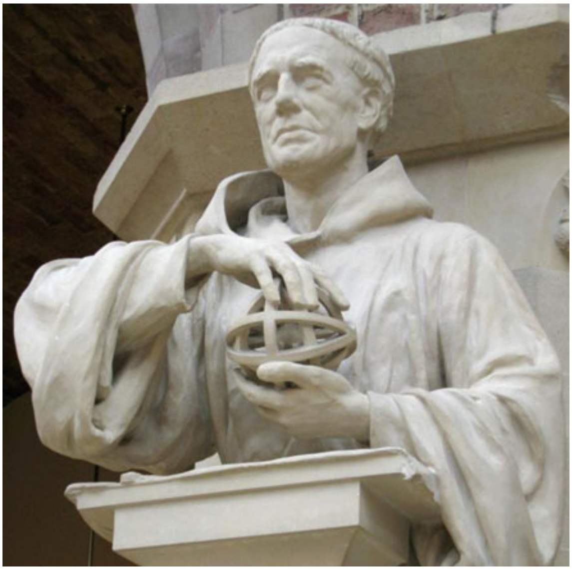
Chapter 14
Bacon, Roger 1214–1268



Statue in the Oxford University Museum

Roger Bacon was born ca. 1214 near Ilchester in Somerset, England, into a family of landowners. Details and dates of his biography remain quite uncertain with opinions often varying widely. He spent eight years at Oxford University, where he received an advanced degree. It is likely that one of his professors at the time was Robert Grossteste who had an interest in the subject of color. Bacon became a professor at Oxford lecturing on Aristotle and his works, probably in 1233. In the early 1240s, Bacon moved to Paris where he was offered a position as a lecturer at the University of Paris. There, he further studied and taught Aristotle's works on

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nature and wrote commentaries on some of them, including those dealing with the subject of color. He also studied in detail the science-related writings of the Islamic scholars Alhazen, Avicenna, and Averroes (ten to twelfth centuries). Either in Paris or after his return to Oxford, he became a Franciscan friar. Bacon returned to Oxford circa 1247 where he further informed himself on the works of Grosseteste and his ideas about science.

The subjects of ancient Greek philosophy and the sciences were not at the time generally approved by the Catholic Church, and Bacon was for a time confined or even imprisoned for teaching subjects not considered to be doctrinal. Circa 1255, he made the acquaintance of Cardinal Guy le Gros de Foulques, who later became Pope Clement IV and who secretly supported him. Bacon wrote several works that he submitted to the pope for his approval including the *Opus majus* (major work, an 840-page effort to present the knowledge about the world of his time, submitted in 1267 [1], the *Opus minus* (less important work) and an *Opus tertium*. Pope Clement died in 1268 with Bacon thereby losing his protector. Bacon lived out his remaining years at the Franciscan House in Oxford. He is believed to have died in 1294. In addition to the three mentioned works, he was the author of many more texts, some discovered much later. He is considered to be an important early force pushing for scientific investigation [2].

14.1 Bacon and Color

Bacon's views on color, originally based fully on Aristotle and the Islamic scholars, developed over his lifetime, influenced by Grosseteste and his views about science. At the time, the most influential view about color in Western civilization was that of Aristotle, with his five hue species arranged between white and black, species thought to be generated by mixtures of white and black. Bacon became influenced by the late ($\sim$second century CE) Greek author Porphyry and his "predicables," a system of classification based on ideas of Aristotle [3]. The five related classes are (1) genus, (2) species, (3) difference, (4) property, and (5) accident. Bacon applied these to colors: He decided that there are five genera: albedo (whiteness), glaucitas (yellowness), rubedo (redness), viriditas (blue–greenness or grueness) and nigredo (blackness). On the next level, the species, there are the colors that represent these genera: white, yellow, red, blue–green, and black. Mixing the principal species results in differences, such as orange and purple, "composite colors" as he also described them. It is not clear what, for Bacon, represented the class of property but there are hints that he thought along the lines of a concept now expressed as colorfulness. Accidentally, he used to designate different levels of lightness and darkness of colors. Thus, he revised Aristotle's system in substantial ways [4]. In each of the five genera, Bacon included a number of typical color names as represented by objects or lights, most of them in the genus *viriditas* ranging from *viridis* (green) to azure (blue–green) and further to caeruleus (sky blue) and venetius (navy blue). Bacon explicitly rejected Aristotle's idea of chromatic colors being the result of different mixture ratios of white and black [4].

The idea of three primary chromatic colors had already been introduced in Chalcidius' fourth century CE translation with commentary of Plato's *Timaeus* [5]. However, the text was largely lost and not referred to by Bacon. Three primary chromatic colors became a standard point of view in the sixteenth century as expressed, for example, by Camillo Leonardi in 1502 [6] and Filippo Mocenigo in 1581 [7]. The concept was described and graphically expressed by Franciscus Aguilonius in 1613, as described in Chap. 4 [8].

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Chapter 15
von Freiberg, Dietrich 1245–1320

Sculptural image of Dietrich von Freiberg on the Fortuna fountain in Freiberg, Saxony, Germany by Bernd Göbel

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It is generally assumed that Dietrich (Theodoric) was from and active in Freiberg in Saxony, Germany. However, it is known that he also spent a considerable amount of time elsewhere in Europe including France and Italy. Unfortunately, his life dates are not accurately known either, though he is believed to have been born ca. 1245.

After studying theology, he proceeded to study logic, in particular the writings by and about Aristotle. In 1271, he was a lecturer in the Dominican Monastery of Freiberg. He studied theology at the University of Paris, France, between 1272 and 1275. He was elected to be the leader of the Dominican Order in the German region in 1293. Around 1297, he was elected to the position of master of theology in Paris. In later life, he continued to be a leader in the German Dominican Order but also spent time in Toulouse, France, and in Piacenza, Italy. An influential German Dominican of his time was Meister Eckhardt (ca. 1260–1327). Both made important contributions to philosophy and theology of the time. Dietrich is also considered to be an early advocate of the scientific method. He is believed to have died ca. 1320 [1].

15.1 Study of the Rainbow

Dietrich had an interest in natural sciences and wrote a number of papers on various matters often covering a given subject and its philosophical implications. On the matter of color and light, he wrote three papers:

De iride et radialibus impressionibus (On the rainbow and impressions created by radiation)

De coloribus (On colors)

De luce et eius origine (On light and its origin)

There is disagreement on the sequence of these writings. It is generally assumed that they were written between approximately 1305 and 1312 [2].

In *De iride,* Dietrich offered an independent experimentally supported, essentially correct, hypothesis of the origin of the rainbow. This involved filling a round glass bottle with water and observing under what angles of view a beam of sunlight was reflected and refracted by glass and water. As was mentioned in Part II, a similar approach was used independently by the Persian philosopher/scientist Kamal al-Din Farisi (1267–1319) which he described in *Tanqih al-Manazir* [3]. Dietrich compared his results to the observations of a beam of sunlight passing through a hexagonal natural crystal that was called “iris” (Fig. 15.1) (Glass prisms only began to be used in the fifteenth century) as well as in crystal spheres and water droplets. He used extensive experiments to arrive at an interpretation of the primary and secondary rainbows (Fig. 15.2).

In *De coloribus,* Dietrich discussed the views of Aristotle, Avicenna, and Averroes. In regard to primary colors, he did not differ from Aristotle’s idea that chromatic colors are the result of mixtures of the extremes, white and black. However, his investigations of the rainbow made him change the sequence of the

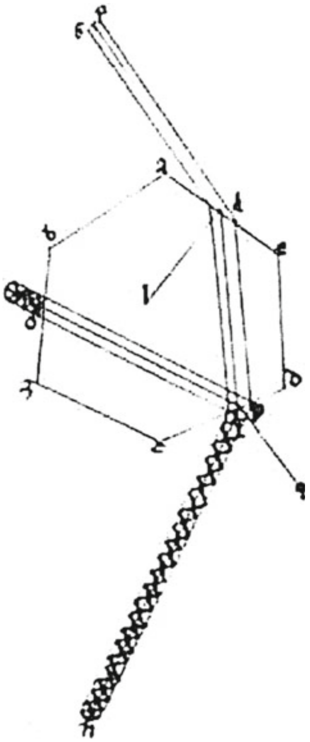

Fig. 15.1 Drawing of the passage of beam of sunlight and its refractions through a hexagonal natural crystal, the beam entering from the bottom left

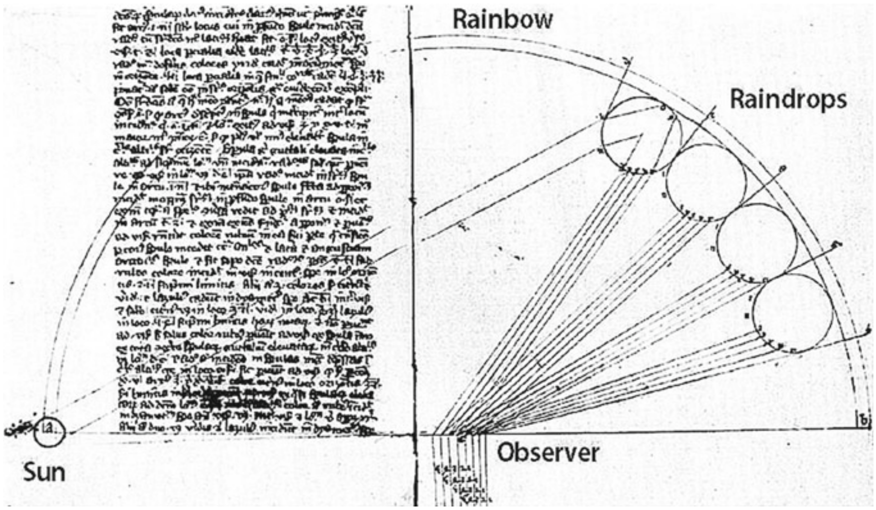

Fig. 15.2 Two pages of the handwritten manuscript of *De iride*, with an illustration of the formation of the rainbow at a specific angle in water droplets of rain [2]

chromatic colors from Aristotle's to be in agreement with the sequence he observed in his hexagonal device and in the rainbow. He said:

> The second kind [chromatic colors] differ thus in that in red and in yellow whiteness prevails, while blackness predominates in green as well as in blue … in the first combinations whiteness predominates, but red is nearer to the extreme, which is white, and yellow farther away. In combinations where blackness dominates blue is closer to black and green is less so. The middle colors stretch in this order to form the rainbow.

Thus, his sequence of primary colors is white–red–yellow–green–blue–black. He did not include purple because it does not appear in the rainbow. This sequence of the chromatic primaries has a factual basis, while those of later authors, such as Leon Battista Alberti (1404–1472) [4] continued to be based on philosophical ideas of the time.

The next chapter includes a discussion of advancements in the field during the Scientific Revolution Period.

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Part IV
The Scientific Revolution Period

Contents

Abstract Part 4 covers a significant period of advancement in science including color formation and visual perception, a time period from about the middle of the 17th to the middle of the 19th centuries. Unlike the relatively quiet period for scientific discovery in the West during the 13–15th Centuries, as discussed in Part 3, the scientific revolution period provided a significant range of discoveries encompassing many domains that may fall under the general umbrella of *Color Science*. This is also the period in which the first industrial revolution began, connected with a spread of capitalism and replacement of manual labor with machinery and other inventions. It is part of a time period known as "The age of enlightenment", bringing in new thinking in many areas. The work of many of the scientists in this period laid the foundations for important discoveries in the 19th and 20th centuries. This Part includes 19 pioneers who significantly contributed to the development of important theories and concepts pertaining to color. Among the first subjects under consideration was the development of systems of ordering perceived colors in a perceptually and logically meaningful way, beginning with Forsius who is considered to be the first Finnish scientist. Another subject pertained to the results of color mixture and the perceptual

separation of colors into primary and secondary ones (see e.g. Boyle). In this period, a key contributor to knowledge about color was Newton who believed in solid scientific experimentation. Newton is arguably responsible for our current understanding of color as a result of light and object interaction. His spectral color wheel has a partly quantitative nature. Establishing a quantitative relationship between what later was called the wavelengths of light and perceived colors was among his key contributions. Goethe, who philosophically disagreed with Newton's views on color, is among the pioneers whose work is briefly discussed. Among other pioneers is a Czech scholar, Purkyně, who contributed significantly to our understanding of visual perception under different illumination conditions. Some of the other pioneers contributed to the formation of color order systems, e.g. Mayer, Lambert, Harris, and Runge. Progress in visual arts and related color concepts were also reported by LeBlon, Schiffermüller and others. Another well-known pioneer of this period is Chevreul who examined the role of surround on the perception of color. Indeed, his seminal work on the effect of simultaneous contrast on visual perception is still being examined. Meaningful conceptual ideas and experimental investigations of the color vision processes were espoused by Palmer, Dalton, Young and Schopenhauer, with some aspects based on experimental data and others on generally informed or philosophically based opinions. They formed a basis for the much more detailed scientific investigations in the later 19th century and forward into the present. A coverage of the history of color science would likely not be complete without mentioning contributions from many of the important pioneers in this period.

Chapter 16
Introduction

The scientific revolution is usually taken to have begun in Europe approximately in the middle of the sixteenth century. It was based on the idea of empiricism that humans can make progress by concentrating on facts, evidence, and experimental research. Some key people influencing this development were the philosopher and early scientist Francis Bacon, the astronomers Nicolas Copernicus and Galileo Galilei, and the scientist and philosopher who, among many other things, discovered gravity, Isaac Newton, as well as the philosopher René Descartes. By the year 1700, science had become a broadly accepted concept with many people pursuing it in many fields. Understanding color vision and color perception was also strongly influenced by it, as many investigators began to empirically evaluate the physics and psychology of color experiences.

The visual pathways in eyes and brain were already reasonably well known in the mid-seventeenth century, as investigated and described, for example, by Descartes [1]. He also performed in the first half of the seventeenth-century experiments with light passing through a glass prism and identified the resulting color experiences as those seen in a rainbow. But he was puzzled why the experienced colors differed at different locations in the spectrum. It was Newton who, inspired by Descartes' writings, performed more quantitative and fundamental experiments and came to understand and interpret the experiences from spectral stimuli and the results of mixtures of such stimuli [2]. His findings are well known to have been very controversial for a long time, but the objective nature of his findings eventually made them accepted.

Another visual phenomenon that was puzzling over many centuries is disk color mixture. It was first mentioned by Ptolemy in the 2nd c. CE. It had been observed on potter's wheels with differently colored blotches on top that, when the wheel was spun, resulted in a uniform appearance of a single color. It was mentioned again in writing in the early second half of the eighteenth century by the Dutch scientist van Musschenbroek [3] and at the same time used as a practical methodology by the Italian physician and naturalist Giovanni Antonio Scopoli who used the concept as a method to objectively define the apparent colors of birds and insects by matching

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them with disk mixture using a black, a white, and four chromatic disks (red, yellow, green, and blue) [4]. About 90 years later, it was used in a more refined form by Maxwell as a tool to quantitatively measure color-matching data of multiple people and to derive from them a form of the average spectral functions related to the activity of cones in human eyes.

A key issue before and during the scientific revolution was the systematic ordering of color stimuli and experiences and the apparent relationships between them. Primary colors were addressed by Forsius and d'Aguilon. Descartes, with others like Galilei, Boyle, and Newton, subscribed to the theory of the philosopher David Hume that all sensory perceptions are in the mind and not qualities of objects. Newton's prismatic experiments and findings were initially so controversial that he did not formally publish them until the beginning of the eighteenth century. Soon thereafter, an anonymous writer introduced in a book on painting a description and illustration of a complete object color hue circle [5]. Color reproduction, based on a black and three chromatic pigments, the precursor of modern color printing, was introduced by Le Blon [6].

Color order was making growing progress with Harris's two-dimensional color chart, followed by Mayer's three-dimensional dual-triangular pyramid proposal, practically demonstrated by Lambert's pyramid, while in the same time period Schiffermüller struggled with the complications of such a system.

In 1777, Palmer, in his book *Theory of colour and vision*, proposed that humans have three kinds of "fibers" in their eyes that result in color vision, an idea that proved to be true and was restated by Young at the beginning of the nineteenth century [7].

Strong views on color were reported by the German poet and student of color science Goethe who wrote books on the history of color vision and his own views on human color vision, supported in part by his own experimental findings. Goethe opposed Newton in many respects regarding color.

At least half a dozen of the pioneers covered in this chapter did their most important work after "the end" of the scientific revolution, i.e., in the nineteenth century, when science had become a routine activity. They are included in the chapter because they were born in the eighteenth century.

Goethe had worked some 40 years on his *Farbenlehre* (color theory) and considered it a key effort in his works [8]. It was published in 1810, with an English translation by Charles Eastlake in 1840. The breadth of his knowledge of the historical development of thinking about colors was surprisingly large, beginning with the ancient Greeks and ending in 1794, with the writings of some 70 authors considered in detail.

John Dalton is best known for his work on an atomic theory of chemistry. In regard to color, his main effort was related to color blindness, as the entry shows. He himself suffered from deuteranopia, lacking the M-cone type in his eyes, as an investigation of a preserved eyeball of his showed in 1995 [9]. Given the fact that his brother had the same kind of color blindness indicated to John Dalton, that color blindness was most likely hereditary.

Thomas Young was a polymath educated and active in many fields, elected to be a member of the Royal Society in England when he was 21. He studied for two years at the Göttingen University in Germany where he learned about Mayer's work on color, likely enhancing his own interest in this subject. He believed in a wave theory of light and related colors and calculated their wavelengths in an inverted scale, based on an estimate of the speed of light.

Philipp Otto Runge was a well-known German painter who became very interested in color order. He was personally acquainted with Goethe with whom he exchanged opinions about color phenomena. He derived his color sphere model from a color triangle based on red, blue, and yellow that he expanded to a hexagon, the intermediate colors being orange, green, and violet, then smoothed it out to a circle and three-dimensionally to a sphere, with middle gray in the center: in a way a predecessor of the Munsell color solid [10].

A story of how practical problems, such as customer complaints about the perceived colors of dyed textiles, resulted in progress and new findings in the color field is that of the French chemist and color scientist Michel-Eugène Chevreul. From 1824 to 1885, he was director of dyeing at Royal Gobelins Manufacturing, a famous tapestry manufacturer founded in the fifteenth century by the Gobelin family in Paris, in 1662 taken over by King Louis XIV and still in operation today. Before assuming that position Chevreul was a chemist specializing in the field of organic chemistry, specifically fats, where he discovered among other things creatine and cholesterol. Based on complaints he received about the optical quality of products at the Gobelins, he started investigations resulting in his stating a law of simultaneous contrast that became of interest to impressionist and post-impressionist painters. His extensive involvement with colors also resulted in hue circle charts, tint/shade scales of the hues, and a three-dimensional semi-spheric color solid [11].

Another example of a scientific intellectual with a broad number of interests and resulting expertise was Jan Evangelista Purkyně who was born in what is today the Czech Republic. He studied originally philosophy but soon became interested in several areas of science such as physiology, pathology of the eye, and psychology, as well as botany. He obtained a degree of medical doctor. His interests in the human eye led him to investigate color perception and its possible basis on activities in the retina. In 1819, he published a book titled "Beiträge zur Kenntnis des Sehens in subjectiver Hinsicht" (Contributions to the knowledge about subjective vision) in which he described many different perceptual phenomena. In 1825, in a new version, dedicated to Goethe whom he had personally met, he described the perceptual effect that became known as the Purkyně effect (pp. 109–110) [12]. But he also wrote a monograph on plant pollen. Among others, he introduced the scientific terms plasma and protoplasma, related to blood. He has a crater on the moon named after him. He is considered by some experts to represent the starting point of neurophysiology.

A different kind of color pioneer was the German philosopher Schopenhauer. As a philosopher, he is best known for his book *Die Welt als Wille und Vorstellung* (The world as will and representation). For Schopenhauer, will is the central force behind the world and life, and representation is the form in which we can experience and understand this form and the world. This world view was considered pessimistic because according to it, we cannot learn anything about the true nature and forces operating in the world, i.e., we have no detailed access to will. This view did not find much support during Schopenhauer's lifetime, but it strongly influenced some later people such as the philosopher Friedrich Nietzsche and the composer Richard Wagner. This point of view also influenced his views regarding color. Color became an important subject early in his life because he personally met Goethe and read his works on color. Studying the literature about color of his time in great detail, he wrote his own theory, *Űber das Sehn und die Farben* (On vision and colors), published in 1816, that was not supported by Goethe [13]. At the end of his life, Schopenhauer was still certain that his views on color were the true ones, thoroughly rejecting those of Newton.

For people born from the sixteenth to the eighteenth century, the subject of color as well as other sensory experiences began to be better understood in several respects. At the same time, certain new factually based theories remained very controversial, as expressed in the extended criticism received by Newton's progress in understanding the relationship, for color-normal observers, between light of specific wavelengths and their mixtures and related perceived colors. But much new progress was made in the nineteenth century.

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Chapter 17

Forsius, Aron Sigfrid 1550–1624

Forsius portrait: 1722 copper plate based on a 1617 woodcut

Aron Sigfrid Forsius was a mathematician, astronomer, and clergyman of Finnish descent. He moved to Sweden and was named Royal Astronomer having exclusive rights to issue almanacs and cast horoscopes.

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17.1 On Vision

Forsius’s Chap. 7 of a manuscript on physics written in Stockholm in 1611 and never printed in book form was titled “On Vision.” It contains two-color order diagrams representing an important bridge between classical and more modern ideas on color order. In the first one, he represented his understanding of classical color order. To this, he added his own interpretation of color order, as represented in Fig. 17.1 and described by him as follows:

> But if you want right to consider the origin and relations of the colors, you should start from the five principle middle colors which are red, blue, green, gold, and gray of white and black. And their gradings, they rise either closer to white by their paleness or to black by their darkness; albeit they are (as above has been made known) related to one another as previously shown. Because red rises to white through pale red (pink) and skin color; to black through purple, brown, violet brown and black brown. Similarly, gold relates toward white through pale gold, wooden and wheat color; to black through burnt gold and blackish brown. Equally blue rises to white through sky blue and pale blue, like Dutch cloth; and to black through dark blue like indigo color that has some brownish to it. So rises also green toward white through verdigris and pale green; to black through blackish green. Gray approaches white by the color of light gray, dapple gray and lime: to black by mouse gray, black gray and pale black. And this is the correct relationship of colors that in their number agree with that of the planets as do the lower colors with the five membranes of the eye, and with the five senses. All this can be seen from the accompanying figure. [1]

In the resulting circular diagram, Forsius used four chromatic and two achromatic categories. This results in four tint/shade scales of simple chromatic colors and a gray scale, placed between the common white on top and black on the bottom. On the left side is a red tint/shade scale. But it descends via purple and violet–brown to black maybe the result of mixture of particular pigments. The scale to the right of it is the gold scale. The next scale, in the center, is the gray scale. This

Fig. 17.1 Forsius’s drawing of four chromatic tint/shade scales and the gray scale between common white on top and black on the bottom

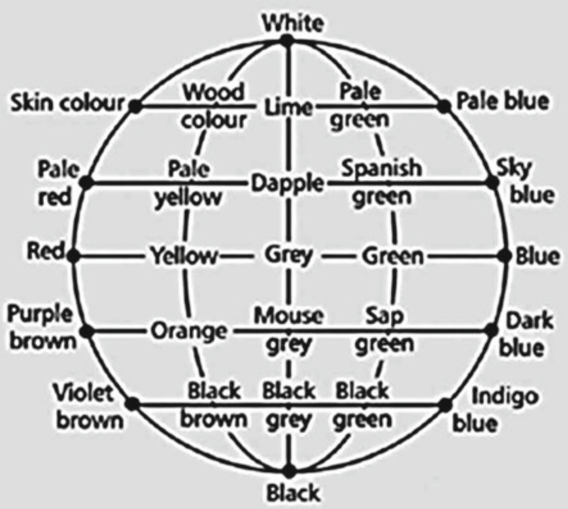

Fig. 17.2 Translations of the color names of Fig. 17.1

is followed next on the right by the green scale and on the far right by the blue scale. Figure 17.2 contains the translations of the color names in Fig. 17.1. Forsius's tint/shade scales may have been influenced by Robert Grosseteste, but it is not known if he had access to Grosseteste's manuscript on color.

Some commentators (e.g., Feller and Stenius [2]) have interpreted Fig. 17.1 as a color sphere, with white and black at the poles and four primary hues: gold (yellow) and blue, as well as red and green opposing each other on the equator. But there is no indication in the text that Forsius had a three-dimensional arrangement in mind. How to properly draw a transparent sphere was well known in the seventeenth century from several sixteenth-century and earlier books on perspective and geometry.

Forsius's manuscript rested in the Swedish Royal Library and was only rediscovered in the twentieth century. Thus, his arrangement of linear tint/shade scales between common white and black did not have a noticeable influence on developments in color order elsewhere. But it represents a step forward in color order in the early seventeenth century.

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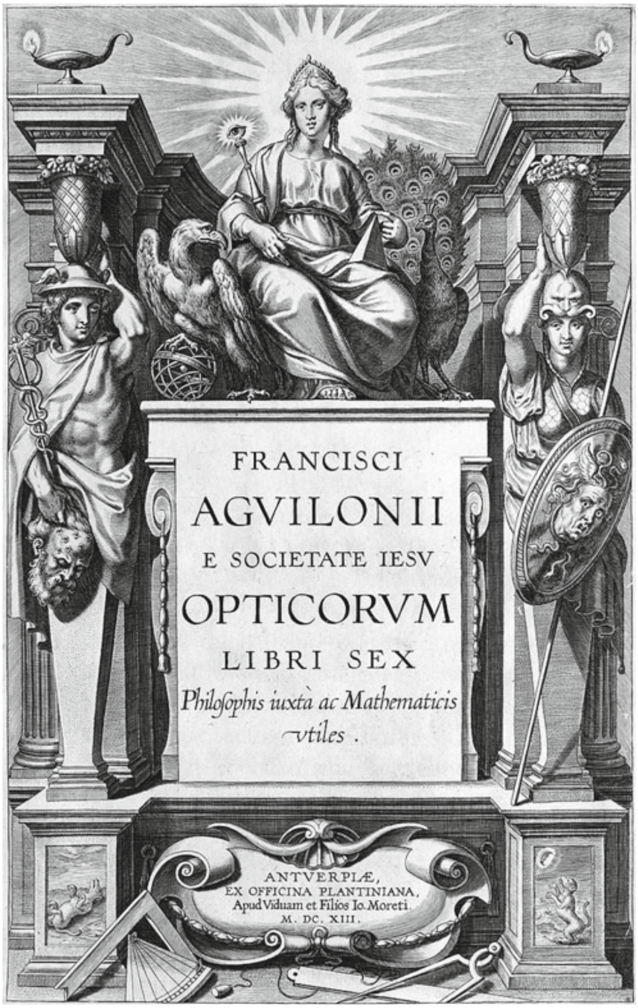
Chapter 18

D’Aguilon, François (Franciscus Aguilonius) 1567–1617



FRANCISCI
AGVILONII
E SOCIETATE IESV
OPTICORVM
LIBRI SEX
Philoſophis iuxtà ac Mathematicis
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ANTVERPIÆ,
EX OFFICINA PLANTINIANA,
Apud Viduam et Filios Io. Moreti.
M. DC. XIII.

Opticorum libri sex, 1613, Wikipedia, public domain

R. Shamey and R. G. Kuehni, *Pioneers of Color Science*,
https://doi.org/10.1007/978-3-319-30811-1_18

D'Aguilon was born on January 15, 1567, in Brussels, Belgium, during the time of the revolution of the Flemish people against the Spanish occupation. His father, Pedro d'Aguillòn, was from an aristocratic family in Salamanca, Spain, and his mother, Anna Pels, was a Flemish woman from Brussels. Pedro was secretary to Phillip II of Spain during his stay in Antwerp. François' secondary education was in the Jesuit College of Clermont in Paris, France. From there, he moved to the University of Douai, today in France. When 19, he joined the Jesuit Order in Douai and continued his studies in philosophy and mathematics. After his graduation, he studied theology in Salamanca. He returned to the city of Tournai (today in France) where he was ordained as a priest in 1596 but also taught mathematics at the Jesuit College. Because of his language skills, he was sent in 1598 to Antwerp as a confessor for Spanish and Italian residents. He became treasurer of the local Jesuit Society until 1608. He was also involved as an architect in building Jesuit churches, the main one in Antwerp. In 1611, he assumed the position of vice-rector of the Jesuit College in Antwerp where he started special education classes in mathematics. At an unknown point in time, he established contact with the painter Peter Paul Rubens (1577–1640) who lived and worked at the time in Antwerp. Both shared an interest in the subjects of optics and color. In 1613, d'Aguilon had his book *Opticorum libri sex, philosophis juxta mathematicis utiles* (Six books of optics, useful to both philosophers and mathematicians) published in Antwerp [1]. Its title page and each chapter heading are illustrated with etchings by Rubens (see Fig. 18.1). D'Aguilon died on March 20, 1617, in Antwerp at the early age of 50 [2]. Rubens' illustration at the beginning of Book V of D'Aguilon's shows a perceptual photometric measurement, also seemingly the first of its kind (Fig. 18.1).

18.1 Opticorum Libri Sex, Philosophis Juxta Mathematicis Utiles

D'Aguilon's book is a densely written (in Latin) broad survey in 684 pages of the knowledge of the time about vision and optics. It ranges back to Aristotle and considers over 30 other important authors after him. It is written in the style of the time of scientists and philosophers, with propositions stated that then are explained and discussed.

The only chapter directly related to color is the first one: On the organ, object and nature of vision. Here Prop. 39 states: "There are five different simple color species, as well as three species of composite colors." The five simple species are white, yellow, red, blue, and black; the three composite species are orange, green, and purple. For each of them, d'Aguilon lists multiple subspecies. He mentions as "friendly associations" mixtures of any of the chromatic colors with white and/or black and also provides examples of such colors. It is not clear if d'Aguilon was familiar with Francis Bacon's work from the thirteenth century where he posited the same five simple colors. D'Aguilon discusses three kinds of color mixture: 1.

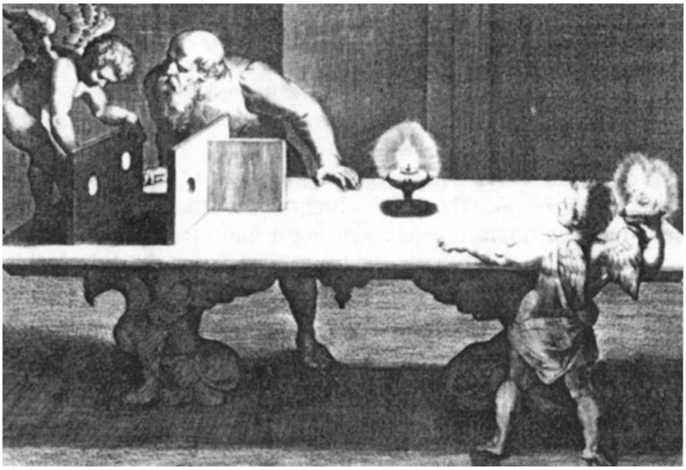
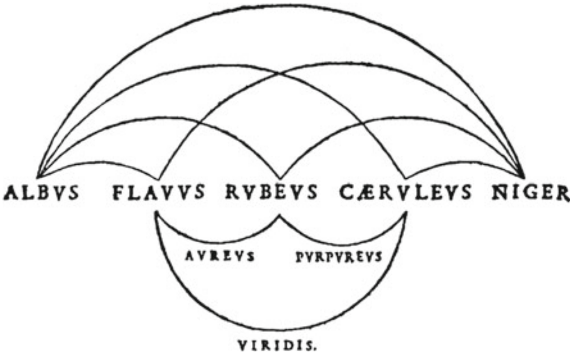


Fig. 18.1 Rubens' heading image of Book V, showing an experiment in perceptual photometry. The brightness of the lights projected through the two holes from a single light and a double light at a larger distance is compared [1]

Colorant mixture (which he called "real colors"), 2. Intentional mixture: a blue object viewed in the yellowish light of a candle appears greenish, and 3. Notional mixture: mixture in the eye of the observer of individual colors "sprinkled" onto the retina.

D'Aguilon provided a graphic illustration of the results of mixture of the five primary colors (Fig. 18.2), seemingly derived from comparable graphic figures found in thirteenth century manuscripts of Boethius' *De musica* or sixteenth century printed manuscripts of Aristotle's *Prior Analytics*. Implicitly, it indicates the continuity of ratios between two or more primaries. It is the first known such graphic representation of color mixture. It was copied in modified form in 1646 by another Jesuit, Athanasius Kircher (ca. 1602–1680).

Fig. 18.2 D'Aguilon's graphic figure of the five primary colors and their mixtures. Albus: white, Flavus: yellow, Rubeus: red, Caeruleus: blue, Niger: black, Aureus: golden or orange, Viridis: green, Purpureus: purple [1]



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Chapter 19
Descartes, René Du Perron 1596–1650

Frans Hals—Portret van René Descartes, Wikipedia, Public Domain

René du Perron Descartes was born on March 31, 1596, in La Haye en Touraine, Indre-et-Loire, (now called Descartes in his honor) in France, was an important philosopher and mathematician, and is dubbed the father of modern philosophy. Descartes was born into the noblesse de robe, whose members contributed

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considerably to intellectual life in the seventeenth century. His father, Joachim, was a conseiller to the Parlement of Brittany at Rennes [1]. From his mother, Jeanne Brochard, he received the name du Perron. He moved to the Netherlands in 1628, at the age of 32, and lived there for more than 20 years to concentrate on his work. Descartes never married, but had a daughter from a maid in the home where he was staying in the Netherlands. His daughter, Francine, was born in 1635 and died of a fever at age five [2]. Descartes' final years were spent in Sweden where he was invited by the Queen of Sweden to organize a scientific academy in 1649. On February 1, 1650, he may have contracted pneumonia and died on 11 February in Stockholm, at the age of 54.

René was the youngest of three children. When he was one year old, his mother died. His father remarried, and René and his older brother and sister were raised by their maternal grandmother and by a family nurse for whom René retained a deep affection. As a child, he may have been often sickly since he was allowed to spend a portion of each day studying in bed. He used this time for meditation and thought. In 1606, Descartes entered La Flèche, a religious college established for the education of the sons of noblemen. He was interested in the mathematical examination of nature using ordinary things for inspiration. According to one account while he was laying in bed and examining the movements of a fly on the ceiling, he thought of a mathematical way to describe the position of the fly. He thus came up with what we now call the Cartesian three-dimensional coordinate system, which allows for precise positioning of objects and for algebraic equations to be expressed as geometric shapes. This laid the foundations for modern mathematical science.

From the Jesuits of La Flèche, he received a modern education in mathematics and physics—including Galileo's telescopic discoveries—as well as in philosophy and the classics, and there began the twin domination of imagination and geometry over his sharp and gifted mind. He described in an early work, the Olympica [3], how he found:

> "in the writings of the poets weightier thoughts than in those of the philosophers. The reason is that the poets wrote through enthusiasm and the power of imagination." The seeds of knowledge in us, "as in a flint," were brought to light by philosophers "through reason; struck out through imagination by poets they shine forth more brightly."

After leaving college at age eighteen, Descartes earned a law degree in Poitiers, France. Then, after graduating, he volunteered as a gentleman in the army of Prince Maurice of Nassau in 1618 and met Isaac Beeckman at Breda. Beeckman aroused him to self-discovery as a scientific thinker and mathematician and introduced him to a range of problems, especially in mechanics and acoustics, the subject of his first work, the Compendium musicae of 1618, published posthumously in 1650 [4]. On March 26, 1619, he reported to Beeckman his first glimpse of "an entirely new science," which was to become his analytical geometry. From 1618 to 1628, he traveled throughout Europe as a soldier. Living on income from inherited properties, Descartes served without pay and saw little action.

While in the duke of Bavaria's army on the Danube, he had the experience in the famous poêle (lit. "stove" or a "well-heated room") and claimed to have been given direction to the rest of his life. He described in the *Discours de la méthode* [5] how, in a day of solitary thought, he reached two radical conclusions: first that if he were to discover true knowledge, he must carry out the whole program himself, just as a perfect work of art or architecture was always the work of one master hand; second that he must begin by methodically doubting everything taught in current philosophy and look for self-evident, certain principles from which to reconstruct all the sciences.

That night, according to his seventeenth-century biographer Adrien Baillet, these resolutions were reinforced by three consecutive dreams [6]. He found himself, first, in a street swept by a fierce wind, unable to stand, as his companions were doing, because of a weakness in his right leg; second, awakened by a clap of thunder in a room full of sparks; and third, with a dictionary, then a book in which he read *Quid vitae sectabor iter*? ("What way of life shall I follow?"), then verses presented by an unknown man beginning *Est et non*; he recognized the Latin as the opening lines of two poems by Ausonius [6]. Before he finally woke up, he had interpreted the first dream as a warning against past errors, the second as the descent of the spirit of truth, and the third as the opening to him of the path to true knowledge. However, this incident may have been elaborated in the telling, and it symbolizes both the strength and the hazards of Descartes's unshakable confidence and resolves to work alone. But he did not make his vision his life's mission for another nine years, during which (either before or after his tour of Italy from 1623 to 1625) he met Mersenne, who was to become his lifelong correspondent and took part in scientific meetings in Paris. The next decisive incident, according to Baillet, was a public encounter in 1628 in which he demolished the unfortunate Chandoux by using his method to distinguish sharply between true scientific knowledge and mere probability.

Descartes has been dubbed as the man who "tried in one bold leap to put himself at the source of everything, to make himself master of the first principles by means of certain clear and fundamental ideas, so that he could then simply descend to the phenomena of nature as to necessary consequences of these principles." This famous characterization of Descartes as the theoretician who "set out from what he knew clearly, in order to find the cause of what he saw," as against Newton the experimenter, who "set out from what he saw, in order to find the cause," has tended to dominate interpretations of both these men who "saw the need to carry geometry into physics [1]."

His best-known philosophical statement is "Cogito ergo sum" (French: Je pense, donc je suis; I think, therefore I am), found in part IV of Discourse on the Method (1637—written in French but with inclusion of "Cogito ergo sum") and in part I of Principles of Philosophy (1644—written in Latin) [5, 7].

Descartes' influence in mathematics is equally apparent; the Cartesian coordinate system—allowing reference to a point in space as a set of numbers, and allowing algebraic equations to be expressed as geometric shapes in a two-dimensional coordinate system (and conversely, shapes to be described as equations)—was named after him.

19.1 Descartes' Thoughts on Color

Descartes believed that all properties, which cannot be described in purely quantitative or geometrical terms, should be banished from science. According to some interpretations, Descartes considered colors an artifact of the mind treating them as mere sensations [8]. Another group of commentators have developed a different interpretation that attempts to reconcile his "objectivist" strand that grants colors an existence in bodies independent from the perceiver and the putative "subjectivist" strand that treats them as sensations, and thus, makes them utterly dependent on the perceiver [9]. Descartes' mechanical theory of vision, presented in the Optics and the Meteorology [5], includes various metaphysical claims about the nature of color itself. However, it may be argued that those assertions may have referred to the external causes of visual perception [9]. He wished to demonstrate the power and superiority of the mechanistic science in explaining visual perception over scholastic Aristotelian accounts, which assumed it to be the result of the transmission of intentional forms or species from the external object to the sensing organs of the perceiver, through a medium such as air.

In the Optics (1637) [5], Descartes declared

> Regarding light and color … we must suppose our soul to be of such a nature that what makes it have the sensation of light is the force of the movements taking place in the regions of the brain where the optic nerve-fibres originate, and what makes it have the sensation of color is the manner of these movements. But in all this there need be no resemblance between the idea which the soul conceives and the movements which cause these ideas (AT VI 130; CSM 1 167).
>
> … the properties in external objects to which we apply the terms light, color, smell, taste, sound, heat and cold, as well as the other tactile qualities … are, so far as we can see, simply various dispositions in those objects which make them able to set up various kinds of motion in our nerves (AT VIII 322: CSM I 285).

Descartes and Locke are understood to have believed that there are no colors in the physical world, as we ordinarily understand them. They held a secondary quality view of colors, i.e., colors being powers or dispositions to cause experiences of a certain type [8]. Descartes in Principles of Philosophy states [7]

> It is clear then that when we say we perceive colors in objects, it is really just the same as saying that we perceived in objects something as to whose nature we are ignorant but which produces in us a very clear and vivid sensation, what we call the sensation of color. ([3]: para. 70; see also paras 68–70)

He argued for the non-inherence of color, where the relation between the material events and the color sensations is arbitrary [8]. In the *Meditations*, talking about colored wax, Descartes argued that the color he saw did not belong (pertinere) to the wax, because it changed when the wax was heated ([7] AT VII 30; CSM II 20). However, Descartes was not the founder of the so-called secondary qualities tradition. One of the most well known of his predecessors that addressed this topic was Galileo who in *il Saggiatore* (1623) wrote that colors are

> nothing but names for something that resides exclusively in our sensitive body, so that if the perceiving creature were removed, all such qualities would be annihilated from existence [10].

In relation to the status of sensible qualities, Galileo stated

> Tastes, odors, colors, and so on are no more than mere names so far as the object in which we place them is concerned, and … reside only in the consciousness. Hence if the living creature were removed, all these qualities would be wiped away and annihilated. [10–13]

Experimentally, Descartes observed that rainbows occurred when water spread from a sprinkler. Using sunlight and a glassy sphere full of water and standing on foot and directing his back to the sun, he watched through a hole in the glassy sphere and shook the sphere upward and downward until he finally discovered brightness at the bottom of the sphere. As we discussed in Chap. III, Kamal al-Din al-Farisi had made similar experiments and obtained the same results as Descartes, many years before him. Using geometric construction and the law of refraction (discussed independently by Ibn Sahl (c. 940–1000 AD), rediscovered in 1602 by Thomas Harriot and in 1621 by Willebrord Snellius and 16 years later by Descartes), he showed that the angular radius of a rainbow is 42°. That is, the angle subtended at the eye by the edge of the rainbow and the ray passing from the sun through the rainbow's center is 42°. He also independently discovered the law of reflection, and his essay on optics contained the first published mention of this law.

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Chapter 20
Boyle, Robert 1627–1691

Artist and date unknown

Robert Boyle was born on January 25, 1627, in Lismore Castle in Ireland, his father being the first Earl of Cork, his mother Catharine Fenton, the daughter of a secretary of state in Ireland. He was educated at home and when he was eight years old and after the death of his mother, he went to Eton College and then spent extended stays in France, Italy, and Switzerland. He had an aristocratic demeanor and was also deeply religious. At the same time, he was much interested in science. In 1644,

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Boyle moved to England to the estate at Stalbridge in Dover bequeathed to him by his father. In Stalbridge, he installed a laboratory and began many kinds of scientific investigations, an activity that preoccupied him during most of the rest of his life. Initially, his experiments involved chemistry, about which he wrote a book in 1661, titled *The Skeptical Chymist*, that established him as a leading force in chemistry at his time. In 1655, he moved to Oxford where he joined a group of natural philosophers. He continued experimental work and hired Robert Hooke (1635–1703) as an assistant. With Hooke's assistance, Boyle developed an improved version of Otto von Guericke's vacuum pump about which he had read in 1657. In England, he is considered the originator of "Boyle's law," the fact that in a closed system and at a constant temperature, the volume and mass of a gas are inversely proportional, elsewhere known as Mariotte's law. While living in Oxford, he published many extended texts on various scientific and philosophical subjects.

20.1 Experiments and Considerations Touching Colours

In 1664, Boyle published a book on "Experiments and Considerations Touching Colours" with over 400 pages, indicating that the subject of color had deeply interested him and led to many experiments [1]. The book was published in two English and six Latin editions, most of the latter in European countries. In 1660, the Royal Society was founded with Boyle as one of its founding members. They published most of his scientific works at the time. Boyle wrote very extensively during his life. The manuscript pages on science alone number over 8000 [2]. In 1668, he moved to London into the residence of his sister Katherine (Lady Ranelagh) who also had an interest in science. He died on Dec. 31, 1691, one week after his sister's death.

Boyle's book on color was written at a time when there was still little objective information about the subject. It is primarily a statement of the state of the art of knowledge at the time. He was puzzled about how to put the multitude of facts on color into a coherent system. The book consists of three parts: The first one is a presentation of the then current knowledge and its problems and missing parts. In the second one, he describes his experiments and interpretation of the nature of whiteness and blackness. In the third part, he describes a further 50 experiments on various aspects of colors and their results. As a chemist, he is particularly confused about the multitude of different colors occurring in various kinds of chemical reactions without any apparent system behind them.

Boyle experimented extensively with prisms that had become popular for investigators since the beginning of the seventeenth century. Boyle chose to test the results obtained from a prism from two small beams of sunlight striking the prism in a darkened room. He reported two images on the wall behind the prism, each displaying red, yellow, green, blue, and purple colors (Fig. 20.1).

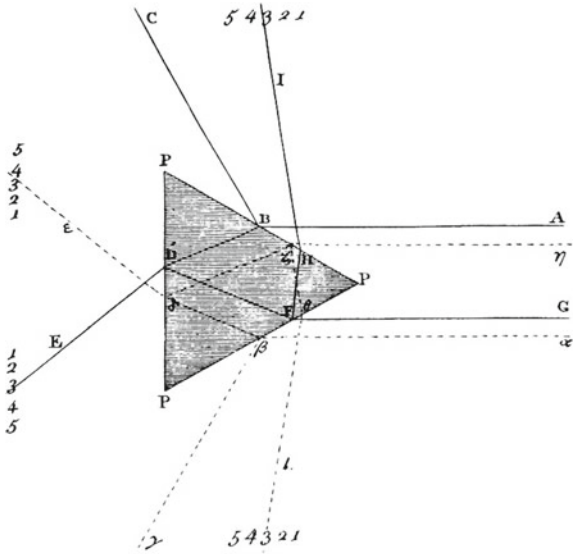

Fig. 20.1 Illustration from [1] of Boyle's experiment with a glass prism. It is struck by two beams of light from the right side. Parts of the light are reflected (C and γ) and parts refracted (E and ε) where five colors are displayed, 1 being red, 2 yellow, 3 green, 4 blue, and 5 purple. He also found the spectra displayed in two other locations, *l* and **I** [1]

Concerning whiteness and blackness, Boyle reported interesting results, such as that light focused with a lens on paper resulted in the burning of the paper much quicker in case of black paper as compared to the white paper. He believed such results to be due to differences in the surface structure. Regarding the mixture of pigments, he stated that there were few colors that he named simple or primary. In order to produce

> almost numberless differing colours … [painters] need employ any more than White, and Black, and Red, and Blue, and Yellow; these five, variously compounded …. being sufficient to exhibit a variety and number of colours such, as those that are altogether strangers to the painters' palettes, can hardly imagine.

He also projected the spectral colors obtained with a prism onto various colored materials and observed the results of mixing "real" and "emphatical" colors. He also projected two spectra obtained from prisms in different ways on top of each other, as he pleased. He only reported having obtained a green from overlapping yellow and blue light and a purple from blue and red.

Boyle's prism experiments, together with those of other authors, proved to be inspirational for young Isaac Newton, a student at Cambridge when Boyle's book got published. When he submitted his early papers on color to the Royal Society, Boyle was one of the reviewers before publication.

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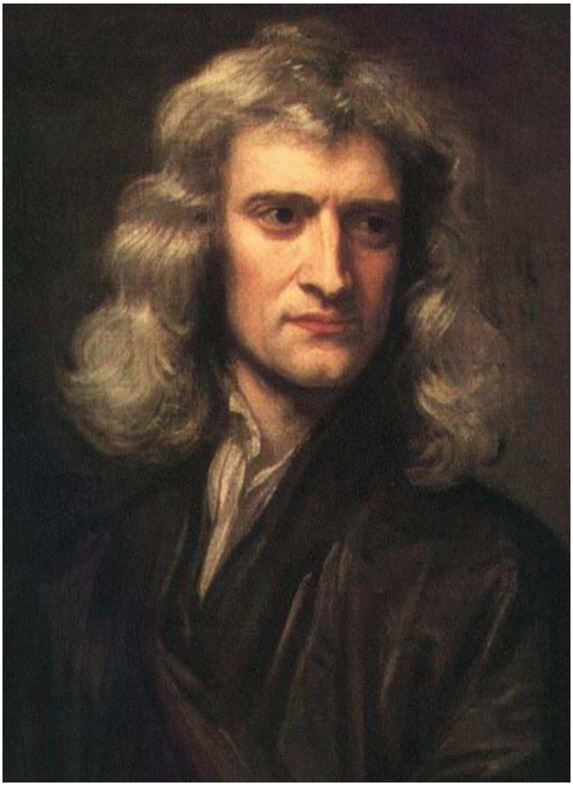
Chapter 21
Newton, Isaac 1642/3–1726/7



Portrait of Isaac Newton in 1689 (age 46) by Godfrey Kneller, Wikimedia

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Isaac Newton was an English physicist and mathematician, who made seminal contributions to several domains of science, and was considered a leading scientist of his era and one of the most influential scientists of all time. He was born prematurely on December 25, 1642, in Lincolnshire,[1] England, of Hanna Ayscough and Isaac Newton (father) [1]. His father passed away before he was born. His mother remarried when he was three years old, and he was left in the care of his grandmother, a situation he resented.

He attended the King's School in Grantham where he learned Latin among other things until the age of seventeen. In 1661, he was admitted to Trinity College, Cambridge, and was educated in Aristotelian philosophy. However, Newton also read the works of Descartes, Galileo, and Kepler. In 1665/6, he spent most of the time at his ancestral place in Lincolnshire because of the dangerous spread of plague in Cambridge. During that time, he did most of his experimental work with glass prisms and much of his mental work that resulted in the publication of *Principia* in 1687.

In 1667, he returned to Cambridge and became a Fellow of the College of the Holy and Undivided Trinity [2, 3]. In 1669, at the age of 26, Newton became the Lucasian professor of mathematics. According to his secretary Humphrey Newton (no relation), his lectures were often poorly attended and few understood him and that sometimes he read to the walls [4]. Newton occasionally traveled to London to attend the Royal Society lectures and was named a fellow in 1672. He became its president from 1703 to 1727. Newton was given various levels of support by the Royal Society. His interpretations of the optical experiments were strongly disputed by Robert Hooke, an employee of the society since 1664, as a result of which he published his book *Opticks* only in 1704, after Hooke's death. He was supported by the society in his bitter and controversial dispute with the German polymath and philosopher Gottfried Wilhelm Leibniz over who had developed calculus first [Leibniz's notations are used today].

Newton also dwelt in politics and was a member of the House of Commons between 1689 and 1690 and then again from 1701 to 1702. In 1705, he was knighted by Queen Anne during her visit to Trinity College. He held two government offices, first he was the Warden of the Mint from 1696 to 1700 and then Master of the Mint from 1700 until his death in 1727. At the time of Newton's funeral, the French philosopher Voltaire who was in England at the time compared Newton to Descartes and said of Newton that "he was never sensible to any passion, [and] was not subject to the common frailties of mankind, nor had any commerce with women [5]." Newton had strong opinions on religion and wrote a number of works, not published during his lifetime, that would have been

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[1] The difference in reported date is due to the use of two calendars: Julian and Gregorian. According to the Gregorian calendar, the date of Newton's birth was January 4, 1643, and that of his death was March 31, 1727.

considered heretic at his time. Newton never married and died intestate in Kensington, London, when his relatives quarreled over the division of his considerable estate. He is buried in Westminster Abbey in London, England.

21.1 Newton's Theory of Color

Arguably our modern understanding of light and color begins with Newton's discovery of light dispersion which he published in 1672. In the late 1660s, Newton started experimenting with the phenomenon of colors and lectured on optics [6]. At the time, it was generally thought that colors were mixtures of light and darkness. It was also believed that prisms imparted colors to light. Through observation of light refraction, Newton realized that this theory was incorrect. He demonstrated that a prism decomposes "white" light into a spectrum of colors. Newton, obtained a triangular prism and began "*to try therewith the celebrated Phaenomena of Colours*." In his notes he states

> having darkened my chamber, and made a small hole in my window-shuts, to let in a convenient quantity of the Sun's light, I placed my Prisme at this entrance, that it might be thereby refracted to the opposite wall. It was at first a very pleasing divertisement, to view the vivid and intense colours produced thereby; but after a while applying myself to consider them more circumspectly, I became surprised to see them in an oblong form, which, according to the received laws of Refraction, I expected should have been circular. [7]

The original sketch demonstrates the darkroom environment where this experiment was conducted. He was the first to use the word spectrum (Latin for "appearance" or "apparition") in this sense. He also used additional prisms to recombine the split components and showed that a spectral colored light does not change its properties by separating out a colored beam and shining it on various objects regardless of whether it was reflected or scattered or transmitted. With respect to colors Newton said

> 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. [4]

During this period, he also investigated the refraction of light and demonstrated that a multi-colored spectrum produced by a prism could be recomposed into "white" light by a lens and a second prism [8]. In the same period, Newton observed that the angle of refraction of different colors by a prism is different [9]. He noted that even when light rays in the form of a circular beam enter a prism, the spectrum of colors that exit in the position of minimum deviation is oblong. The length of the colored spectrum was in fact about five times as great as its breadth. He stated that it is the interaction of the object with light that creates the color of the object and not the object itself. This is known as Newton's theory of color.

From this work, Newton concluded that the lens of any refracting telescope would be adversely affected by the dispersion of light into colors. This is also referred to as chromatic aberration. He constructed the first reflecting telescope in the late 1668 using a mirror to avoid this problem, and this resulted in the first known functional reflecting telescope, which is today known as a Newtonian telescope [10]. Newton used a custom composition of highly reflective speculum metal to grind his own mirrors and then employed what is now known as "Newton's rings" to judge the quality of the optics for his telescopes and demonstrated his device to the Royal Society in 1671 [11]. Their interest resulted in Newton publishing his notes, of colors, [12] which was later expanded into his book *Opticks*. Newton was the first to demonstrate the use of a prism as a beam expander in his book, and he describes, via diagrams, the use of multiple-prism arrays (see Fig. 21.1). Some 278 years after Newton's discussion, multiple-prism beam expanders became central to the development of narrow-linewidth tunable lasers.

In 1704, Newton also discussed the corpuscular theory of light whereby the light is considered to be made up of extremely small particles (which we now call photons). Newton argued that light is composed of particles or corpuscles, which were refracted by accelerating into a denser medium. To transmit forces between particles, Newton posited the existence of the ether. However, he replaced ether with occult forces based on Hermetic ideas of attraction and repulsion between particles and his considerable writings on alchemy. It has been said that Newton was not the first of the age of reason: He was the last of the magicians. Indeed, Newton's interest in alchemy cannot be isolated from his contributions to science [11] since during his time there was no clear distinction between alchemy and science.

Later, physicists favored a purely wavelike explanation of light to account for the interference patterns and the general phenomenon of diffraction. Later on, Young and Fresnel combined Newton's particle theory with the wave theory and indicated that color is the visible manifestation of light's wavelength.

The experiment shows light passing through a hole and then collected by a lens and focused on the prism, which then refracts white light into its spectral components. The experimental sketch also shows a second prism that is used to show a narrow band of light is not further decomposed. A separate experiment was used to show the reversibility of the process.

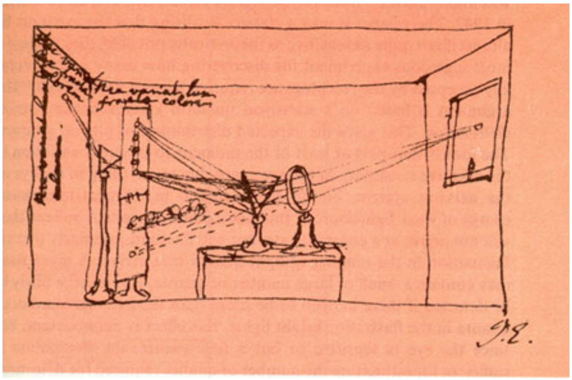

Fig. 21.1 Newton's sketch of refracting sunlight with a prism

1. *The color circle*

   In his observation of white light dispersion into spectral components, Newton divided the spectrum into seven named colors: violet, indigo, blue, green, yellow, orange, and red (see Fig. 21.2). He placed the colors in a circular fashion and called it a color circle. He used it to demonstrate the results of mixtures of spectral lights, including complementarity (those that when mixed cancel each other out and result in white, gray, or black). The size of each segment differed from the other according to his calculations of its wavelength, the seven musical tones or intervals of the eight sounds and of its corresponding width in the spectrum. The choice of seven colors was out of a belief, derived from the ancient Greek, that colors, objects in the solar system, the musical notes, and the days of the week were connected. This likely explains the selection of indigo as another hue between blue and violet. Some argue, however, that in Newton's prismatic colors "indigo" would be placed as a color that is today called blue; whereas, "blue" would correspond to cyan.

   Newton proposed a method to determine the "fullness or intenseness" of combined colors on the circle based on the distance of the center of the combined gravity of the circles for each of the rays of light from whiteness (the distance from O to Z in the figure shown for color Y, which arises from the composition of all the colors in the given mixture). The color circle was, if lacking the non-spectral colors, an early representation of what became centuries later, in a modified form, the chromaticity diagram. In his system, Newton had connected violet to red in the circle, and thus, a large gamut of purples was not shown. Newton described the complementary colors and their mixture and stated

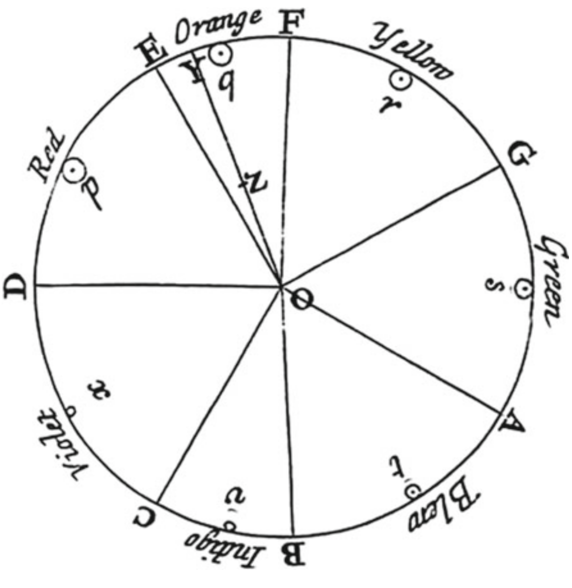

Fig. 21.2 Colors and the associated musical notes in Newton's color wheel, shown in his book Opticks of 1704. The circle completes a full musical octave, from D to D [8]. Colors on opposite sides are complementary

> If only two of the primary colours which in the circle are opposite to one another be mixed in an equal proportion,…, the colour compounded of these two shall not be perfectly white, but some faint anonymous colour. [8]

Newton's concept of complementary colors was demonstrated more thoroughly in the nineteenth century by color theorists. Helmholtz established the complementary stimulus pairs, and Ogden Rood (1831–1902) emphasized that to reveal applied colors in their natural brilliance a knowledge of the complementary hues was required [13].

A version of Newton's color circle without the indigo blue was adopted by painters to describe complementary colors. Nonetheless, this circular diagram became the model for many color systems of the eighteenth and nineteenth centuries. The conceptual arrangement of colors in this form also allowed the painters' primaries (red, yellow, blue) to be arranged opposite their complementary colors (e.g., red opposite green), as a way of denoting that each complementary color would enhance the other's effect through optical contrast.

In addition to his work on optics, Newton made seminal contributions to several other scientific disciplines. In his book the Principia or "Mathematical Principles of Natural Philosophy," which was published in 1687, Newton formulated the laws of motion and universal gravitation and is considered to have laid the foundations for classical mechanics [14]. He also introduced the notion of a Newtonian fluid, studied the speed of sound, and developed an empirical law of cooling among other major contributions made to scientific discovery. Newton's image appeared on the Bank of England notes for about 10 years in the 1970s and 80s (see Fig. 21.3) [15]. He has also been commemorated on stamps from numerous countries (see Fig. 21.4) [16].

Fig. 21.3 Newton was the Warden, and then The Master of the Royal Mint in England and his picture appeared on the One Pound note, almost three centuries later [15]. With permission to reprint from The Bank of England

Fig. 21.4 Examples of stamps commemorating Newton, top left to bottom right Germany, Benin, Hungary, and France [16]

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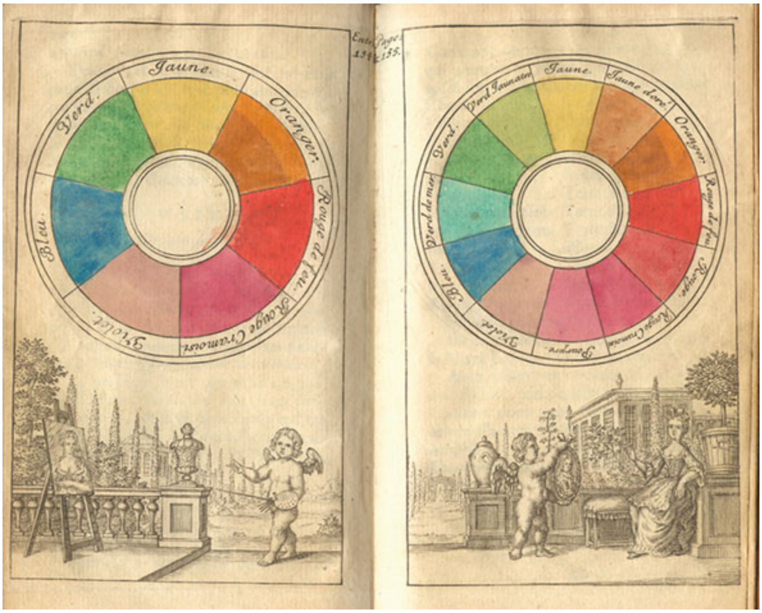
Chapter 22
Anonymous (C. B.) Ca. 1660



Hand-illuminated engravings showing the 7-hue (left) and the 12-hue circles in the section on pastel painting in the Dutch edition of 1708 of Traité de la peinture en mignature (note that in some of the segments the pigments have deteriorated).

The first, hand-illuminated, color circle appeared in public in 1708 in a Dutch edition of a popular French small book on miniature painting, *Traité de la mignature*, first published in 1673 simultaneously in Paris and Rouen [1]. The author of the original edition was speculated about but never identified. Several editions and reprints were issued in France between 1674 and 1697 as well as in

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1711. A German translation was printed in 1688 and a French edition published in Holland in 1687.

The single edition containing the hand-illuminated color circle was an enlarged version printed in French, with the title *Traité de la peinture en mignature* (Treatise on miniature painting) in 1708 in The Hague in Holland by the firm of the brothers Louis and Henri van Dole [2]. In 1744, a reprint of this edition with modified engravings of the figures was published by Lobedanius in Utrecht, Holland.

Among other textual additions, the 1708 edition contains a chapter on pastel painting, a subject not covered in any earlier edition. Its author is also unknown, but clearly different from the author of the original work. In regard to the pastel section, the advertisement in the book states: "One finds here something rather curious, relating to primitive colors and the generation of composed colors. This should be of considerable interest to amateurs [of pastel painting] because up to now one has not seen anything on that subject, except for a small article found written by M. Félibien" [André Félibien, 1619–1695].

The general idea of yellow, red, and blue as chromatic primaries reaches back into the fourth century CE. A limited list of authors proclaiming this idea is as follows:

Year	Author	Color terms	Descriptive term
Ca. 325	Chalcidius	Pallidus, rubeus, cyaneus	Generic colors
Ca. 1266	Roger Bacon	Glaucus, rubeus, viridis	Principal species
Ca. 1609	Anselm de Boot	Flavus, ruber, caeruleus	Principal colors
Ca. 1613	Franciscus Aguilonius	Flavus, rubeus, caeruleus	Simple colors
Ca. 1664	Robert Boyle	Yellow, red, blue	Simple, primary
Ca. 1680	André Félibien	Jaune, rouge, bleu	Principal, primitive

22.1 Traité de la Mignature

The unknown author in the 1708 Dutch edition of *Traité* made the following statements about primitive colors and color mixtures:

> Primitive colors: Properly, there are not more than three primitive colors, those that cannot be composed of other colors, but from which all other colors can be mixed. These three colors are yellow, red and blue, because white and black are not properly colors, white being nothing but the representation of light and black the absence of that same light.
>
> Mixed colors: All other colors are mixed from these four primitive colors, such as yellow and fire red forming orange; crimson and blue producing violet. Finally, blue and yellow make green. … All these colors are vivid, but if one mixes them in other pairs, for example, orange with violet, fire red with blue, violet with green, and green with orange or with fire red, the mixtures produce nothing but dirty and disagreeable colors (pp. 152–154).

In the book, there are two hand-colored images showing primitive and mixed colors in hue circles (see figure at the opening page). The first one contains seven colors because at the time there was no pigment of neutral red hue in general use. Primitive red is, therefore, mixed from fire red and crimson. In the 12-hue circle, the three primitive colors are located at 120° angle intervals. Between pairs of them there are always three mixtures. The intermediate ones are orange, purple, and green. Secondary mixtures are golden yellow, fire red, crimson, violet, sea blue, and yellowish green.

It should be noted that these hue circles appeared only four years after the publication of I. Newton's book *Opticks* with its spectral hue circle (Book I, Part II, Fig. 11) [3].

The hand painted figures, directly or indirectly, are the precursors of several later color circles such as those by M. Harris (ca. 1770), J. I. Schiffermüller (ca. 1772), F. G. Baumgärtner/E. Müller (ca. 1803), P. O. Runge (ca. 1810), M. Klotz (ca. 1816), G. Grégoire (ca. 1815), and others.

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Chapter 23
Le Blon, Jacob Christoph 1667–1741

Four intermediate (C, Y, M, B) colors of the engraving of Cardinal Fleury by Jacob Christoph Le Blon (1738), National Library of France, Public Domain

R. Shamey and R. G. Kuehni, *Pioneers of Color Science*,
https://doi.org/10.1007/978-3-319-30811-1_23

Jacob Christoph Le Blon was born on May 2, 1667, in Frankfurt-am-Main, Germany, a descendant of Huguenots fleeing France in 1576, who had settled there. His maternal grandmother was a daughter of the artist and engraver Matthaeus Merian the Elder (1593–1650). Showing an early interest in engraving and painting he had, sometime between 1696 and 1702, an extended stay in Rome where he is reported to have studied art under the painter and engraver Carlo Maratta (1625–1713) [1]. Around 1702, Le Blon moved to Amsterdam, where he worked as a miniature painter and engraver. In 1708–1709, he is known to have made colorant mixing experiments in Amsterdam and in 1710 he made his first color prints with yellow, red, and blue printing plates. In 1717, he moved to London where he received a royal patent for the three-color printing and a related textile weaving process [2]. Circa 1722, he published a small book on painting, *Coloritto,* in French and English [3]. There he stated that "Painting can represent all visible objects with three colors, yellow, red, and blue." During his stay in England he produced several dozen images printed from three or four plates in multiple copies that initially sold well in England and on the continent. In the long run, his enterprise did not succeed; however, Le Blon left England in 1735, moving to Paris where he continued producing prints by his method. In 1740, he began work on a collection of anatomical prints for which he had a solid list of subscribers. He died on May 16, 1741 in Paris. A detailed technical description of Le Blon's method was published in 1756 by Antoine Gautier de Montdorge who supported him during his final years in Paris [4].

23.1 Three- and Four-Plate Printing Process

The idea of three chromatic primaries, yellow, red, and blue, was quite well established in Le Blon's time among painters, graphically represented by Aguilonius in 1613 and described by Boyle [5, p. 220]. What was new in Le Blon's work is that he applied this concept to color printing of images in an entirely new fashion making greater and much subtler detailing and coloration possible. It required experience in deconstructing an image in terms of the three prime colorants so that printing multiple copies, based on only three or four plates, produced good quality coloration. It required the ability to mentally resolve the image into its presumed primary chromatic components and understanding and predicting the effects of superimposed printing inks in certain areas, for which extensive trial and error work was required. Le Blon manually engraved copperplates, using the mezzotint process, with the relative components of the three primary colors printed successively in registration in the sequence blue, yellow, and red onto the paper substrate. As he gained experience he at times used a fourth plate printing in black to achieve greater tonality and contrast, thus, employing an early version of the CMYK process. Le Blon used the pigments Prussian Blue, Stil de grain (Yellow lake), a mixture of Red lake and Carmine for red, and a common printer's black ink [4]. The pigments were dispersed in copal tree resin dissolved in copal oil to make

Fig. 23.1 J. C. Le Blon, Head of a woman, ca. 1720 (three-color printing process)

the inks. Examples of his work are shown as the title image for this entry and below (see Fig. 23.1). The technical problems associated with the process prevented it from becoming a standard method and lithographic printing of color images from up to a dozen wood engravings or stones per image continued until H. E. Ives' invention of the chromatic halftone printing process ca. 1890.

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Chapter 24
Mayer, Tobias 1723–1762

Public Domain, Wikipedia

Tobias Mayer, born February 17, 1723 in Marbach, Germany, a mathematician, astronomer, cartographer, and physicist, was the only child of a fountain builder and his wife. Mayer was 10-years-old when his father passed away and he grew up in impoverished circumstances in the nearby city of Esslingen, spending some years in an orphanage. He taught himself mathematics and in his later teens earned some money teaching it. Mayer also showed early interest and capabilities in drawing and

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painting. He moved to Augsburg to obtain more training, working for the engraver and publisher J. A. Pfeffel. When 18 he wrote and published an elementary book on mathematics and at 22 a much more detailed work on the same subject [1].

His capabilities and the fact that he had designed an accurate map of Esslingen, later published, provided for him in 1746 an offer to join the firm of the cartographer Homann in Nürnberg, at the time perhaps the most important map publisher in Europe. In 1751, he married Maria Gnüge and a year later their son Johann Tobias was born, in his later life mathematician/physicist. In the same year, Tobias Mayer's reputation as a scientist resulted in an offer of a professorship in economy and mathematics at the University of Göttingen, where he remained until his untimely death on February 20, 1762 due to a typhus infection. In 1754, he also became the supervisor of the Royal Observatory of Göttingen, built some 10 years earlier. His major scientific achievements are a data table of the moon and highly detailed drawings of the surface of the moon based on a new methodology to achieve high accuracy, and the development of a new much more accurate methodology for the determination of longitude. The latter effort resulted in his widow receiving a 3000-pound sterling award from the British Parliament. One of the craters of the moon is named "T. Mayer" [2].

24.1 Double Triangular Pyramid Color Solid

Mayer's combined interests in mathematics and painting resulted in an attempt to develop a mathematical model of the relationships between colors. Not accepting, on practical grounds, Newton's idea of seven main colors in the spectrum, Mayer decided to base his model on the painter's primaries yellow, red, and blue. He placed these at the corners of an equilateral triangle and divided the lines between them into 12 presumably perceptually equal parts which, he assumed, could be represented by corresponding weights of the pigments used as primaries. These grades were to represent perceptually noticeable differences of comparable size. The interior of the triangle is filled with colors that are mixtures of all three primaries. All of them are identified numerically, such as $r^8g^2b^2$ consisting of eight parts of the R primary and two parts each of the G and B primaries (Fig. 24.1). The 91 colors of the triangle of Fig. 24.1 can also be lightened or darkened, by addition of white or black pigments, again in twelve increments each. As these scales must end in single white or black he gave the resulting solid the form of a double triangular pyramid, with a total of 819 defined colors [3]. In his German translation of the original Latin text H. Lang defined Mayer's system as attempting to meet five then novel conditions:

1. All possible object colors are represented.
2. All colors are the result of mixtures of three primary colors.

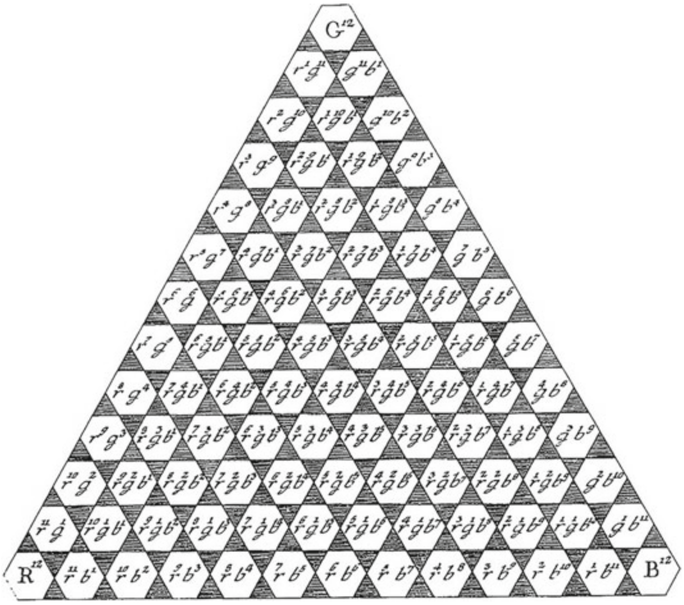

Fig. 24.1 Central plane of Mayer's double triangular pyramid color solid [3]

3. Each color is represented by a triple number indicating the content of the three primaries.
4. The totality of all colors in the system is contained in a three-dimensional color solid.
5. The differences between neighboring colors correspond to perceptual differences [4].

Mayer presented his ideas in 1758 in a public meeting of the Society of Sciences in Göttingen, a report of which was published in the newspaper *Göttingische Anzeigen von gelehrten Sachen* some three weeks later [5]. This report was the basis of J. H. Lambert's work on his triangular color pyramid [6]. Mayer had not done much experimental work to implement his system. As pointed out by Lambert, Mayer had not been aware of the varying coloristic strength of the three primaries, requiring consideration for the purpose of obtaining perceptual uniformity of the scales.

In 1958, Mayer also invented a new coloration method for prints. He proposed, and produced an example, the coloration to consist of sections of wax containing different amounts of pigments to achieve different colors [7]. Multiple prints could then be produced from the wax collage. The idea proved to be too complex to be practical and was not pursued after his death.

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Chapter 25
Schiffermüller, Ignaz 1727–1806

Wikipedia, Public Domain

Ignaz Schiffermüller was born on November 2, 1727 in Hellmonsödt near Linz in Austria and was educated in Linz. When 19 he joined the Jesuit order and studied theology in Wien, as well as botany, ornithology, and mineralogy. In 1759, he became a lecturer at the Theresianum Institute in Wien, a private boarding school founded in 1746, where he remained for 15 years. He continued to be engaged in the natural sciences, with special interest in butterflies that pointed him also in the

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direction of color science. His primary reputation is that of a leading entomologist of his time. In 1776, he together with another Theresianum teacher, J. N. M. Denis (1729–1800), published *Systematisches Verzeichnis der Schmetterlinge der Wiener Gegend* (Systematic register of the butterflies of the Vienna region), containing descriptions of 1150 different species. It was widely recognized as an exemplary presentation of the subject matter. In 1775, he was named an imperial councilor and moved to a college in Linz. He died in Linz on June 21, 1806. He left several extensive collections, among them one of butterflies [1].

25.1 Versuch Eines Farbensystems

As an entomologist, Schiffermüller saw the need for a standardized color nomenclature and atlas of color samples that could be used as reference materials in entomological studies. In 1772, he published *Versuch eines Farbensystems* (An attempt toward a color system [2], in which he discussed the issues that would need to be addressed and the potential uses of such a system for various purposes. In the frontispiece, the book contains a hand-colored continuous hue circle with 12 identified hues (Fig. 25.1), in part based on those described in the book *L'optique des couleurs* by the French Jesuit R. P. Castel (1688–1757) [3]. The circle illustrates what Schiffermüller called "blühende Farben" (florid colors), i.e., saturated or full colors. In regard to desaturated colors, Schiffermüller proposed tint/shade scales (mixtures of the full color pigments with white or black pigments). In his book, he showed examples of three blue hues (Fig. 25.2). As he describes on page 29 of [2], the left column (a) is to represent a tint/shade scale of a reddish tinged blue, the central column of a blue neither reddish nor greenish and the right column of a greenish tinged blue. (It is obvious that in Fig. 25.2 from a specific surviving copy of the book the middle column is erroneously colored or the pigments have deteriorated, since all samples are very dark.) The samples in row G are to represent the blooming or full colors. In a separate table, he named each of the samples in German, Latin, and French. Sample Ga is described as ultramarine blue, sample Gb as blue and sample Gc as Queen's blue or high blue.

It is evident from his text that Schiffermüller had become aware of multiple problems and issues in assembling such a color atlas that could be used by entomologists, artists, or other potential users as reference. A major problem he identified was the absence of colorant standardization and the considerable variation in hue and strength of different pigments, natural or man-made, marketed by different sources under given common names.

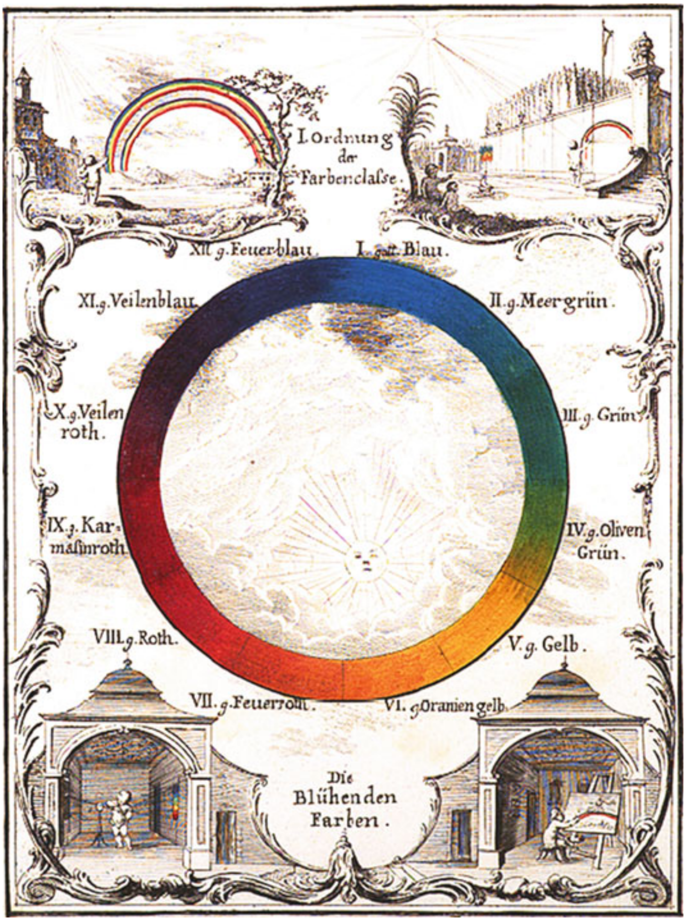

Fig. 25.1 Frontispiece of Versuch eines Farbensystems with the 12-hue continuous hue circle

Lambert's book on the color pyramid was published in the same year, thus Schiffermüller was not aware of the necessity to fill a three-dimensional space with color samples. A "color lexicon" such as envisaged by Schiffermüller and containing 4600 named samples was published in Germany in 1782 by Prange [4], followed in 1794 by the *Wiener Farbenkabinett* with 5400 samples.

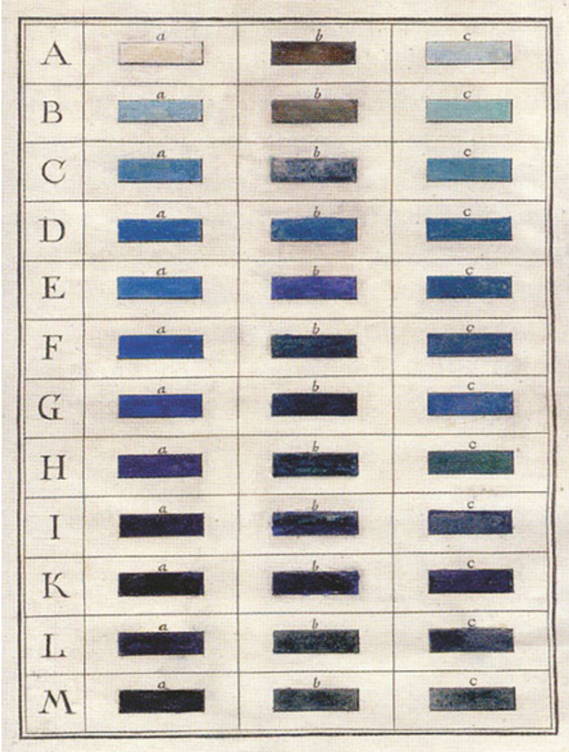

Fig. 25.2 Tint/shade scales from white via the full color to black of three blue hues

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Chapter 26
Lambert, Johann Heinrich 1728–1777

Artist unknown

R. Shamey and R. G. Kuehni, *Pioneers of Color Science*,
https://doi.org/10.1007/978-3-319-30811-1_26

Johann Heinrich Lambert was born on August 26, 1728 in the city of Mulhouse, then an enclave of Switzerland (now part of France). He was largely self-educated, going to school only until age 12. By age 17 he assumed the job of secretary to a newspaper publisher in nearby Basel, Switzerland. He also began to work as a private tutor. At age 20 he became tutor to three boys in the family of Count Peter von Salis in Chur, Switzerland, a position he held for 10 years. There he had access to the count's large library and was able to travel widely in Europe with his charges. In 1755, he began to publish scientific articles on a number of subjects. In 1756, he traveled with his pupils to Göttingen in Germany where he met Tobias Mayer and was elected a member of the *Königliche Gesellschaft der Wissenschaften* (Royal Society for the Sciences). In 1759, he published his work on light measurement, *Photometria* [1], introducing his mathematical formula for the law of absorption of light (Lambert's law), described non-mathematically a few years earlier by Pierre Bouguer. In 1764, he followed an invitation by the Swiss mathematician Leonhard Euler to come to Berlin where, after some initial difficulties, Frederic II appointed him to a position in the *Königlich-Preussische Akademie der Wissenschaften* (Royal Prussian Academy of Sciences). Lambert established an important position as mathematician, physicist, astronomer, and philosopher. He also had considerable interest in the art of painting. Among many other achievements, Lambert was the first to mathematically prove the irrationality of the number π. He died on September 25, 1777 in Berlin, Germany [2].

26.1 Lambert's Color Order System

In 1758, Tobias Mayer presented his public lecture on a three-dimensional color order system, of which a report was published in *Göttingische Anzeigen für gelehrte Sachen* (Göttingen reports on learned matters), read by Lambert. In 1768, Lambert published an article *Mémoire sur la partie photométrique de l'art du peintre* (Dissertation on the photometric component of the art of the painter, [3]) in which he discussed the effect of light on the appearance of colored materials. Soon after and as a result of Mayer's premature death, he began work on an implementation of Mayer's conceptual system, with assistance of the Prussian court painter Benjamin Calau (1724–1785). The result was published in 1772 as *Beschreibung einer mit Calauischem Wachse ausgeführten Farbenpyramide* (Description of a color pyramid painted with Calau's wax [4]) containing a hand-colored abbreviated version of the conceptual color pyramid (Fig. 26.1). Lambert and Calau had to solve several practical issues, for example, they determined the relative strength of the pigments they used. When mixing the three primaries they obtained near-black colors. As a result, Lambert saw no need for the lower half of Mayer's double pyramid. The Lambert/Calau pyramid is the first three-dimensional representation of a systematically developed color solid.

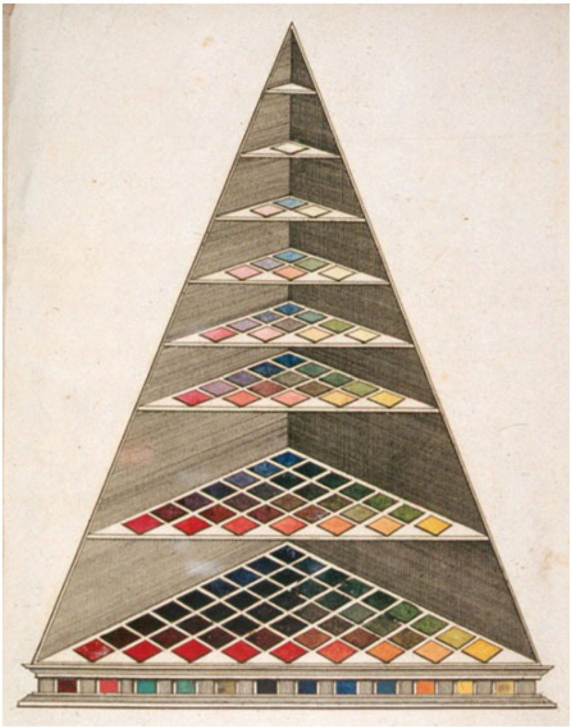

Fig. 26.1 Lambert's illustration of his triangular color pyramid [4]

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Chapter 27
Harris, Moses, 1730–1788

Moses Harris, Selfportrait, 1780

R. Shamey and R. G. Kuehni, *Pioneers of Color Science*,
https://doi.org/10.1007/978-3-319-30811-1_27

Little is known about the life of Moses Harris, who was born on April 15, 1730, in England. Like Ignaz Schiffermüller, Harris was an entomologist and engraver who engraved his own copperplate illustrations. He was introduced at an early age to the study of insects by his uncle who was a member of the Society of Aurelians, a group of people in London studying insects. Around 1762, Harris became the secretary of the Aurelian Society. Harris exhibited some of his drawings at the Royal Academy. He also provided illustrations for books related to nature of other authors. Perhaps, his best-known and most important work is the wonderfully illustrated *Aurelian: a natural history of English moths and butterflies* (1766). Harris died ca. 1788, leaving behind his wife and son John (1767–1832) who also became a well-known illustrator [1].

27.1 The Natural System of Colours

Concerned with obtaining a more objective definition of colors in entomology and in other fields, he designed two comparably designed color charts, published sometime between 1769 and 1776 in a very brief book (6 pages of text) with a lengthy title, the main part of it being *The Natural System of Colours* [2]. It is dedicated to the painter Joshua Reynolds, then the president of the Royal Academy. The system is based on the three primaries red, yellow, and blue, resulting in the "mediates" orange, green, and purple. There are two hand-colored hue circles, each displaying 16 hues. The first is titled "prismatic,' meant to be based on spectral colors (Fig. 27.1). Harris was not knowledgeable concerning the difference between additive and subtractive color mixtures. He represented the mixture of the three primaries in the center "by three triangular pieces of stained glass," as being black, thus the result of subtractive mixture. This is supported by green being designated as the median between yellow and blue, only valid in mixture of colorant primaries. The colors shown in the two charts are hand-painted, presumably with water colors (see Fig. 27.1).

The actual charts are not in agreement with the written text: Each of the 18 hues is "… divided into twenty parts or degrees of power, from the deepest or strongest, to the weakest; or from the outermost to the innermost circle, called teints …" The charts show only 10 teints of each hue, each numbered at increments of 2 from 2 to 20. Each teint scale is supposedly from the full color on the outside to the darkest appearing teint in the innermost circle. In different remaining copies, different coloring approaches appear to have been used, as the figures below show. (Complete tint/shade scales from white via the full color circle to black were first indicated in P. O. Runge's color sphere of 1810.) The appearance of growing darkness and reduced "strength" was achieved by an increasing number of black circular lines in each teint field, starting with zero in the outermost circle and ending with 11 in the innermost one, thereby relying on the color assimilation effect, a standard engravers' technique for shading. As a result, the samples of each hue decrease in chromatic intensity from the outside of the circle to the inside while at

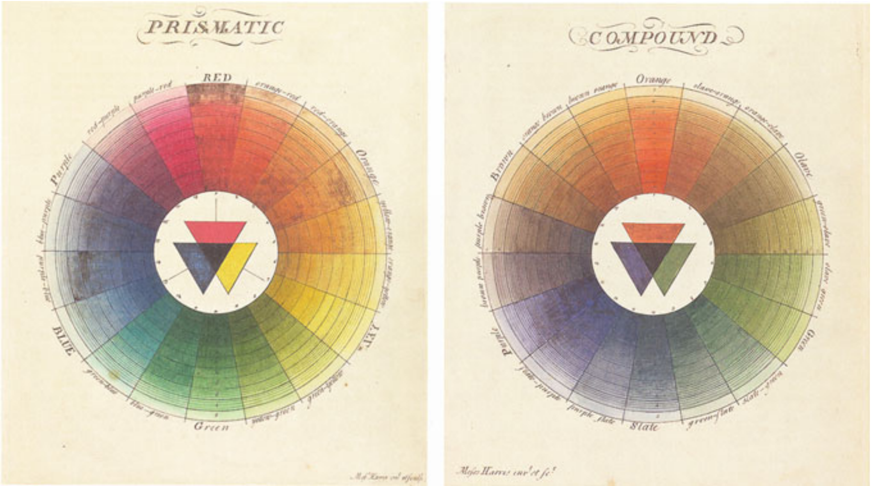

Fig. 27.1 "Prismatic" and "Compound" charts from Harris' "The Natural System of Colours"

the same time appearing increasingly dark. Based on 20 teint circles, Harris calculated the total number of differing colors in the "prismatic" chart as 360. The second chart is named "compound," with its key colors being the mediates of the first chart. The key new colors in this chart are brown, slate, and "olave." Given the fact that orange, green, and purple are present in both charts, Harris counted only 300 colors in the "compound" chart, for a total of 630 in both charts. Harris considered the charts useful for painters to find the most contrasting hues, located on either chart directly opposite. The numbering of hues and teint levels allowed for a numeric definition of a given color, useful for communication.

A second edition of the book appeared posthumously in 1811. The coloration of its charts was distinctly different from that of the original edition [3]. Copies of the first edition are extremely rare. The colors in their charts have usually deteriorated to a smaller or larger extent. It is considered one of the rarest books about color. A reprint edition was produced in 1963 by Faber Birren [4].

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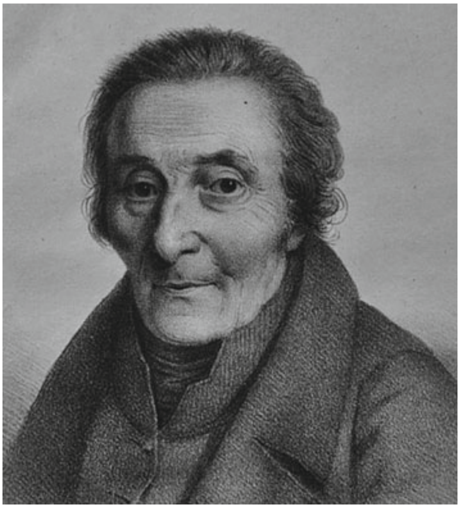
Chapter 28
Palmer, George 1746–1826



Louis Fehr: George Palmer, ca. 1820

George Palmer, also known as "George Giros de Gentilly named Palmer," was an English dye chemist, color theorist, inventor, and soldier. According to his obituary, Palmer was born ca. 1746 on a ship to English Catholic parents. Due to the eighteenth-century restrictions on activities of English Catholics, Palmer lived a double life between England and France. Nothing is known about his early years. Circa 1775 he introduced a solution of tin as a new mordant for the dyeing of wool fabrics in Louviers, France, using the name Giros de Gentilly [1, 2].

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28.1 Theory of Colours and Vision

In 1777, located in London, Palmer published the book *Theory of Colours and Vision*, a French edition of which was published in the same year in Paris, translated by Palmer's friend Denis-Bernard Quatremère d'Isjonval, at the time active in the textile manufacturing facility Disjonval in Sedan, France, owned by his family [3, 4].

In 1781, J. H. Voigt of Gotha, Germany, editor of *Magazin fuer das Neueste aus der Physik und Naturgeschichte* (Journal for the latest physics and natural sciences news), describes meeting with Giros von Gentilly and the latter's conjectures about color blindness [5]. In 1785, Palmer, living in Paris, had *Lettre sur les moyens de produire, la nuit, une lumière pareille á celle du jour* (Letter concerning the means of producing at night a light equal to daylight) published describing the modification of oil-lamp light with a blue glass mantel, a technology that became fashionable for a time [6]. In 1786, Palmer published *Théorie de la lumière, applicable aux arts, et principalement á la peinture* (Theory of light applicable to the arts, principally to painting [7]. Toward the end of that decade, likely as a result of the French Revolution, Palmer became a mercenary soldier in the Corps of Engineers, at different times for Sweden, Austria, and Russia, reaching the rank of major, as described in his obituary [8]. For a time in the early nineteenth century, he lived near Leipzig in Germany where he reported on four technical inventions, one of which being a fire-extinguishing powder, a demonstration of which was reported in a local newspaper. In 1811, Palmer moved to Copenhagen into retirement and died there destitute in 1826 [9].

Palmer made lasting contributions to the development of color science by being the first to propose that there are three different mechanisms in the human eye that account for color vision: "The superficies of the retina is compounded of particles [light sensors] of three different kinds, analogous to the three rays of light, and each of these particles is moved by its own ray" [3]. This statement has proved true in regard to the number of different daylight sensor types, the cones, in the human eye, if not in regard to the claim of three kinds of light. Thirty-five years later, a similar statement was made by the eminent physicist Thomas Young [10].

Voigt, in his report on Giros von Gentilly, describes him as having stated that color blindness arises if one or two of the three kinds of "particles" in the retina is inactive, a statement found to be valid [5]. In 1786, Palmer provided a hypothesis for the complementary nature of the successive contrast effect by stating that it is due to fatiguing of one or two of the light sensor types, an explanation that continues to be accepted as valid, as does his conjecture that the different kinds of sensor take different times to recover upon exposure to strong light.

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Chapter 29

Goethe, Johann Wolfgang von 1749–1832

J. K. Stieler, 1828 (Wikimedia Commons)

Johann Wolfgang von Goethe was born on August 28, 1749, in Frankfurt, Germany, to a lawyer and the daughter of the mayor of Frankfurt. He studied law in

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Leipzig and Strasbourg (France). Based on his early fame as a poet and novelist, Goethe, at age 26, was invited by the 18-year-old Duke of Sachsen-Weimar to join his court as an advisor. He moved to Weimar where he remained until his death on March 22, 1832. At times, he worked as a diplomat and a public servant for the duke. He became known as the pre-eminent German poet, novelist, and playwright. The philosophical nature of much of his writing and his battle with Kant influenced several later philosophers, such as Hegel, Schopenhauer, Nietzsche, and Wittgenstein. Goethe's interests were very broad, including pictorial art and certain aspects of science, most importantly in the latter the metamorphosis of plants, where he displayed a pre-Darwinian point of view, as well as the source and nature of color experience.

29.1 Goethe's Theory of Colors

He considered his *Farbenlehre* (Theory of Colors) [1] the most important of his works. Goethe's views on science were strongly influenced by the very complex relationship between objectivity and subjectivity. He believed strongly in experimentation, with variability in conditions and multiple replications, which might lead to objective truths. Circa 1793 Goethe wrote an essay *Der Versuch als Vermittler von Objekt und Subjekt* (The experiment as mediator between subject and object) which he shared with his friend, the poet Friedrich Schiller, in 1798 in which he described the value of scientific experiments as a bridge between subjectivity and objectivity and the possibility of establishing via multiple experiments of this kind the existence of objective laws of nature [2]. The essay was only published in print in 1823.

His interest in color began early in his life and received input during his extended journey to Italy in 1787 where he began studying Leonardo da Vinci's manuscripts on painting. His first writings on the subject of color date from 1791: *Beiträge zur Chromatik* [Contributions to chromatics], 1792: *Von den farbigen Schatten* (Concerning colored shadows), and 1794: *Versuch, die Elemente der Farbenlehre zu entdecken* (Attempt at discovering the elements of color theory). Zur *Farbenlehre,* in three volumes, was published in 1810, the same year P. O. Runge (well acquainted with Goethe) published his *Farben-Kugel* (Color sphere). The first volume of *Farbenlehre* presents his description and interpretation of physiological colors, physical colors, and chemical colors, a chapter on the possibly singular natural source of color experience, a chapter about the relationship of color science with other intellectual domains such as philosophy, mathematics, general physics, and natural history, and one on the general esthetics of color. Volume 2 is an extended attack on and critique of the color work of Isaac Newton, its main component being the "unnatural" methodology used by Newton when splitting daylight into its spectral components. Goethe considered it replaced by his method of investigating the effect of the prism when viewing contrasting boundaries in daylight. The result in the former case is the classical spectrum of colors, in the latter the series of so-called boundary or edge colors (for an informative discussion see [3]). Recent complex optical experiments have shown that there is no discrepancy between Newton's and Goethe's findings (e.g., Rang [4]). The third volume consists of an extended, if somewhat prejudiced, review of the history of color science (*Geschichte der Farbenlehre*), beginning with the ancient Greeks and ending with contemporaries of Goethe.

Goethe's fundamental view of perceived colors was that they are the result of interaction between lightness and darkness, an idea already introduced by Aristotle. Goethe saw it confirmed by his experience with boundary colors when viewing edges of white and black fields through a prism, for example, viewing through it the hexagonal charts of Fig. 29.1, illuminated by daylight.

Goethe devised a color circle consisting of six hues in three complementary pairs, with a purplish red on top, followed on the left, warm side by orange and yellow, and on the cold, right side by violet and blue, with green on the bottom. Colors diametrically opposite are approximately complementary. Such opposing colors were viewed by Goethe as harmonic pairs. He also used their relationships in the circle to demonstrate presumed psychological effects.

The response to Goethe's *Farbenlehre* was mixed. However, in a commentary of 1892 Hermann von Helmholtz said: "And I for one do not know how anyone, regardless of what his views about colors are, can deny that the theory [Goethe's] in

Fig. 29.1 Partial collection of color-related equipment and materials owned by Goethe in the Goethe-Nationalmuseum in Weimar

itself is fully consequent, that its assumptions, once granted, explain the facts treated completely and indeed simply" [5].

The English painter Charles Eastlake published in 1840 a translation of Part I as "Theory of Colour" [6]. It became an important source of information for painters, such as J. M. W. Turner. In an introduction to a modern version of the translation in 1970 (remaining in print today), D. B. Judd wrote: "This book can lead the reader through a demonstration course not only in subjectively produced colors (after images, light and dark adaptation, irradiation, colored shadows, and pressure phosphenes), but also in physical phenomena detectable qualitatively by observation of color (absorption, scattering, refraction, diffraction, polarization, and interference)" [7].

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Chapter 30
Dalton, John 1766–1844

Wikimedia

John Dalton was an English chemist, physicist, and meteorologist who is best known for his work in the development of modern atomic theory and his research into color blindness.

R. Shamey and R. G. Kuehni, *Pioneers of Color Science*,
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John Dalton was born in the county of Cumberland in England in 1766 and received his early education from his father who ran a private Quaker school. He started his own school aged 11 and at age 15, he joined his brother teaching in a school in Kendal [1]. He was barred from attending English universities because he was a dissenter (a Christian opposed to state religion and mandatory membership in the Church of England) but acquired scientific knowledge from John Gough, a blind philosopher with wide-ranging scientific interests. However, in 1793 he was appointed as teacher of mathematics at New College, Manchester (a dissenters' college). On October 3, 1794, Dalton was elected as a member of the Manchester Literary and Philosophical Society and a month later, he presented his first paper entitled, "Extraordinary facts relating to the vision of colors with observations." The society's *Memoirs and Proceedings* have been published continuously since its first edition which, when it was launched in 1783, was the only regular scientific journal in the United Kingdom except for the *Philosophical Transactions of the Royal Society*. As a result of this paper, congenital color vision deficiency is still referred to as "Daltonism" because he was the first to describe the condition in detail and the paper also stimulated great debate amongst other investigators [1]. In 1800, he left New College and began private teaching and in 1808, he published the atomic theory for which he is most famous. He became President of the Manchester Literary and Philosophical Society in 1817, a post he retained until his death in 1844.

30.1 Dalton's Color Blindness

Dalton noticed that only males were afflicted with his condition and we now know that color blindness, or color deficiency as it may more properly be referred to, is much more prevalent amongst males than females. He also recognized that the condition must be hereditary since he and his brother had the same condition.

In his 1794 letter, Dalton wrote:

> The flower was pink but it appeared to me almost an exact sky-blue by day; in candlelight however it was astonishingly changed, not having then any blue in it but being what I call red – a color which forms a striking contrast to blue.

Thirty-six years prior to Dalton's famous 1794 letter, Thomas Young had postulated that congenital color vision defects arose from the photoreceptors but Dalton refused to believe it [1]. As a result of his meticulous observations, Dalton believed that the fluids in his eyes must contain a blue colorant and he instructed that on his death his eyes be subject to a post-mortem analysis. No trace of the blue colorant was found. Interestingly, Dalton found twenty-five others (including, notably, his own brother) who suffered the same failure of color constancy though most saw no change. Dalton also wrote that the red end of the spectrum was "little more than a shade or defect of light."

We now know that Young was essentially correct; that is, that congenital color vision defects result from genetic mutations that mean that one (or more) of the three visual pigments found in the cones of our retina have anomalous spectral absorption properties or are absent entirely. Young believed that Dalton was a protonope—that is, that he was missing the long-wavelength sensitive visual pigment. Although the post-mortem examination of Dalton's eye did not reveal the blue colorant that Dalton had predicted, the remaining eye was preserved between two sheets of glass until it was analyzed by Mollen et al. who concluded that Dalton was indeed a dichromat but was a deuteranope rather than a protonope [2].

Dalton's theory that color deficiency was caused by a long-wavelength absorbing colorant in the fluids of his eyes ultimately proved to be incorrect. He was also not the first to "discover" color blindness. However, he made a substantial contribution to the understanding of color blindness through his meticulous observations and he also inspired other scientists to study this fascinating phenomenon.

1. *Atomic theory*

   Although Dalton's name is indelibly associated with color deficiency by far his most important work was in the area of atomic theory, which he formally first published in 1805. The main points of Dalton's atomic theory were:

   1. Elements are made of extremely small particles called atoms.
   2. Atoms of a given element are identical in size, mass, and other properties; atoms of different elements differ in size, mass, and other properties.
   3. Atoms cannot be subdivided, created, or destroyed.
   4. Atoms of different elements combine in simple whole-number ratios to form chemical compounds.
   5. In chemical reactions, atoms are combined, separated, or rearranged.

   There is uncertainty about how Dalton arrived at his atomic theory [3]. Also, there was no evidence available at the time to scientists to deduce how many atoms of each element combine to form compound molecules so that Dalton, for example, wrongly assumed that water was composed of a single oxygen atom combined with a single hydrogen atom. Nevertheless, the essential features of his theory have survived to this day and his theory can be said to be one of the bedrocks of modern chemistry.

   Dalton made notable contributions to meteorology (where he made over 200,000 observations, published several important essays on the gas laws (his law of partial pressures became known as Dalton's law), and wrote about rain, the color of the sky, and refraction.

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Chapter 31
Young, Thomas 1773–1829

Wikimedia, Public Domain

Thomas Young was an English polymath with interests ranging from physics to Egyptology. He was born in 1773, in Somerset, England into a large Quaker family[1] and had nine siblings. He was a child prodigy, learnt to read by age two,

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[1] The Quakers are a group of Christians who use no scripture and believe in great simplicity and that truth is continuously revealed directly to individuals from God. They were formed in England in the eighteenth Century and were known as the Society of Friends.

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and taught himself Latin at age six. Young has been described as "The Last Man Who Knew Everything" [1]. He died in London in 1829 at the age of fifty-five.

At the age of fourteen, Young had learned Greek and Latin and was acquainted with French, Italian, Hebrew, German, Aramaic, Syriac, Samaritan, Arabic, Persian, Turkish, and Amharic languages [2].

Young began to study medicine in London at St Bartholomew's Hospital in 1792, moved to the University of Edinburgh Medical School in 1794, and a year later went to Göttingen, Lower Saxony, Germany, where he obtained the degree of doctor of medicine in 1796 from the University of Göttingen. In 1793, he offered an explanation of how the eye accommodates itself to vision at different distances based on changes in the curvature of the eyes crystalline lens [3]. In 1797, he entered Emmanuel College, Cambridge. In the same year, he inherited the estate of his granduncle, Richard Brocklesby, which made him financially independent, and in 1799, he established himself as a physician at 48 Welbeck Street, London (now recorded with a blue plaque). Young published many of his first academic articles anonymously to protect his reputation as a physician.

As a gentleman of independent means, Thomas Young had a keen interest in science. Although he had decided on a career in medicine, he did not substantially practice but continued scholarly studies at Emmanuel College, in Cambridge. In 1801, he was appointed a professor of natural philosophy (mainly physics) at the Royal Institution and in the same year proposed that three types of retinal particles might exist, each associated with one of the principal colors "red, yellow, and blue" [4]. In 1802, he became foreign secretary for the Royal Society. In an 1803 paper, he changed his primary colors to red, green, and violet. While it is debated whether Young was the first to propose this idea, his views were one of the earliest statements pertaining to the fundamental property of "trichromacy" that characterizes human spectral discrimination.

Young resigned his professorship in 1803, fearing that its duties would interfere with his medical practice. His lectures were published in 1807 in *Course of Lectures on Natural Philosophy and the mechanical arts* [5] containing a number of anticipations of later theories.

In 1811, Young became a physician to St George's Hospital, and in 1814, he served on a committee appointed to consider the dangers involved in the general introduction of gas into London. In 1816, he was secretary of a commission charged with ascertaining the precise length of the second's or seconds pendulum (the length of a pendulum whose period is exactly 2 s), and in 1818, he became secretary to the Board of Longitude and superintendent of HM Nautical Almanac Office.

In 1827, Young was chosen as one of the eight foreign associates of the French Academy of Sciences. In 1828, he was elected a foreign member of the Royal Swedish Academy of Sciences.

31.1 Trichromatic Color Vision and Wave Theory of Light

Among the early conceptual ideas regarding Young's color vision theory was his hypothesis that vision depends on three kinds of "nerve fibers," (today known as the three cone types in the retina of the eyes), a concept that was later expanded by H. von Helmholtz. Young had briefly presented this idea in the 1801 Bakerian Lecture: on the theory of light and colors, which was published in 1802 [4]. In this lecture, Young expressed his ideas as follows:

> Now 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 each sensitive filament of the nerve may consist of three portions, one for each principal colour.

In Young's own judgment, of his many achievements the most important was to establish the wave theory of light. However, he would have to overcome a major obstacle, Isaac Newton's century-old views described in "Opticks" according to which light consisted of particles. Nevertheless, Young put forth a number of theoretical reasons supporting the wave theory of light and developed two enduring demonstrations to support this viewpoint. On 24 November 1803, Thomas Young described his historic experiment to the Royal Society of London, which was destined to become a classic. He started his lecture in the following way…

> The experiments I am about to relate… may be repeated with great ease, whenever the sun shines, and without any other apparatus than is at hand to everyone.

The lecture was published in the following year's Philosophical Transactions of the Royal Society of London, [6] and is still reprinted and read today. Thus, with the ripple tank, he demonstrated the idea of interference in the context of water waves and with his interference or double-slit experiment, and he demonstrated interference in the context of light as a wave.

In the paper entitled *Experiments and Calculations Relative to Physical Optics*, published in 1804, Young described an experiment in which he placed a narrow card (approx. 1/30th in.) in a beam of light from a single opening in a window and observed the fringes of color in the shadow and to the sides of the card [6]. He observed that placing another card before or after the narrow strip, such that to prevent light from the beam from striking one of its edges, caused the fringes to disappear. This supported his notion that light is composed of waves. Young performed and analyzed a number of experiments, including interference of light from reflection off nearby pairs of micrometer grooves, from reflection off thin films of soap and oil, and from Newton's rings. Figure 31.1 shows an illustration from his lecture notes published in 1807.

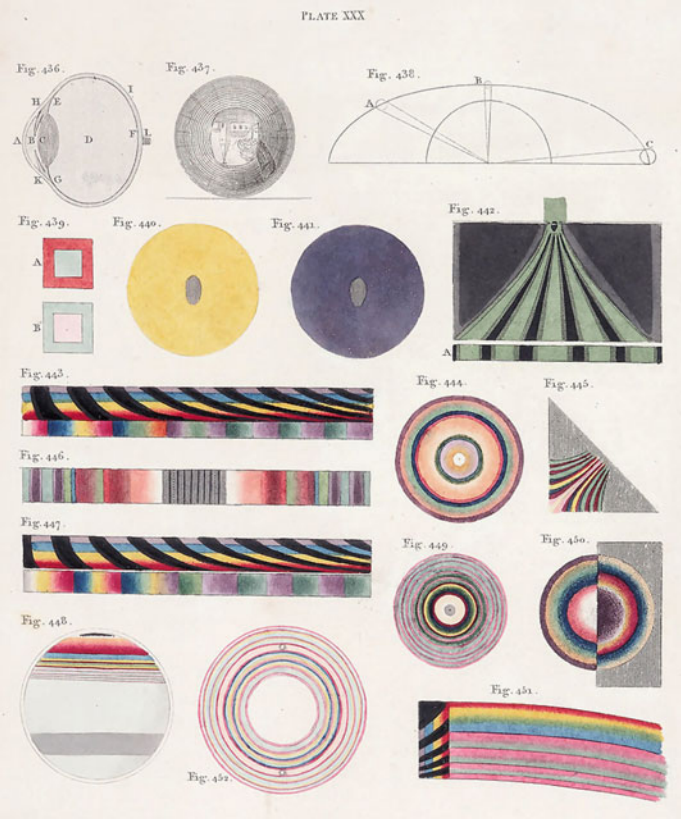

Fig. 31.1 Plate from "Course of Lectures" of 1802, published in 1807 [5]

Young also performed two important diffraction experiments using fibers and long narrow strips. In his *Course of Lectures on Natural Philosophy and the Mechanical Arts* [5], he gives Grimaldi credit for first observing the fringes in the shadow of an object placed in a beam of light. Within ten years, much of Young's work was reproduced and then extended by Fresnel.

As Young pointed out "*The nature of light is a subject of no material importance to the concerns of life or to the practice of the arts, but it is in many other respects extremely interesting…*"

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Chapter 32
Runge, Philipp Otto 1777–1810

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Philipp Otto Runge was born on July 23, 1777, the ninth of 11 children of a tradesman and cargo shipowner and his wife in Wolgast, Pomerania, on the Baltic Sea, then under Swedish rule. As a child, he was frequently ill with tuberculosis, being often educated at home. In 1795, he began a commercial apprenticeship at his older brother Daniel's firm in Hamburg. In 1799, Daniel supported Otto financially

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to begin the study of painting at the Copenhagen Academy. In 1801, Otto moved to Dresden to continue his studies, where among others he met his future wife Pauline Bassenge and the painter Caspar David Friedrich. He also began to study extensively the writings of the seventeenth-century mystic Jakob Boehme. In 1803, on a visit to Weimar, Runge unexpectedly met Johann Wolfgang von Goethe and the two formed a friendship based on their common interests in color and art. After marrying Pauline in 1804, they moved to Hamburg. But due to imminent war dangers (Napoleonic siege of Hamburg) they relocated in 1805 to his parental home in Wolgast where they remained until 1807, then returning to Hamburg. Together they had four children, the last born on the day after Runge's premature death in 1810. In March of 1810, Runge became ill with tuberculosis again to which he succumbed on December 2 of the year. Runge was of a mystical, deeply Christian turn of mind, and in his artistic work, he tried to express notions of the harmony of the universe through symbolism of color, form, and numbers. He considered blue, yellow, and red to be symbolic of the Christian trinity, equating blue with God and the night; red with morning, evening, and Jesus; and yellow with the Holy Spirit. [1] During his short life, he became one of the most important German painters of the Romantic period.

32.1 Die Farben-Kugel

Runge's interest in color was the natural result of his work as a painter and of having an enquiring mind. Among his accepted tenets was that "as is known, there are only three colors, yellow, red, and blue" (letter to Goethe of July 3, 1806 [2]). His goal was to establish the complete world of colors resulting from mixture of the three primaries, among themselves and together with white and black. In the same lengthy letter, Runge discussed in some detail his views on color order and included a sketch of a mixture circle, with the three primary colors forming an equilateral triangle and, together with their pair-wise mixtures, a hexagon. He arrived at the concept of the color sphere sometime in 1807, as indicated in his letter to Goethe of November 21 of that year, by expanding the hue circle into a sphere, with white and black forming the two poles [3].

A color mixture solid of a double-triangular pyramid had been proposed by Tobias Mayer in 1758 and implemented in the form of a triangular pyramid by J. H. Lambert, facts known to Runge. His expansion of that solid into a sphere appears to have had an idealistic basis rather than one of logical necessity. In 1808, he hoped to provide scientific support for the sphere form with disk color mixture experiments. Encouraged by Goethe and other friends, he wrote in 1808 a manuscript describing the color sphere, published in Hamburg early in 1810 as *Farben-Kugel* (color sphere) by his friend Friederich Perthes [4]. An included hand-colored plate shows two different views of the surface of the sphere as well as horizontal and vertical slices demonstrating the organization of its interior (Fig. 32.1).

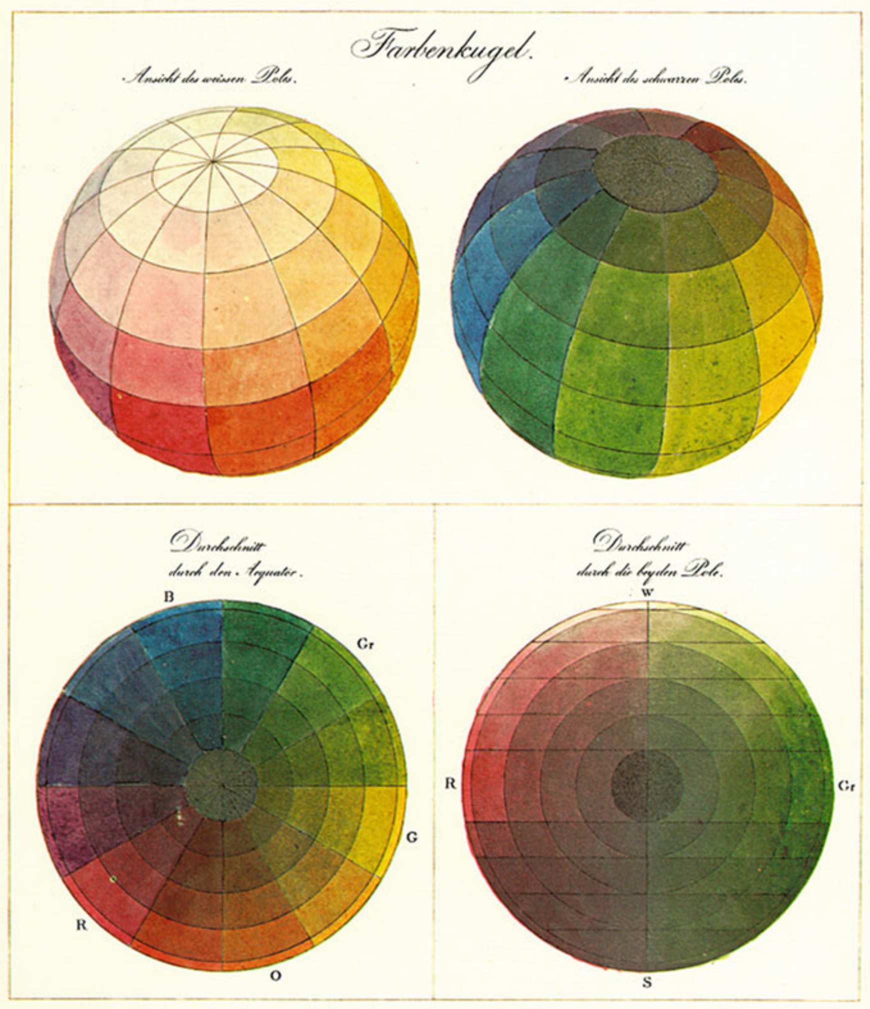

Fig. 32.1 Hand-illuminated illustration from P. O. Runge, Farben-Kugel [4]

In addition to a description of the color sphere, the book contains an illustrated essay on rules of color harmony by Runge and one on color in nature written by Runge's friend Henrik Steffens. Runge's premature death limited the impact of this work. Goethe, who had read the manuscript before publication, mentioned it optimistically in his *Materialien zur Geschichte der Farbenlehre* of 1810 as "successfully concluding this kind of effort" [5]. More detailed similar systems were published soon thereafter by Gaspard Grégoire in France and by Mathias Klotz in Germany [6, 7].

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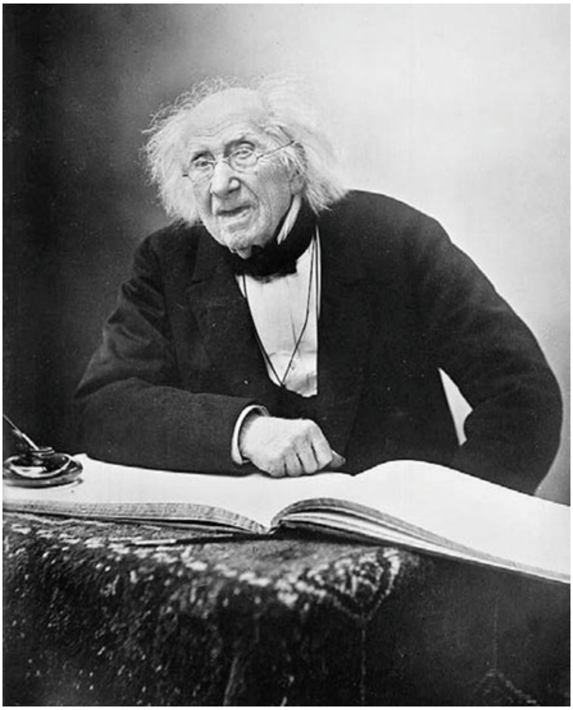
Chapter 33
Chevreul, Michel-Eugène 1786–1889



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Michel-Eugène Chevreul was one of the most important chemists of nineteenth century in France. He also made significant contributions to the domain of color science. He was born on August 31, 1786, in Angers, France, to a family of

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surgeons and his father, Michel, was a well-known physician and the dean of the local medical school [1].

In 1818, Chevreul married Sophie Davallet, the daughter of a government tax official, and they had a son, Henri. After his wife's death in 1862, Chevreul forsook almost all social life and resided in the Museum of Natural History in Paris [2]. At his centenary birthday, the French government minted a medal (depicted at the end of this article), published a beautiful copy of his color book, and celebrated his life as a national event. Chevreul received letters of commendation from many heads of state and monarchs, including Queen Victoria. In 1889, as his health declined, his son Henri came to be with him in Paris. However, sadly Chevreul suffered the death of his son 13 days before his own death on 9 April 1889 at the age of 102 [1, 2]. He was honored with a public funeral. In 1901, a statue was erected to his memory in the museum where he worked.

Chevreul's childhood coincided with the midst of the terror of the French Revolution. He witnessed much violence and suffering, including in 1793, the execution of two young girls. As a result, he maintained a lifelong aversion to politics. He received private education before entering the Ecole Centrale, a new scientific school in Angers in 1799, where for four years he studied Greek, Italian, botany, mineralogy, mathematics, physics, and chemistry. He was not attracted to his family's professional tradition of medicine. At the conclusion of his studies, he decided to become a chemist. In 1803, at around the age of seventeen, Chevreul left for Paris and entered Nicolas Vauquelin's chemical laboratory as his assistant at the National Museum of Natural History and was placed in charge of the chemical analysis of samples [1, 2].

In 1810, at the age of twenty-four, Chevreul obtained his first position as an assistant naturalist at the Museum. Three years later, he became a professor of chemistry at the Lycée Charlemagne, one of the leading schools in France. His examination and analysis of the nature of animal fat, initially from a sample of soap, and the discovery of the different acids resulted in the publication of a book in 1823 that made him a famous chemist [3]. One year later, he published another book to explain the methodology that enabled him to make his discoveries [4].

Chevreul rose rapidly through the scientific ranks during the 1820s and 1830s. In 1824, he became director of dyeing at the Manufactures Royales des Gobelins, the national tapestry workshop and for nearly sixty years, he taught courses in chemistry at these two institutions. He was director of the Museum from 1864 to 1879 [5].

He produced books on the history and philosophy of science and continued his scholarly endeavors into the 1880s, his last publication appearing in 1888. During his career in the nineteenth century, he made significant strides toward a better understanding of chemistry. Chevreul excelled at the elemental analysis of organic substances and established the molecular formulas for many important chemical compounds. He established the melting point as a key criterion for the purity of a substance, a characterization technique, which is still in use today.

33.1 The Law of Simultaneous Contrast of Colors

Chevreul's main responsibilities as director of the dyeing department at Gobelins were to look after the quality of the wool, the quality and stability of the dyes and their brightness, and the kind of cloth to which they had to be applied to (wool, silk, and cotton). As director of the department, Chevreul conducted a considerable amount of work on color. This included color classification, color application, as well as his most famous book *The Principles of Harmony and Contrast of Colors and their Applications to the Arts,* in 1839 (translated into English in 1854) [6], which was once considered one of the twelve most important books on color [7].

At the Gobelins, Chevreul examined a complaint from the weavers regarding the low strength of some dyed samples and specifically black-dyed wool samples, used for blue and violet shades in draperies. As a chemist, he analyzed the dyed samples, compared them against those dyed in London and elsewhere, and concluded that the quality of the dyed material was not in question. He hypothesized that the "lack of strength" was a perceived effect related to the colors being viewed side by side. Through experimentation, Chevreul realized that the appearance of an isolated color sample was different from that juxtaposed to another. His observation on the general effect of the simultaneous contrast of colors is summarized as:

> 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. [6, 8]

His observations also included what he called the principle of color mixing (which corresponds to what is known today as chromatic assimilation). Chevreul noted that this was valid for samples that varied in hue or in lightness and stated:

> If we look simultaneously upon two stripes of different tones of the same colour, or upon two stripes of the same tone of different colours placed side by side, if the stripes are not too wide, the eye perceives certain modifications which in the first place influence the intensity of colour, and in second, the optical composition of the two juxtaposed colours respectively. Now as these modifications make the stripes appear different from what they really are, I give to them the name of simultaneous contrast of colours; and I call contrast of tone the modification in intensity of colour, and contrast of colour that which affects the optical composition of each juxtaposed colour. [6, 9]

In the case of lightness differences, the modified appearance is an exaggeration of the difference. However, in the case of hue differences, the observed effect is dependent on what Chevreul considered complementary colors. He pointed out that red and green; orange and blue; greenish-yellow and violet; and indigo and orange–yellow are complementary colors [6, 10]. He noted that the modification of the appearance of juxtaposed colors consists of perceiving each color as slightly tinted with the complementary color of the juxtaposed one. If the two samples viewed are themselves complementary colors, e.g., red and green, the two hues will not be modified, rather they will be enhanced, thus red will appear redder and green will appear greener.

It should be noted that Chevreul was not the first to “discover” this phenomenon and others including Prieur had also noted this effect [11]. Chevreul acknowledged this and devoted a chapter to the experiments made by others [6]. However, he classified and structured these phenomena and carefully distinguished different kinds of contrast, including the simultaneous contrast, the *successive contrast*, and a mixed effect. Successive contract is observed when one or more colored objects are seen for a certain length of time in sequence resulting in their complementary colors being viewed [6]. Even though simultaneous contrast is often related to chromatic induction, successive contrast is generally associated with chromatic adaptation; for this reason, the concept of afterimages is often used today instead of successive contrast [5].

In the case of mixed contrast, the effects of simultaneous and successive contrasts are combined. This occurs when after having looked at one color for a certain length of time, another color is viewed. The resulting sensation is a combination of the second color and of the complementary color of the first one.

Chevreul also created a three-dimensional general color classification system to facilitate color comparisons. The system is composed of a hue circle, shown in Fig. 33.1, which is divided into 72 steps. The second dimension corresponds to the scale of lightness whereby each of the 72 hue sections is divided into 20 segments from the center (white) to the diameter (black), numbered from 1 to 20, respectively. The third dimension is given by a quadrant perpendicular to the circle and corresponding to a saturation scale, divided into 10 sections, with the least saturated

Fig. 33.1 Chevreul’s chromatic circle containing main hues [9]

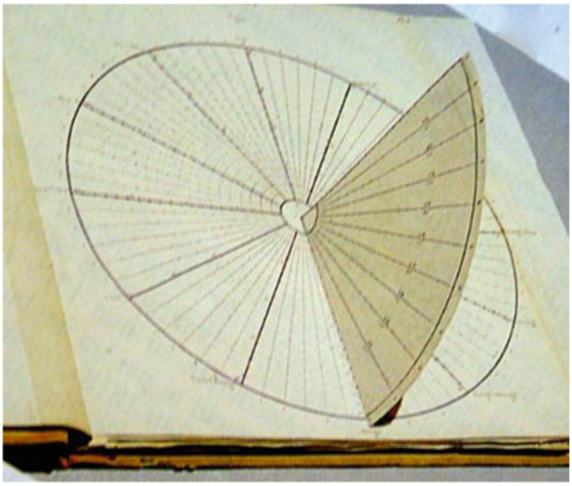

Fig. 33.2 The hemispheric construction from *De la loi du contraste simultané des couleurs*, published in 1839 [6, 9]

colors located in the center as shown in Fig. 33.2. This color classification system was the most complex at the time and would enable distinction of well over 14,000 nuances. Chevreul continued to work on color classification systems and published several important books on the topic [9, 12, 13].

Chevreul gave many public lectures, which were attended by artists and practitioners and had a large influence on generations of artisans, even before the publication of his book on simultaneous contrast in 1839. This included many fields as diverse as tapestry and stained-glass restoration, to shop signs and gardening. His work also had a significant influence on painters, from the 1830s up to the beginning of abstract painting.

In 1826, Chevreul became a member of the Academy of Sciences in France. In the same year, he was elected a foreign member of the Royal Society of London, followed by a foreign member of the Royal Swedish Academy of Sciences in 1829 and a Foreign Honorary Member of the American Academy of Arts and Sciences in 1868 [14]. Chevreul was President of the Academy of Sciences in France first in 1839 and again in 1867 [15]. He was awarded the Copley Medal from the Royal Society of London in 1857 [1]. Chevreul lived through the entire French Revolution and saw the unveiling of the Eiffel Tower. His name is among the 72 inscribed on the Eiffel Tower [1, 2].[1]

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[1] Michel-Eugène Chevreul commemorative medal honoring his 100th birthday by R. Roty (Paris, 1886), Public Domain.

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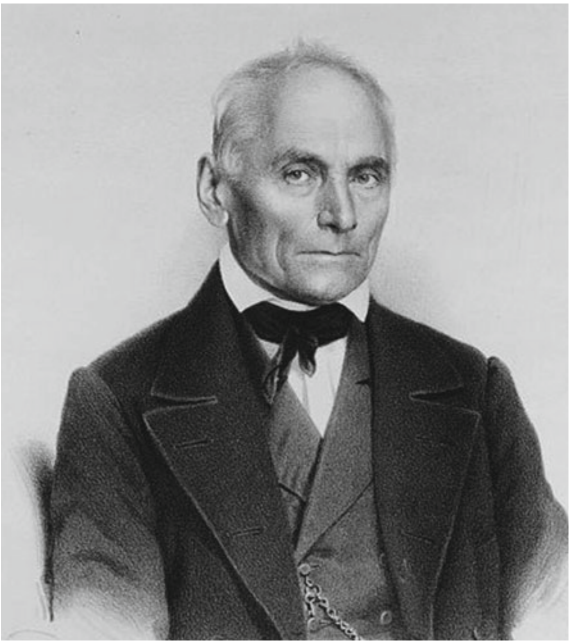
Chapter 34
Purkyně, Jan Evangelista 1787–1869



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Jan Evangelista Purkyně was born sometime between December 17 and December 19, 1787, in the castle in Libochovice near Litomeřice, Bohemia (then part of the Austrian monarchy), now in the Czech Republic. Purkyně died on July 28, 1869.

He was the oldest son of Josef and Rozálie (born Šafránková) Purkyně. His father worked as the chamberlain of Libochovice manor. Jan learned to observe

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nature and people initially from his father, who used to take him on trips with the owner of the manor. He inherited diligence and discipline as well as a sense of humor from his mother. Jan began to read early and was introduced to Komensky′s illustrated children's book *Orbis Pictus*. He also learned to read Latin and Greek texts from a priest by the name of Schiffner in Libochovice.

In 1793, Purkyně′s father died leaving his wife Rozálie with their two sons Jan and Josef. With assistance from Rozálie′s friends, Jan was enrolled at the Piaristic grammar school. After graduation from that school (1804) and upon recommendation of his teachers, Jan went to a monastic school in Dobrá Voda. Due to his excellent performance, he managed to complete the three-year program in one year. He then started to teach at the lower grammar school in Strážnice, and from there, he went to teach at the Piaristic Institute in Litomyšl. There, he devoted himself to the study of philosophy, history, and poetry and became a devoted fan of the German philosopher F. W. Schelling.

In 1807, Jan began to study philosophy at Prague University. He had to leave his studies after the third year because of financial reasons and he began to teach Baron Hildprandt's son Ferdinand in Blatná. With Hildprandt's financial support, Jan went back to Prague in 1812 to study medicine. Upon completion of his medical program, he applied for several faculty positions but was not accepted in any of them. In 1819, he wrote a doctoral thesis about subjective aspects of vision [1].

In 1822, Jan secretly traveled to Germany and was introduced to a minister of state by the name of Schultz who arranged for him a meeting with Goethe. In 1823, and upon the recommendation of Goethe, the Prussian king signed a decree which nominated Purkyně a professor in the Medical School of Wroclaw (Breslau in Prussia) where he continued his research [2]. There, he lectured on physiology, eye pathology, and psychology, but his lectures were not well attended. He continued his study of subjective visual perception and in 1825 had his comprehensive work on this topic, dedicated to Goethe, published [3].

In 1827, Jan Evangelista Purkyně married Julie Anežka Rudolphi in Berlin. They had two daughters and two sons. Both of his daughters died of cholera. Purkyně became a member of the Leopoldina Science Academy in 1829. In 1830, he was named a professor of botany at Wroclaw University. In 1834, his wife Julie died, leaving Purkyně with two young sons. He did not remarry.

Purkyně turned his focus to botany and was awarded the Montyonov prize in France for his monograph *De cellulis antherarum fibrosis nec non de granorum pollinarium formis* in 1833. In 1836, the State Secretary accepted Purkyně′s suggestion for the establishment of a physiological institute (the first in Central Europe). In 1849, by the emperors' decree, Purkyně was called back to Prague as a professor. Purkyně was later nominated as a member of London's King Society. He was also honored as the guardian of Matice česká—a committee for edification of language and literature from 1852 to 1858. In 1857, with the support of Purkyně, the first Czech industry school (1857) was opened in Prague where he became the Principal from 1857 to 1859. Purkyně was a leading scientific polymath of his time. A discussion of his contributions is found in N. J. Wade, J. Brožek, *Purkinje's Vision: The Dawning of Neuroscience* [4].

34.1 Subjective Visual Phenomena and the Purkyně Effect

Jan Purkyně was one of the early pioneers of what we now call Vision Science. As a medic Purkyně studied differences in subjective visual phenomena including light/shade, galvanic and vassal patterns (embranchment of vassals in his own eye), glare patterns, subjective feelings in darkness (phosphenes), blind spot, unity of both eyes' visual fields, double sight, indirect sight, colorblindness in the peripheral retina, light patterns, and afterimages. Probably, one of the most well-known contributions of Purkyně to Color and Vision Science is that which bears his name, the Purkyně effect.

As a medical student, during spring walks through the flowering countryside, Jan observed that after the sunset the color of flowers appeared to change; red blossoms appeared darker, yellows faded in appearance, and the blues seemed brighter. Purkyně studied this phenomenon systematically and found out comparable results with other objects' colors. That is, under decreased illumination blue colors appeared lighter than reds. He focused his studies on this topic and in 1818 he defended in the faculty of medicine his dissertation "Contributions to the knowledge of sight from a subjective sense" [1]. The simulated effect is shown in Fig. 34.1 in the picture of blue and red flowers under three illumination conditions: average (when cones are active), dim (when rods intrude), and dark (when cones become mostly deactivated). This phenomenon is believed to be in part due to the contribution of rods to the perceived colors in the scene. Rods are activated at low levels of illumination and are associated with night vision, whereas cones are activated at much higher levels of illumination and are associated with day and color vision. Under certain conditions, e.g., during dawn or dusk, there is just sufficient illumination to activate cones, but illumination is low enough to activate rods also. If the contribution of rod signals to the overall image and thus the perceived color exceeds about 10%, the effect becomes known as rod intrusion. Since the rods' peak sensitivity is around 496 nm, which is much closer to the peak sensitivity of the short-wavelength-sensitive cones (responsible for blue colors at 419 nm) compared to that of long-wavelength-sensitive cones (responsible for red

Fig. 34.1 Observing red and blue flowers under average (left), dim (middle), and dark (right) illumination conditions. The simulations show that under low levels of illumination the blue colors appear much brighter compared to red ones (images recreated)

colors at 558 nm), the overall perception of the observed scene is shifted toward blue at low levels of illumination when rods become activated. Therefore, blue colors appear brighter, whereas red colors appear very dull and almost black.

1. *Objective eye examination techniques (1823)*
   Purkyně recommended a technique for systematic objective examination of eyes using reflective pictures. In this process, the candle flames mirror on the front and back of the cornea and then on the front and back of the retina. Purkyně examined the possibility of using reflective pictures to measure the curvature of the cornea (which became the principle of keratometry and ophthalmometry) and its use in the diagnosis of eye diseases and defects. After many years, Purkyně obtained an achromatic Plossl microscope, which he placed in his own apartment since he did not have a suitable place within the university. Among other things, he observed eye luminescence and the possibility of observing the background of eyes in vivo, a principle of ophthalmometry which was later established by Helmholtz in 1850.

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Chapter 35
Schopenhauer, Arthur 1788–1860

L. S. Ruhl, 1815, Wikimedia

Arthur Schopenhauer was born in Danzig (today Gdańsk, Poland) on February 22, 1788. Both his parents were descendants of wealthy German families, active in trade. Their business was moved to Hamburg, and Arthur's father died soon after.

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His mother, an author of books, moved in 1805 to Weimar where she continued her writing career and hosted a literary salon which attracted also J. W. von Goethe. In 1809, Schopenhauer became a student at Göttingen University where he studied metaphysics and more general philosophy. In 1811, he moved to Berlin to continue his studies. When visiting his mother in Weimar he became acquainted with Goethe and his recently published book *Farbenlehre* (Color theory) which he studied and discussed at length with its author. Beginning in 1814, Schopenhauer worked on his seminal philosophical text *Die Welt als Wille und Vorstellung* (The world as will and representation), published in 1819. During the same time, he wrote his small text *Űber das Sehn und die Farben* (On vision and colors) published in 1816 [1]. He became a lecturer in philosophy at Berlin University in 1820, an occupation lasting only a few months. After other failed attempts at a professorial career, he moved in 1833 permanently to Frankfurt where he continued his philosophical work, living by himself. He died of a heart attack on September 21, 1860. He is considered one of the most influential philosophers of his time [2].

35.1 Űber Das Sehn Und Die Farben (on Vision and Colors)

Űber das Sehn und die Farben was based on extended conversations Schopenhauer had with Goethe and his own studies of Newton's work *Opticks*. Unsurprisingly, he developed his own ideas on the subject ending up in finding fault in the views of both Newton and Goethe. Living in Dresden at the time, he is known to have read at the Royal Library 37 works on the subject of color theory to establish detailed knowledge. He sent his manuscript to Goethe, reminding him in 1815 that he had been waiting for months for a response. In the end, Goethe was not pleased with the text and did not offer support. The general response to the work was limited and mixed.

Based on a new interest, a second revised and enlarged edition was published in 1854, with a third, posthumous edition following in 1870 [3, 4]. In the introduction to the second edition, Schopenhauer stated: "By now I have had 40 years of time to test my color theory in every respect and under many different conditions: however, my conviction of its complete validity has not changed for a single moment. At the same time, the validity of Goethe's color theory remains as evident to me as it was 41 years ago when he demonstrated his experiments to me." For reasons that are not clear, Schopenhauer's name or that of his book made no appearance in von Helmholtz's *Handbuch der physiologischen Optik* of 1867 even though he referred to several philosophers as well as Goethe [5].

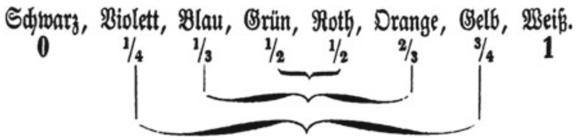

Fig. 35.1 Schopenhauer's representation of the portions of the spectrum occupied by the three pairs of complementary colors, with violet having the lowest brightness, next to black, and yellow the highest, next to white [3]

Key arguments of Schopenhauer[1]

1. The colors themselves, their relationship to each other, and the laws of their appearance all rest in the eye itself are only a special modification of the activity of the retina.
2. Every color is the qualitative half of the complete activity of the retina, completed by another color, its complement.
3. The colors form a continuous circle within which there are no borders, no solidly defined points. Every color is generated by the separation of the circle into two halves, immediately defining its complement.
4. The infinite number of possible colors that are the result of the infinite number of modifications of the activity of the retina must also depend on a similarly infinite variability in stimuli of an outer source that can have the finest transitions from one to the next.
5. The shadowy nature of color we have found to be based in the eye is the result of the activity of the retina being only half for each color, with the other half being inactive, resulting in the grayness of colors.

Figure 35.1 shows the three pairs of complements according to Schopenhauer and their related relative activity of the retina, located between complete inactivity (0) and full activity (1).

Schopenhauer's arguments, in their formulation, were relatively new at the time. They, and the surrounding text, indicate a detailed and solid level of knowledge and insight. However, much of the text is a verbose attack against Newton and his followers and a defense of Goethe's views, often without factual basis, and indicates that Schopenhauer, as most of his contemporaries, had no understanding of the difference between additive and subtractive color mixture. A particular, modern interpretation of Schopenhauer's model is provided by J. Koenderink [6].

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[1] In his own words, translated from [4, pp 68–70].

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Part V

Nineteenth Century to Present Day: The Industrial and Modern World

Contents

Abstract The largest section of this book covers the most recent discoveries and contributions from scientists over the modern era. Entries cover a period from the end of the industrial revolution to the beginning of the 21st Century. Over sixty pioneers are listed in this chapter. Contributions are listed based on pioneers' date of birth to provide a measure of the historical order of the work. Among the pioneers listed in this chapter there are several Nobel laureates, including Schrödinger, Lippmann, Ostwald, and Hubel. Renowned vision scientists including von Helmholtz, König, von Kries and Hering, and many other notable color pioneers including Munsell and Land are also listed. Several were past presidents of the Optical Society of America, including Judd, Hardy, and

MacAdam. With respect to the academic disciplines and the fields of activity, the majority of pioneers were physicists or psychologists, but the group also includes chemists, mathematicians, optical engineers, physiologists, entrepreneurs, and a few artists, demonstrating the truly multi-disciplinary nature of research in the field. We have strived to incorporate, in this first edition, the most notable individuals from as many different disciplines as possible. Without a doubt, the story of lives and labors of the pioneers is one of inspiration. Their trials and tribulations is a reflection of humanity's desire to comprehend the world. The story of color is largely the story of humans and it will continue to inspire, awe and fascinate us.

Chapter 36
Introduction

36.1 Nineteenth–Twenty-First Century

Color affects us in profound ways. Some of our feelings and reactions to the colors can be attributed to culture and society, while others originate from our psychological constitutions. The field known as color theory contains our current knowledge about colors, which is still largely theoretical in nature. Most of the content of the current color theory was developed in the nineteenth and twentieth centuries. Therefore, as the reader will note, this chapter covers the lion's share of the contributions, discoveries, and inventions represented in this book. Physicists, in particular, examined various visual phenomena and greatly contributed to our understanding of the underlying reasons for their occurrence, which helped advance color science. Coverage of the history of color science would not be complete without mentioning contributions from many of the individuals who are introduced in the present chapter. The coverage, however, is by no means inclusive of everybody who made notable contributions. With sufficient public interest, future potential editions may remedy such shortcomings.

The period covered in this chapter includes pioneers who were born after 1800 and starts with the German Gustav Fechner who was interested in the mind-body problem. His studies included the discovery of perceived colors from slowly flickering black-and-white patters (known as Fechner color effect) and of color afterimages. In 1850, Fechner determined that the magnitude of a perception experienced is proportional to the logarithm of the stimulus intensity, now termed Fechner's Law. This laid the grounds for modern psychophysics.

In the same period, Helmholtz established his trichromatic theory of color vision based on the works of Newton, Young, and his own extensive experimental data. He also established the first detailed quantitative data for the relationship between color stimuli and percepts. Based on logic alone, Grassmann in 1853 noted that Helmholtz's then arguments regarding the existence of only two fundamental color

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vision processes in the eye were likely in error. He therefore proposed ideas of color mixture laws, which are currently considered fundamental components of a trichromatic theory of color vision.

Another important center of scientific discovery was in Great Britain where the polymath James Maxwell was advancing the field of optics and the study of color vision. Maxwell examined color mixing principles and demonstrated that white light could be the result of a mixture of red, green, and blue lights. He was instrumental in laying the foundations for practical color photography in 1861.

Physicists throughout the world, including the USA, were actively engaged in specifying color. In 1879, Ogden Rood described three colorimetric parameters, hue, purity, and brightness and estimated the number of discernible colored lights to be about 400 million. His *Modern Chromatics* book included a discussion of complementary colors and effects of contrast, influencing many artists including Seurat and Pissarro and likely contributed to the pointillism movement.

At the same time, in England, Lovibond was running a brewing company and was interested in finding a method to determine the color of his products. His solution, in what became the forerunner of the commercial colorimetry, was his invention of the Tintometer, a visual color-matching device which employed subtractive primaries of adjustable density (e.g., a series of cyan, magenta, yellow, and neutral glass filters) to match the colors of his liquids.

Back in Germany, Ewald Hering, in 1878, developed an alternative, opponent, and color vision theory postulating three opponent pairs of fundamental (unique) hues, yellow–blue, red–green, and white–black. This was first met with skepticism as it was at odds with the trichromatic theory proposed earlier by Helmholtz. A series of exchanges ensued between Hering and Helmholtz and Hering's model received some support. It was some hundred years later when Hering's model formed the basis of the Swedish Natural Color System atlas.

In the same time period, in Munich, von Bezold was studying lightning, color mixture, and binocular vision. In 1873, he showed that the apparent hue of a light stimulus changes due to variations in luminance or lightness of the stimulus, in what later became known as the Bezold–Brücke Effect. He also observed that the appearance of small stimuli is affected by changes in the color of surrounding stimuli, the so-called Bezold spreading effect. In the 1860s, the Czech physicist Ernst Mach had also noted that when viewing band regions of differing illumination or tone the brain exaggerates the difference between the regions that are touching, resulting in the light areas as appearing lighter and the dark areas as darker. This became known as the Mach band effect. In Britain, Abney, who was studying photography, had developed an emulsion to capture the far-infrared solar spectrum in 1887. One of his observations led to what is now called Abney's Law, "a compounded stimulus's luminance is linearly and additively related to the luminances of its components." In 1909, he also discovered that perceived hue changes with increasing luminance of the stimuli, which became known as the Abney effect. These phenomena espoused the complexity of deciphering the visual experience.

Photography was also developing at a rapid pace and Jonas Lippmann, with no formal education beyond high school, developed a system of color photography in 1886 in France in what was certainly the first spectral imaging system. Lippmann's work presaged modern photographic and holographic processes, and he received the 1908 Nobel Prize in Physics for this work.

The American mathematician and scientist, Christine Ladd-Franklin, who was among the first female graduate students at John Hopkins University, became interested in Helmholtz's research when she investigated how points in space are dealt with by binocular vision. She had the opportunity to attend König's lectures in Berlin. There, she developed an evolutionary theory of color vision, which was presented in 1892, involving three stages: the most primitive involving the black-and-white vision; the second stage adding yellow–blue, with the third adding red–green vision. This attracted considerable discussion in the following years.

Helmholtz trained a number of excellent students who continued to advance our understanding of the physiology of vision. These included Johannes von Kries, who was considered to be his greatest disciple. Von Kries proposed that individual components present in the organ of vision are completely independent of one another, and each is fatigued or adapted exclusively according to its own function, though he also recognized that this was likely too simplistic a view. His work became the foundation of chromatic adaptation models. Von Kries was also among the first proponents of the so-called zone theory of color vision that assumed trichromatic receptors (the cones) and opponent processing of the visual information, which was examined in greater detail in the following years. Another talented student of Helmholtz was Arthur König. An excellent physicist, König (together with C. Dieterici), in 1886, determined the spectral sensitivity functions of the three implied cone types and found that color normal individuals varied noticeably in their results. In 1892, he showed that dichromats only had two such functions. The data became known as the König fundamentals and were used for colorimetric calculations.

The technology of color printing owes a great deal to the work of Eugene Ives who, after leaving school at 12, became interested in the process. In 1875, he invented the halftone printing process for black-and-white photographs. Based on Maxwell's trichromatic principles and through many additional inventions, in 1892, Ives obtained a patent for a trichromatic camera and later revolutionized color printing.

By the beginning of the twentieth century, activity pertaining to color order systems had once again become fervent. The American artist Albert Munsell felt that the best way to educating students about color was through a sound color order system. In 1900, he patented a balanced color sphere that, when spun rapidly, resulted in a gray appearance. Munsell coined the term *Chroma* to define a chromatic intensity scale and described a color order system in 1905 based on the three attributes value, chroma, and hue. The Atlas of the Munsell color system was published in 1907. In 1917, he formed the Munsell Color Company. Munsell's system is perhaps the most important color atlas system yet developed. His efforts coincided with a similar body of activity by Wilhelm Ostwald, a Latvian of German descent, who was trained as a chemist and received the Nobel Prize for the discovery of chemical catalysis in 1909. He had considered color science to belong to the psychological domain. Nonetheless, he decided to develop a harmonious color order system, which he published in 1917/18. In 1918, he demonstrated the existence of metameric object colors and introduced the term *metamerism.* One of Ostwald's students, Thomas Luther, was named assistant director and later a professor of physical chemistry at the Ostwald Institute at the University of Leipzig. However, Ostwald did not enjoy teaching and eventually resigned from his position and Luther was named director. This put him in a difficult position and thus he decided to move to the Technical University of Dresden where he launched his color research. He improved the chemistry of color photography. In 1927, Luther developed the secondary colorimetric functions for Hering's four perceptually primary colors, yellow vs. blue and green vs. red, and trained a number of students, including Manfred Richter.

Meanwhile, the illumination industry was rapidly growing, and the need for lamps that accurately simulated various lighting conditions was becoming increasingly obvious in industrial and retail trade settings. The Canadian Norman Macbeth invented the illuminometer in 1915 to determine the spectral properties of light sources. He also developed and patented the use of high and low color temperature illuminants for testing metamerism. The question of how much light was necessary to provide adequate "seeing" had become relevant and important. The American Matthew Luckiesh developed many lamps including daylight simulating lamps while working at General Electric and examined the relations between lights and seeing. He noted how the level of illumination could have a physiological effect on people and recommended appropriate lights for different settings, including the White House in 1933, which gained him a reputation as "the father of the science of seeing."

Scientific discoveries pertaining to the psychology of color perception were also evolving. The German physicist and psychologist David Katz examined the phenomenology of vision, including shape, structure, space, color, and movement, and defined three appearance modes of colors: film, surface, and volume. From 1907 to 1933, Katz and his students performed many experiments related to color appearance involving illumination changes, surround as well as light and dark adaptation to elucidate the role of external conditions on color vision. In 1923, the German Rudolf Kohlrausch investigated an observation by Helmholtz regarding the effect of hue on the perceived brightness of a stimulus. Kohlrausch observed that stimuli with luminance values identical to that of the achromatic surround often appear, to various degrees, lighter (more glowing) than the gray. This became known as the Helmholtz–Kohlrausch effect.

The need for an objective specification of color was increasingly felt in industrial and academic circles. Such specification, however, required the advent of accurate instrumentation to measure the spectral properties of the colored stimulus. Irwin Priest, who was working at the National Bureau of Standards in the USA, together with E. Lange, developed the Priest-Lange reflectometer in 1920 and invented a dispersion colorimetric photometer in 1924 for measuring light sources and an apparatus to measure dominant wavelength, purity, and brightness of color samples. This paved the way for further discoveries in the field.

The König fundamentals had provided a means of specifying color normal observers and with the advent of methodology to specify the spectral properties of light sources as well as the stimuli the ground was set to improve the mathematical definition of color. The Austrian physicist and Nobel laureate Erwin Schrödinger had become interested in color through the writings of the German philosopher Arthur Schopenhauer, who in turn was influenced by Goethe. Schrödinger used differential geometry to describe a color space and inferred the total color difference (in units of just-noticeable differences). In 1925, he also offered a mathematically detailed connection between the Young–Helmholtz trichromatic theory and Hering's opponent-color theory.

The mathematical specification of the average normal observer, however, required additional experiments. In the late 1920s, two British scientists working independently, John Guild who worked at the National Physical Laboratory in England and David Wright, who was at the Imperial College, conducted a series of color-matching experiments for a total of 17 observers. This formed the basis of the international standard for measuring color, the CIE 1931 Standard Colorimetric Observer. Meanwhile, research by B. H. Crawford and W. S. Stiles in England in 1933 showed a reduction of brightness and the change of hue and saturation for stimuli entering the periphery of the iris compared to stimuli entering the center of the iris. This became known as the Stiles–Crawford effect.

From the 1920s to 1940s, the illumination industry was actively researching more efficient fluorescent lamps. Elliot Adams, at the General Electric Company, examined fluorescent and other gaseous discharge lamps, but he was also interested in the mathematical representation of the color. In 1942, he suggested two models "chromatic value" and "chromatic valence" for perceptually uniform color spaces. His models became the precursor of the modern CIELAB and CIELUV uniform color spaces. However, further observations showed that Adams V_y parameter did not sufficiently accurately represent a perceptually uniform lightness scale. American chemist, Isaac Godlove, in 1933, co-wrote an article on the neutral value scale which eventually resulted in the cube root version of the CIE L^* lightness scale.

The specification of object color over this period was based on determination of CIEXYZ attributes. In 1923, Adams had advocated the use of opponent axes of red–green and yellow–blue which were considered to be easier to comprehend. Richard Hunter was a laboratory apprentice at the National Bureau of Standards under the energetic Chief Irwin Priest in 1927. There he designed a visual reflectometer. He later met with Deane Judd and was encouraged to build the first multipurpose reflectometer in 1938. Having conceived the "Lab" color scales in 1942, he designed and developed a number of instruments for the measurement of color and gloss. [In 1952, he formed, Hunter Associates Laboratory, Inc. (HunterLab), which is currently located in Virginia.]

In the same period, the American physicist Arthur Hardy was also pursuing the development of instrumental methods for measurement of color. In 1935, he filed a patent for the first recording spectrophotometer, which significantly contributed to the advancement of colorimetry in the following years.

With mass productions, the industrial reproduction of color required accurate predictive models of color admixture. Paul Kubelka, born in Czechoslovakia to Austrian parents, with Franz Munk, published a theory of light absorption and scattering by a layer of paint, in 1931, which became known as the Kubelka–Munk theory. In the following years and with the advent of computer technology, this model became the leading theory for colorant formulation. Several mathematicians examined, refined, and corrected the available mathematical models of the color of the time. The American physicist Deane Judd wrestled throughout his career with the relationship between color stimuli and color perception. This was an important period in the activities of the International Commission on Illumination (CIE). Judd developed a polynomial function to describe the relationship between Munsell value and luminance factor, which while accurate, was considered cumbersome and was not adopted. He conducted a large number of additional studies, some of which became the basis for the CIE u,v color diagram in 1960.

Industrial quality control of products necessitated the development of defined light sources for visual assessment. The Munsell color system had also become the most widely used system for the specification of the color of products. The American Dorothy Nickerson studied and improved the Munsell system and its definition in the CIE colorimetric system. In 1936, Nickerson published the first color difference formula for industrial use, based on the addition of increments of Munsell hue, chroma, and lightness scale values.

Another domain where the color science front was advancing was the neurophysiological examination of color perception. In Britain, William Rushton laid the groundwork for the establishment of the modern theory of nervous excitation and propagation in 1935 and developed the principle of univariance. He noted, "the output of a receptor depends upon its quantum catch, but not upon which quanta are caught." Several of the laws of color mixing are a direct consequence of this principle.

During the Second World War, vision research focused on night vision, camouflage, aerial and flicker vision, among other things. In America, Arthur Hardy who was chair of Massachusetts Institute of Technology's physics department created the Visibility Laboratory with Seibert Duntley in 1939. He applied optics to such problems as camouflage, misdirection of aerial bombardment, target location, and visibility of submerged objects at sea. Meanwhile, the Deutsches Institut für Normung (DIN, German institute for industrial standards) had decided to develop a national standard color system and atlas. Manfred Richter was asked to take charge of this activity in 1941. Taking the Ostwald system as reference the resultant perceptually uniform DIN6164 space contained hue, saturation, and darkness as its three attributes and became the German industrial standard system.

In England, the temporary blinding effects of gunfire flashes during the war inspired B. H. Crawford to study vision under such conditions. "Crawford Masking" as it became known, referred to perception of a bright stimulus prior to a later less bright stimulus. Crawford also determined the average spectral response of the human eye under low levels, scotopic, and illumination conditions. This led to the international standard for spectral luminous efficiency for scotopic vision (the $V'(\lambda)$ function). In America, Edwin Land's company was commissioned to develop new kinds of night vision goggles and a system that could reveal enemies in camouflage uniforms. In the years after the War, Land continued to cooperate with the US government and was involved in the development of the U2 spy plane.

Meanwhile, Ralph Evans, who was leading color quality research at Eastman Kodak's Color Technology Division, was convinced that a better understanding of color perception would result in improved color photography and printing. Leo Hurvich and Dorothea Jameson conducted research on distance perception at Harvard University and were among those that joined Kodak in 1947. Evans was interested in the appearance of color stimuli under specific conditions. He concluded that certain test colored stimuli exhibit a grayish appearance against a white surround of a certain luminance that diminishes steadily as its luminance increases, up to a point where the apparent grayness disappears and eventually the test appears fluorent. He developed the G_0 function that showed zero-grayness to vary across the spectrum as a function of dominant wavelength and used the term 'brilliance' to describe this perceptual parameter. He concluded that chromatic stimuli have five independent variables: hue, saturation, lightness, brilliance, and brightness. The work indicated the complexity of color appearance. Dorothea Jameson and Leo Hurvich married in 1948 and continued to investigate the perceptual aspects of hue, saturation, and brightness of colors in an academic setting. They supported the opponent-color vision theory. Using hue cancellation method, they identified the locations of unique hue stimuli as approximately 475 nm for blue, 500 nm for green, 580 nm for yellow, with red located near the high end of the spectrum. However, it has since become evident that the human visual system has a more complex neurological basis.

Meanwhile, the US government and several industrial sectors had become interested in determining the relationship between color and its psychological effect on safety, employee morale, productivity and sales in the 1940s. The American Faber Birren, who came from an artistic background, examined the relationship between color, perception, and emotions. His recommendations included the functional use of color, especially in hospitals and schools such as changing wall and interior colors to reduce visual fatigue and using bright colors on machinery to reduce accidents. These recommendations were adopted by the Occupational Safety and Health Administration and are still in use today.

In the mid-1940s David MacAdam, who was trained under Hardy at MIT, established Hardy's reflectance spectrophotometer as a reliable industrial measuring instrument and invented a tristimulus integrator as an accessory. In 1942 and assuming that the basis of color difference perception was the statistical error in matching the appearance of a given color stimulus, he conducted an extensive experiment with one observer, the result of which was expressed in the CIE chromaticity diagram in the form of statistically derived ellipses.

In the field of psychology, the German Gestalt movement was gaining momentum in the USA. The American Harry Helson, who was a proponent of the approach, examined visual perception and postulated his adaptation-level theory in 1947. He noted that an individual's basis of judgment of a stimulus is based on their prior subjective experiences as well as their recollections of how they perceived similar stimuli in the past and in different situations. This view was debated in the following years.

A mathematical description of color stimuli that occupied a field of view larger than 2° necessitated a re-examination of the color-matching functions of observers. The Englishman Stanley Stiles, in the late 1950s, spent much time and effort in constructing a visual colorimeter to redetermine the color-matching functions of the normal observer. This provided the major basis for what became the CIE 1964 supplementary standard colorimetric observer for a field size of 10°.

In the meantime, Land at the behest of his three-year-old daughter had developed the Polaroid instant camera in 1947. He conducted a series of color reproduction experiments with projectors and in 1959 concluded, "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." In 1964, Land proposed the "retinex" (derived from *retina* and *cortex*) model, a mathematical model to predict the influence of surrounding color fields on the appearance of a test field which in the following years received some criticism from other researchers.

The psychology of color perception was further advanced with the findings of Stanley Stevens who examined brightness perception as a function of adaptation. In a publication in 1961, Stevens summarized psychophysical scaling data for perceptual stimuli and illustrated that all perceptual data could not possibly follow the logarithmic relationship as predicted by Fechner. Stevens proposed power functions with various exponents depending on the perception being scaled. This is now known as the Stevens Power Law. In an intriguing experiment, Stevens also demonstrated that as the level of lighting increases, dark colors look darker and light colors appear lighter. This is known as the Stevens Effect and was used in mathematically modeling color appearance.

The need to facilitate the formulation of colorants to match a given stimulus resulted in a collaboration between H. R. Davidson and H. Hemmendinger in America. Around 1954, Hugh Davidson developed the first automatic tristimulus integrator and attached it to the GE-Hardy spectrophotometer. This provided a quick way of obtaining tristimulus values. In 1958, Henry Hemmendinger, together with Davidson, developed Colorant Mixture Computer (COMIC). This was an analog computer for matching reflectance functions of dyed or painted samples with related colorants. This technology replaced centuries-old color matching by trial and error. They also quantified performance errors in colorimetry, incurred by photometric equipment and by human observers and examined the breakdown in a color match incurred by changing either the illuminant or the observer. The process was significantly enhanced when Eugene Allen developed a set of basic mathematical equations for color matching, using matrix algebra and the Kubelka–Munk equations in 1966. The methodology became an important basis for the widespread industrial use of digitally based computer colorant formulation. Allen proposed matching algorithms for both one- and two-constant Kubelka–Munk data, the former for dyes and the latter for pigments.

Over this period Gunter Wyszecki introduced the mathematical concept of "metameric blacks," psychophysical definitions of blacks with tristimulus values 0, 0, 0 that, within limits, can be added to a spectral reflectance to form the various possible metamers having an identical set of tristimulus values under a given light in 1958. With Stanley Stiles, he developed mathematical methods to calculate the number of possible metamers for given chromaticities.

After Macbeth Sr. passed away, his son Norman Macbeth Jr. took over the affairs of the Macbeth Company, which merged with Kollmorgen Corp. in the mid-1960s. In 1967, Macbeth Jr. invited Bartleson to join Macbeth Corporation. In the same year, Bartleson with Ed Breneman on the effect of light and dark surrounds on apparent contrast, which later became known as the Bartleson–Breneman effect. Among the products developed by GretagMacbeth Company was the Macbeth ColorChecker Color Rendition Chart, by McCamy, Marcus, and Davidson in 1976.

Calvin McCamy also invented an annular illuminator that would ensure azimuthally uniform illumination in a 45/0 spectrophotometer which made measurements more reproducible. Meanwhile, in 1970, Ralph Stanziola co-founded Applied Color Systems, Inc. (later Datacolor) and developed the first colorant-dispenser system driven by computer color matching in 1979 and patented a Maxwell-disk-based color simulator in 1980.

During this time, a need for academic and industrial training in color technology had become evident. Rensselaer Polytechnic Institute established a new research laboratory to run the undergraduate and graduate program in color science. Fred W. Billmeyer and Max Saltzman co-authored a popular textbook, *Principles of Color Technology,* which went through two editions during this period (1966 and 1981). Fred Billmeyer also initiated the journal *Color Research and Application* and was the founding editor until 1986.

Meanwhile, the American psychologist Jozef Cohen had gotten involved in the psychophysics of color between 1946 and 1949 and, after an intermission, again later in the mid-late 1960s. In the 1980s, together with W. E. Kappauf, he examined a concept that he named fundamental color metamers. Using principal component analysis, he decomposed a reflectance or a spectral power function into two components: the fundamental function and a metameric black function, a concept that was introduced by G. Wyszecki in 1953. Cohen named the resulting space the fundamental color space. It gained wider traction after publication in 1988, and his findings provided much new insight into the nature of color stimuli.

The neurophysiological processes involved in color vision were continued to be examined during this period. In 1972, Boynton, together with his colleague D. I. A. MacLeod, proposed a Luther-inspired chromaticity diagram based on normalized cone response functions. This psychophysical colorimetric system was widely used in scientific efforts.

Japan had also become an important center of color research after the Second World War. Indow Tarow had a fascination with the mathematics of psychological findings. He examined the implicit global structures of the visual space relating to its geometry, taking into account the various conditions of viewing, surround and illumination. He also examined the Munsell space using the method of multidimensional scaling in 1988. Meanwhile, Yoshinobu Nayatani was interested in color vision and modeled chromatic adaptation, color appearance, and observer metamerism. For Nayatani, gray had a special role as a central color in the opponent-color order system. He discussed how the two opponent axes change from red–green to red–gray and gray–green and from yellow–blue to yellow–gray, and gray–blue. Several other scientists in Japan have examined and advanced the psychology of color perception, color imaging, and color reproduction techniques.

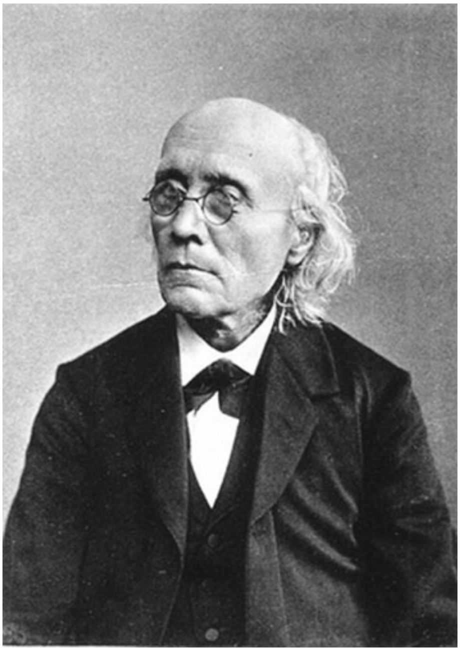
Further advances in establishing relationships between neurobiological activities related to vision in the brain and the corresponding visual experiences in consciousness continued with the works of David Hubel and Torsten Wiesel in America. Hubel and Wiesel's electrophysiological measurements of signals in cells of the lateral geniculate nucleus of cats earned them the Nobel Prize in medicine or physiology in 1981. This pioneering work enabled an entirely new path of research concerning the neurobiology of the mammalian visual system. In the USA, the De Valois' were also interested in the question of the representation of spatial vision in the brain. In 1993, Russell and Karen De Valois developed a multistage color vision model and realized that the responses of opponent-color cells in the lateral geniculate nuclei were not in agreement with implicit perceptual performance and developed a more complicated four-stage model in general agreement with then current neurophysiological findings. More than 20 years later, it appears that the activities in the brain related to color perception are even more complex than assumed and a broadly supported model is yet to be developed.

The history of advances in the study of color from an artistic perspective requires a separate volume but it is important to include some of the key individuals in the twentieth century who had a significant impact in the field. The Swiss Johannes Itten and the German Josef Albers were influential artists and educators in this period. Itten largely excluded scientific developments from the mid-nineteenth century onwards and supported the idea of subjective harmony while regarding color expression as involving objective rules. He presented a dictionary of color and color combinations in which complementary colors were expected to have opposite meanings, secondary colors were expected to combine the meanings of the primaries they "contained," and meanings could be modified by contrast effects with surrounding colors. Josef Albers, on the other hand, was interested in the perception of color as conditioned by changing light, shape, and placement and spent many years examining the topic. His "Homage to the Square" attracted praise and criticism. In his *Interaction of Color* book, published in 1963, he stated, "every perception of color is an illusion … we do not see colors as they really are. In our perception they alter one another." These general claims about the color experience and the system of perceptual education had wide traction in the artistic community but may have been somewhat misleading, likely due to a misconception of the aesthetic appreciation of color, simultaneous contrast, and the underlying psychological effects.

Due to the multi-disciplinary nature of color science domain, there are likely several individuals, with important and significant contributions to the field, who have not been included in this volume. Nonetheless, the hope was to include as many of the leading pioneers as possible to provide the reader with a historical perspective of advances in this field. Many of these pioneers spent their lifetimes in the pursuit of their discoveries. In the busy and overwhelming information technology age, it is easy to forget that behind each discovery and invention lies a heap of trials and tribulations, with all the glories and despairs over a journey that we call life.

We stand on the shoulders of giants…

Chapter 37
Fechner, Gustav Theodor 1801–1887



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Gustav Theodor Fechner was a German experimental psychologist and philosopher. He is also considered by many to be the father of modern psychophysics. Initially, Fechner took a degree in medicine and worked in that area for a while. During that time, he began publishing a series of humorous and satirical articles and poems lampooning the medical profession. These were published under the pseudonym

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Dr. Mises and one of his most famous publications of this genre was on the Comparative Anatomy of Angels (1825). The writings of Dr. Mises certainly provide insight into the breadth and depth of Fechner's intelligence and abilities.

Fechner then moved on to physics by learning about contemporary advances in electricity and magnetism through translation of great French works as well as handbooks of chemistry and physics into German. With this new knowledge in hand, Fechner taught at the University of Leipzig, eventually obtaining a professorship and making distinguished contributions to the field. Interestingly, Dr. Mises also continued to publish on occasion.

All along, Fechner was interested in the mind–body problem and desired to determine an empirical relationship between the physics of the world (and body) and the perceptions of the mind. Some of his studies in this vein included the discovery of perceived colors from slowly flickering black-and-white patterns (known as Fechner's Colors or Fechner–Benham Colors after Benham made the work accessible in English) and the detailed study of color afterimages. It was the study of afterimages that set Fechner off in his next direction. He was studying afterimages by staring at the sun through colored filters. This led him to give up his chair in physics in 1840 due to induced photophobia from eye injuries that made him an invalid, and overly sensitive to light, for about a decade.

37.1 Fechner's Law

During this period, on October 22, 1850, while lying in bed, he finally figured out the basis of linking physical measurements in the environment with human perceptions in the mind that is currently referred to as Fechner's law. Based on his knowledge of Weber's law (coined by Fechner) that, for many perceptions, the ratio of just-noticeable change in a stimulus to the initial magnitude of a stimulus is a constant, Fechner figured out that the differential equation implied by Fechner could be integrated and he assumed that the just-noticeable differences could be summed to predict perceptual magnitude. The resulting relationship, now termed Fechner's law, mathematically suggested that the magnitude of perception would be proportional to the logarithm of the stimulus intensity.

More modern knowledge tells us that the specific relationship depends on the perceptual quantity and that it is not valid to sum JNDs to predict magnitudes of differences. Nonetheless, Fechner's contribution was very significant in founding the field of psychophysics. Fechner published further details of the theory and practice of psychophysics in his seminal work, *Elements of Psychophysics* (1860), which remains a useful guide for practitioners in the field [1]. Interestingly, Fechner is also credited with being the first to introduce the concept of the median to formal data analysis.

From Boring's introduction in Adler's translation of *Elements of Psychophysics*, we find that Fechner was for seven years a physiologist (1817–1824), for 15 years a physicist (1824–18390, for 12 years an invalid (1839–1851), for 14 years a psychophysicist (1851–1865), for 11 years an experimental estheticist (1865–1876), and for periods throughout a philosopher.

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Chapter 38

Grassmann, Hermann Günther

1809–1877

Grassmann portrait, artist unknown

Hermann Gunther Grassmann was born on April 15, 1809, in Stettin in Pomerania, near the Baltic Sea (today Szczecin in Poland), the third of 11 children of a pastor and high school mathematics teacher and his wife. After passing through high school, Grassmann moved to Berlin to study theology, with later addition of

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mathematics and sciences. In 1844, he published his major work in mathematics, *Die lineale Ausdehnungslehre, ein neuer Zweig der Mathematik* (Linear extension theory, a new branch of mathematics) [1], a general calculus of vectors. *Ausdehnungslehre* was not a success, apparently clearly ahead of its time. In 1846, Grassmann received an award for expanding on a mathematical problem sketched earlier by Leibniz. Grassmann married in 1849, and he and his wife had 11 children. His father, though teaching at a high school, had been named professor a few years before he passed away in 1852. In that same year, Hermann Grassmann assumed the position of mathematics professor his father had held at the Stettin Gymnasium. In his later years, unhappy about the continuing lack of attention to his mathematical efforts, he became interested in the history of languages. He learned Sanskrit and prepared a dictionary and a translation of the sacred collection of Indian Vedic hymns, the *Rigveda*, one of the oldest extant written records in an Indo-European language, dating to the mid-second millennium BCE [2]. Both works immediately gained much admiration and support from linguists. Grassmann died on September 26, 1877, in Stettin.

38.1 Grassmann's Laws

In 1852, Hermann von Helmholtz published an article, based on his results of experimental work in color mixture with a spectroscope of his own design. He concluded that Newton's structural design of his color circle, based on his own experiments with mixing spectral lights, must be in error and that there are only two spectral colors, blue and yellow, that when mixed result in colorless appearance [3]. Grassmann applied mathematical logic to the problem and in 1853 published a paper "*Zur Theorie der Farbenmischung*" (On the theory of color mixture) [4] in the same journal as Helmholtz, claiming that Helmholtz was likely in error. He postulated four "assumptions" about color mixture:

1. Every impression of color may be analyzed into three mathematically determinable elements—hue, intensity of color, and brightness of the intermixed white light.
2. If one of two mingling lights is continuously altered (while the other remains unchanged), the impression of the mixed light is also continuously changed.
3. Two colors, both of which have the same hue and the same proportion of intermixed white, also give identical mixed colors, no matter what homogeneous colors they may be composed of.
4. The total intensity of any mixture is the sum of the intensities of the lights mixed.

A modern interpretation of the content of assumptions 2–4, as provided by Wyszecki and Stiles, [5], are the following four laws:

1. Symmetry law: If color stimulus **A** matches stimulus **B**, then stimulus **B** matches stimulus **A**.
2. Transitivity law: If **A** matches **B** and **B** matches **C,** then **A** matches **C**.
3. Proportionality law: If **A** matches **B,** then **aA** matches **aB**, where **a** is a positive factor of the radiant power of the stimulus.
4. Additivity law: If **A** matches **B** and **C** matches **D**, then (**A** + **D**) matches (**B** + **C**) (applicable to additive mixtures).

These laws do not explicitly consider variations in conditions, in eye adaptation, or variation in color matching functions between observers (see, e.g., Brill and Robertson) [6].

The laws are considered fundamental components of a trichromatic theory of color vision. In response to Grassmann's paper, after modifying his spectroscope, Helmholtz redid the color mixing experiments and was able to determine multiple complementary pairs in the spectrum, thus confirming the basic validity of Grassmann's laws [7].

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Chapter 39
Helmholtz, Hermann Ludwig von 1821–1894

Image by Ludwig Knaus, 1881

Hermann Ludwig von Helmholtz was born on August 31, 1821, in Potsdam near Berlin, Germany, into a well-educated family. His father, an educator, taught him the classical languages and introduced him to philosophy. Helmholtz studied medicine in Berlin under physiologist Johannes Müller, at the same time attending lectures in physics and mathematics. Müller was an adherent of the then broadly accepted philosophical nativism. Helmholtz spent much of his life finding objective arguments against nativism and in favor of empiricism. After spending several years in military service in Potsdam and a stint as associate professor of physiology at the Prussian University, he became a full professor of anatomy and physiology in

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Bonn. Three years later, he moved to the University of Heidelberg and in 1871 became the professor of physics at the University of Berlin, where he remained until his retirement. Helmholtz had a broad range of interests, from astronomy to physics, physiology, and the relationship between the physical world and human sensory perception. In 1847, he wrote an important article on the conservation of physical force [1]. In 1850, Helmholtz invented the ophthalmoscope for inspecting the interior of eyes for medical purposes and revolutionized the practice of ophthalmology [2]. Among Helmholtz's many students were H. R. Hertz, M. Planck, A. A. Michelson, W. Wundt, and W. Kohlrausch (the co-discoverer of the Helmholtz–Kohlrausch effect). Helmholtz died on September 8, 1894, in Berlin.

39.1 Trichromatic Theory of Color Vision

In sensory perception, he specifically covered hearing and, most extensively, vision. His most important publication is *Handbuch der physiologischen Optik* (Treatise on physiological optics), a 900 + page work whose first edition was published in 1867 when he was in Heidelberg [3]. The book's main sections are (1) Anatomical description of the eye, (2) Physiological Optics, (3) Dioptrics of the eye, (4) Sensations of vision, including Simple colors and Compound colors, (5) Intensity and duration of the sensation of light, (6) Contrast (including colored shadows), and 7. Duplicity theory [4]. A second edition authored by Helmholtz was published posthumously in 1896, supervised by Helmholtz's assistant Arthur König who also added over 7800 literature references [5]. A third edition was published in 1909, consisting of the second edition, with contributions by A. Gullstrand, J. von Kries, and W. Nagel [6]. It was translated into English by J. P. C. Southhall and published with an additional contribution by the Optical Society of America [7].

Helmholtz built his trichromatic theory of color vision on Newton's findings, Young's theory of three sensor types in the eye, Maxwell's experimental findings of color mixture, and his own extensive experimental data concerning various aspects of color vision. He developed a spectral light mixture apparatus (see portrait) with which, after initially unsatisfactory results causing the mathematician G. Grassmann to challenge his data, he established the first detailed quantitative data for the relationship between color stimuli and percepts. Mathematical models of his findings and concepts were a standard procedure in his work. Under his guidance, his assistants König and Dieterici developed in 1885 a first quantitative version of a trichromatic chromaticity diagram (Fig. 39.1).

While Helmholtz developed an experimentally supported general psychophysical theory of vision, he was also concerned about and experimented with many additional phenomena of the human visual system. He is the first to mention color constancy, saying that "we always start out forming a judgment about the colours of bodies, eliminating the difference of illumination by which the body is revealed to us." [6] The color vision theory of Helmholtz, based on Young's conjecture of three sensor types, is known as the Young–Helmholtz theory of trichromatic color vision.

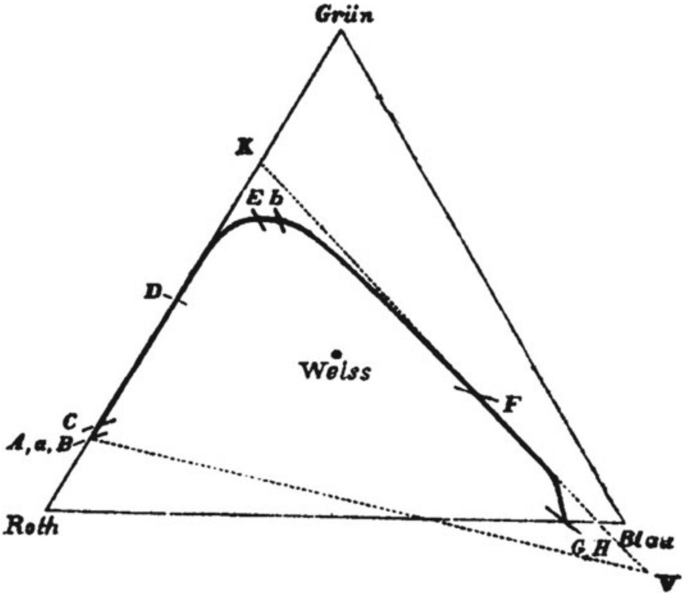

Fig. 39.1 Chromaticity diagram based on König and Dieterici's fundamental color sensitivity functions determined in Helmholtz's laboratory. Loci of spectral color stimuli are on the curved solid line. Letters indicate loci of Fraunhofer lines in the spectrum [5]

Helmholtz's rival Ewald Hering developed a theory of color vision essentially based on psychology to which he gave a presumed physiological basis. Both views attracted followers [8]. Today, the controversy has been narrowed but still remains. Interestingly, their expressed epistemological views were not as might be expected: Helmholtz viewed lights and colors as symbols. In 1852, he said "Light and color percepts are only symbols for the relations of reality; with the latter they have as little and as much similarity or relationship as the name of a person or its written form with the person itself." Hering, on the other hand, believed that, in perception, our access to real objects is a direct one.

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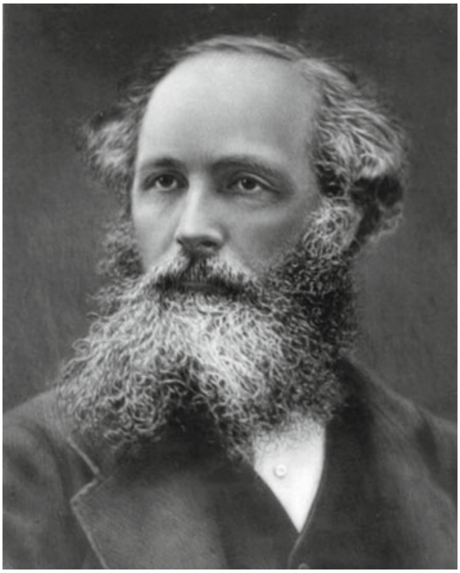
Chapter 40
Maxwell, James Clerk 1831–1879



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James Clerk Maxwell was born on June 13, 1831, in Edinburgh, Scotland, to a family of comfortable means, and was the only child of his parents. He is considered a pioneer in several fields of science. Maxwell contributed greatly to the field of optics and the study of color vision and helped lay the foundations for practical color photography. Over a period of 17 years, from 1855 to 1872, he published a series of papers concerning the perception of color, color blindness, and color theory [1]. He died in Cambridge at the age of 48 of abdominal cancer in 1879 [2].

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Maxwell had a keen intellect and an unquenchable curiosity from childhood. Maxwell's formal schooling began unsuccessfully, and it is reported that he was treated harshly by his private tutor for being slow and disobedient [3]. He was then sent to the prestigious Edinburgh Academy to continue his education. At the age of 13, he won the school's mathematical medal as well as the first prize for English and poetry. At the age of 14, he wrote his first academic paper on *Oval Curves*, which was presented, on his behalf, at the Royal Society of Edinburgh.

When 16 years old Maxwell was enrolled at the University of Edinburgh. There, among many other things, he learned about disk color mixture (Fig. 40.1) from one of his professors, James D. Forbes (1809–1868), who was working on a color classification system. During his undergraduate studies, Maxwell also examined the properties of polarized light [4]. At age 18, he contributed two papers to the Transactions of the Royal Society of Edinburgh. One of these, On the Equilibrium of Elastic Solids, laid the foundation for an important discovery on the temporary double refraction produced in viscous liquids by shear stress [5]. In October 1950, Maxwell moved to the University of Cambridge's Trinity College where he graduated in 1854 with a degree in mathematics. He stayed at the Trinity College after graduation until 1856 when he accepted the position of professor of natural philosophy at Marischal College in Aberdeen [6]. In 1858, he married Katherine Mary Dewar who regularly assisted him in his experimental work. In 1860, he was granted the chair of natural philosophy at King's College in London. He stayed

Fig. 40.1 Young Maxwell demonstrating one of his spinning color wheels (clerkmaxwellfoundaation.org)

there until 1865, working primarily on electromagnetism. He and his wife returned to his inherited estate in Glenlair, Scotland, until he became the first Cavendish professor of physics at Cambridge University, where he stayed until his untimely death. He is considered the "father of electromagnetics." He is also the inventor of a thought experiment on thermodynamics, resulting in what is known as "Maxwell's demon."

40.1 Composition of Colors

The nature of perception of color was one of Maxwell's interests, which had begun in Scotland. Using an improved version of a disk mixture apparatus, he demonstrated that white light results from a mixture of red, green, and blue light. His paper *Experiments on Colour* was a fundamental study of the color mixing principles and was presented to the Royal Society of Edinburgh in 1855 [3]. In the following years, he built a visual spectrometer in which he could mix and adjust spectral lights. The results of his own and his wife's mixture data, published in 1860, demonstrated that only three primary lights are required to match any spectral or composite light. In the same year, he was awarded the Royal Society's Rumford Medal "For his researches on the composition of colors, and other optical papers."

Based on his trichromatic theory, Maxwell proposed in the late 1850s a method for practical color photography. He suggested that if a scene is photographed three times separately but using red, green, and blue filters, and the resulting black-and-white transparent images are then superimposed on a screen using projectors equipped with similar filters, the result would be a full-color reproduction of the image as seen by the human eye. Together with the photographer Thomas Sutton, he demonstrated this in 1861 at the Royal Society (Fig. 40.2). As the image

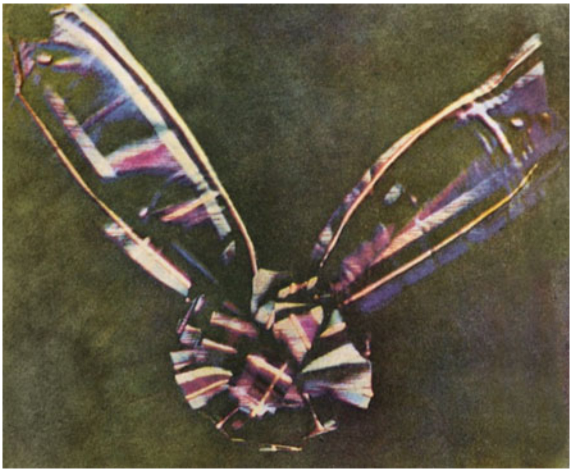

Fig. 40.2 Reproduction of the Scottish tartan image using the photographic images and color filters employed by Maxwell and Sutton in their demonstration in 1861

Fig. 40.3 Examples of stamps bearing Maxwell's portrait from San Marino (left), Mali (center), and Mexico (right)

of the Scottish tartan shows, due to the fact that the filters were less than optimal, the outcome was less than perfect and commercial color photography required another 45 years of invention. Maxwell has been commemorated on stamps from numerous countries (Fig. 40.3).

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Chapter 41

Rood, Ogden Nicholas 1831–1902

Image from Notable New Yorkers of 1896–1899: a companion volume to King's handbook of New York City (1899) by Moses King

Ogden Nicholas Rood was an American physicist, best known for his work in color theory. He was a descendant of Scottish immigrants arriving in America in the seventeenth century and was born on February 3, 1831, in Danbury, CT. His father was an ordained minister [1].

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Rood graduated from Princeton College. He continued his postgraduate studies at Yale College and then moved to Berlin and Munich (Germany) to continue his pursuit of physics, while also following watercolor painting as an amateur, which was an interest that he practiced throughout his life. Rood was active in several fields of investigation among which were optics, photography, and color. His first appointment was as a professor of chemistry at Troy University in Troy, NY. In 1863, Rood was appointed as a professor of physics at Columbia College in the city of New York, a position he held until the end of his life. He eventually held positions as Chair of Physics at Columbia University and Vice President of the American Association for the Advancement of Science. During his lifetime, he published over 50 articles in scientific journals about half of which were on optics and color. He performed many kinds of experiments concerning color, the purpose of which was to clarify the understanding of color effects and interactions resulting in meaningful quantitative data. Rood died on November 12, 1902, in New York [2].

41.1 Modern Chromatics and Other Contributions

Of particular interest among the articles on color written by Rood is an 1876 article “The constants of color” in which he described the three parameters hue, purity, and brightness of color percepts produced by lights and where he estimated the number of discernibly different lights to be 400 million. His other important articles include the 1878 article “Photometric comparison of light of different colors;” the 1880 article “On the effects produced by mixing white with colored light;” and the 1890 article “On a color system.” The most important among his writings on color is the 1879 book “Modern chromatics, with application to art and industry.” The theories covered in this book were based on ideas by Newton, Goethe, and others, but Rood made the work more accessible and particularly attractive to artists. It was also published under the title “Students’ text-book of color” beginning in 1899. A French edition was published in 1881. The information in the text was broadly based on the findings of Helmholtz, Maxwell, and others, with many experimental results and insights by Rood included. An example from his book is shown in Fig. 41.1, which in a semi-quantitative manner illustrates the contrast effect when a red stimulus sample is juxtaposed on the perceived colors of other samples on the color circle.

Rood’s descriptions, together with those of Maxwell and Chevreul, had an influence on impressionist artists and their successors. Rood’s theory of contrasting colors was particularly influential. George-Pierre Seurat, the founder of neo-impressionism and the foremost pointillist, and Camille Pissarro are known to have been influenced by Rood in their paintings. In his book, Rood discussed the difference between additive and subtractive color stimulus mixture and the effect of additive stimulus mixture when viewed at a distance, resulting in the terms chromo-luminarism and pointillism. Rood suggested that small dots or lines of different colors, when viewed from a distance, would blend into a new color. He

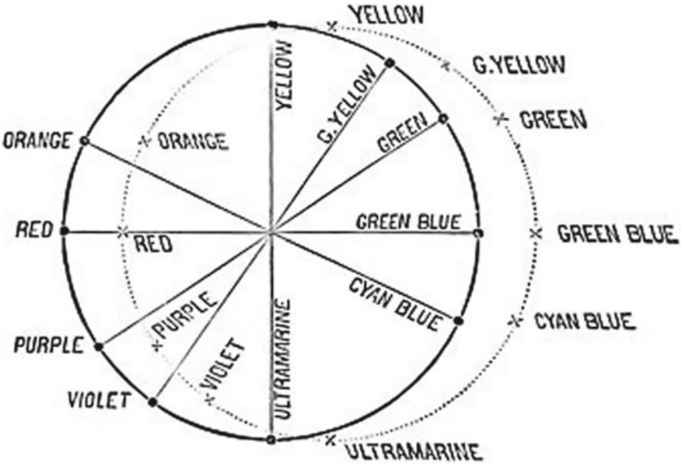

Fig. 41.1 Complementary colors (solid circle) and the contrast effect on them (dashed circle) when juxtaposing them with a red sample [1]

believed that the complementary colors of his color wheel, when applied in pairs by the artist, would enhance the presence of a painting. The book, in its various editions, became broadly influential as a scientifically based but easy to comprehend, up-to-date text on color science at the time. Albert H. Munsell reported that he also studied Rood's book when he was a 21-year-old art student and the book first appeared. Munsell obtained a positive response from Rood on his color sphere when the two met in 1899.

Clearly, Rood's interest in colors encompassed both the scientific and artistic points of view and these provided him with ideas to develop a systematic order of colors. In addition to a double cone system with black and white on either tip, Rood produced a color circle, on the basis of experiments using rotating disks, a given color point placed precisely opposite to its complementary partner.

The Smithsonian's first curator of birds, Robert Ridgway, was one of America's best-known scientists in the nineteenth and twentieth centuries and a well-known figure in the fields of taxonomics and color study. He created the most important and painstaking color dictionary at the time, Color Standards and Color Nomenclature, which he self-published in 1912. Ridgway named four colors for Rood which were Rood's Blue, Rood's Brown, Rood's Lavender, and Rood's Violet [3].

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Chapter 42
Lovibond, Joseph Williams 1833–1918

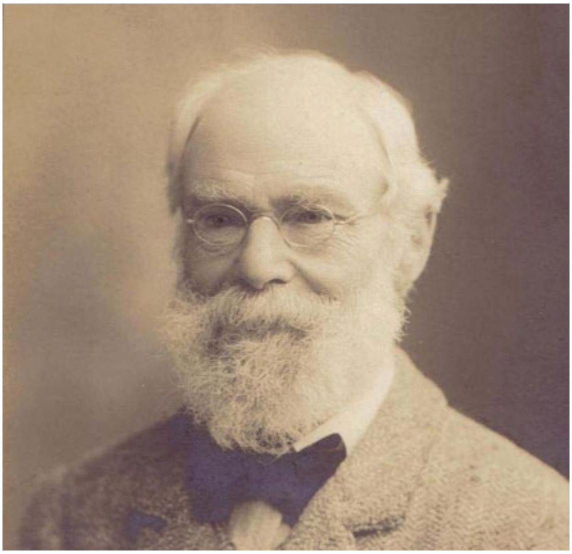

Image courtesy of the Tintometer Ltd., www.lovibondcolour.com

Joseph Lovibond was a British chemist, brewer, and is credited with inventing the commercial colorimetry, the Lovibond Tintometer.

A slightly modified text based on his obituary published in Salisbury Times on April 26, 1918, provides a short history of Joseph Lovibond's full and varied life. "He was the son of Mr. John Locke Lovibond [a prominent brewery owner], of Long Sutton, Somerset, and Greenwich and was born in 1833. He entered the mercantile marine at the age of 13, three years later was gold mining in California [and he apparently accidentally lost his earnings from his mining work], returned

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home and became actively associated with Lovibond's Brewery at Greenwich in 1854, and remained connected with it till the end, for a long time in the capacity of chairman. Around 1868, he went to Salisbury and purchased a brewery in the Friary and thenceforward shared his working time between the two businesses, traveling weekly to London."

"His wider fame was due to his discovery and perfecting of a method of measuring color. In his practical work as a brewer, he had found the need of some such instrument, the only method then available being that of the spectroscope. Years of quiet pursuit of a hobby resulted in the formation of a company to work out his ideas with an instrument, which achieved international recognition under the name of the Tintometer. By means of this [instrument], the color values of a wide range of fluids and solids can be accurately tested and matched, to the great gain of a large number of industries including those of brewing, dyeing, steel making, oil making, flour milling, tanning, for medical use in blood testing, for water analyses, and so forth. His invention gained for him international recognition, with gold medals from exhibitions at Turin, at Panama, at Brussels (where much apparatus was lost in a disastrous fire), and silver medals from very many other exhibitions and scientific and technical societies.

42.1 Lovibond Tintometer

Lovibond propounded a new theory of light and color and had written several works on the subject; his three books "Light and Colour Measurements," "Colour Phenomena," and "Colour Theories" are well known and accepted as standard works. He asserted that there were not seven primary colors (as we used to be told were to be seen in the rainbow) but only six made up of three dominants, red, yellow, and blue and three subordinates, orange, green, and violet. In the later part of his life, he spent much time in carrying out a series of "camouflage" investigations for the War Office.

It is said that an inventor seldom sees the success of his labors, therefore it was with pleasure that those associated with him realized he both saw and knew the value and success of his work for some years before his death. In 1895, his company was registered to work out the practical application of the invention. The Tintometer Ltd. continues to carry on his work in the original workshops and laboratory at No. 1, The Friary, Salisbury. [1].

In Lovibond's "Light and Colour Theories" [2], we read "the writer was formerly a brewer, and this work had its origin in an observation that the finest flavour of beer was always associated with a colour technically called 'golden amber,' and that, as the flavour deteriorated, so the colour assumed a reddish hue." Such observations of the relationships between beer quality and observed color led Lovibond to his work on color standards as a reliable means of reference. This also led to the development of an instrument, the visual colorimeter, in which such standards could be systematically and objectively applied. It is reported that after failed experiments with paint, on solids, a visit to Salisbury Cathedral in 1880 gave him the inspiration to use stained glass for his colorimeter, which he introduced in 1885 [3].

The general form of Lovibond's Tintometer was a visual colorimeter in which a split field is viewed. One-half of the split field represented the test sample, perhaps a cuvette of beer placed in a beam of light. The other side of the split field was composed of subtractive primaries of adjustable density (e.g., a series of cyan, magenta, yellow, and neutral glass filters) that could be adjusted to select the density and overlapped one another in the adjacent beam of light. By adjusting the density of the filters, observers would match the test color stimulus and record the densities of the standard filters required for the match.

While brewing beer might have been the motivation for the Tintometer (Fig. 42.1), by 1914, the system was in use in a wide variety of additional industries including tanning, wine and spirits, dyeing and printing, paint, water chemistry, ceramics, various oils, and hematology. In many cases, specific versions of the instrument and the reference standards were produced for a given application. In addition to the two gold, five silver, and two bronze medals already mentioned, the system was also presented with a number of awards by international juries (including two gold) along with significant recognition from ten scientific societies (one gold, three silver, and five bronze medals and a diploma). Lovibond worked tirelessly in promoting his system through lectures and demonstrations around the world. He created a technically successful system that also met with commercial success. In fact, The Tintometer Limited still exists to this day with products such as color standards and scales, visual colorimeters (including versions of the Lovibond Tintometer), and photoelectric colorimeters and spectrophotometers. For

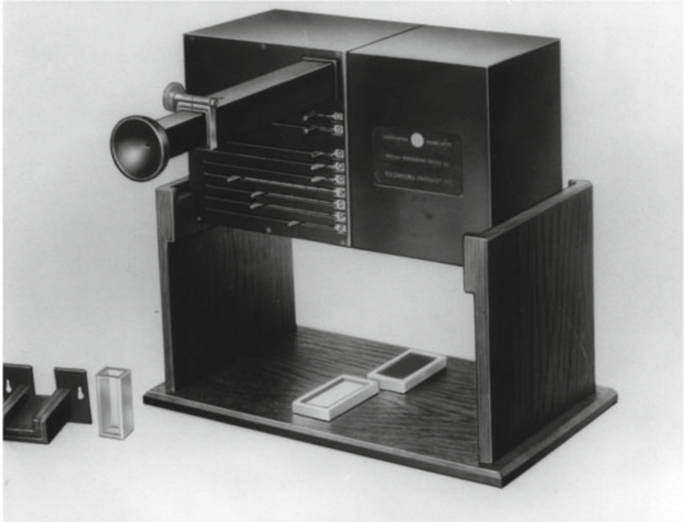

Fig. 42.1 Lovibond Tintometer [4]

example, one can still purchase instruments and standard color scales designed for American (ASBC) and European (EBC) methods of specifying beer color. Lovibond's initial inspiration is still being addressed by the progeny of his instruments using his very techniques.

By the time of his death in 1918, Joseph Lovibond had established himself as a pioneer in the field of color science and his company, The Tintometer Limited, was already known throughout the world for its range of instrumentation and expertise in the field of colorimetry. In the history of The Tintometer Limited, it is stated that "The Company was founded in 1885 by Joseph Lovibond, a prominent brewery owner who developed the 'colorimeter' as a means of ensuring the quality of his beer. By 1893, he had perfected his research and introduced the first instruments. Much has developed since then. Today, the company is bringing colour measurement to the next generation. While still recognizing the importance of traditional methods, The Tintometer Ltd is introducing new techniques to bring measurement and quality control to an even higher level, developing creative solutions to ensure the continued reputation of the Lovibond® brand" [5].

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Chapter 43
Hering, Karl Ewald Konstantin
1834–1918

Wikipedia

Karl Ewald Konstantin Hering was born on August 5, 1834, in Alt-Gersdorf in Saxony, son of a Lutheran pastor and his wife. He studied medicine at the University of Leipzig, obtaining an MD degree in 1860. For the next five years, he practiced medicine in Leipzig and pursued personal interests in vision on the side, publishing five *Beiträge zur Physiologie* (Contributions to physiology) between 1861 and 1864 [1]. He was married in 1863, and he and his wife had a son,

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Heinrich Ewald. In 1865, he was appointed professor of physiology at the Josephinum Academy in Vienna. In 1870, he became the successor of J. E. Purkinje as professor of physiology at the University of Prague where he remained for 25 years, studying among other things the electrical actions of nerves and muscles, as well as the perception of light and color vision. In 1895, he was invited to join the University of Leipzig where he remained until his retirement in 1915. During his lifetime, Hering assumed the role of anti-Helmholtz, scientifically and philosophically battling with him concerning several subject matters [2]. Hering died on January 26, 1918, in Leipzig.

43.1 Opponent-Color Vision Theory

Hering developed a theory, alternative in detail to that of Helmholtz, concerning spatial perception based on images in two eyes. Publication of and the response to Helmholtz's first edition of the *Handbuch der physiologischen Optik* in 1867 [3] provided a basis for Hering to consider in detail the issues of color perception and develop his own, different theory. The result was the presentation in 1874 of six extended contributions to the Imperial Academy in Vienna, published in book format in 1878 as *Zur Lehre vom Lichtsinne* (On the theory of the light sense) [4]. Hering considered the Young–Helmholtz theory to give too much weight to physics and not enough to the perceptual aspects of color. In response, he developed an opponent-color theory postulating three opponent pairs of fundamental colors (*Urfarben*), yellow–blue, red–green, and white–black, building on earlier ideas by H. Aubert and E. Mach. The hues are arranged according to simple principles in a hue circle (Fig. 43.1), the complete arrangement of all colors of a given hue being in a triangle, with white, black, and full color at the corners and "veiled" colors filling the interior. Hering called the result, in the form of a double cone, the "natural color system." He also proposed dissimilation/assimilation processes in the eye/brain as physiological basis of the opponent system, in opposition to the Young–Helmholtz theory involving three fundamentals. A commercial version of the Natural Color System atlas was introduced in 1979 by the Scandinavian Color Institute as the Swedish Natural Color System (NCS).

Today, the perceptual aspects of Hering's system continue to be considered essentially valid, with its physiological part being short of reality. Despite many attempts a psychophysical model of the four hues, presumed fundamental and their mixtures, that also meets other components of the colorimetric system is still lacking at this time. A major issue is the fact that while mean unique yellow and blue stimuli are essentially complementary, unique green and unique red stimuli are far from it, complicating any model with the purpose of representing a perceptually meaningful and at the same time colorimetrically valid model.

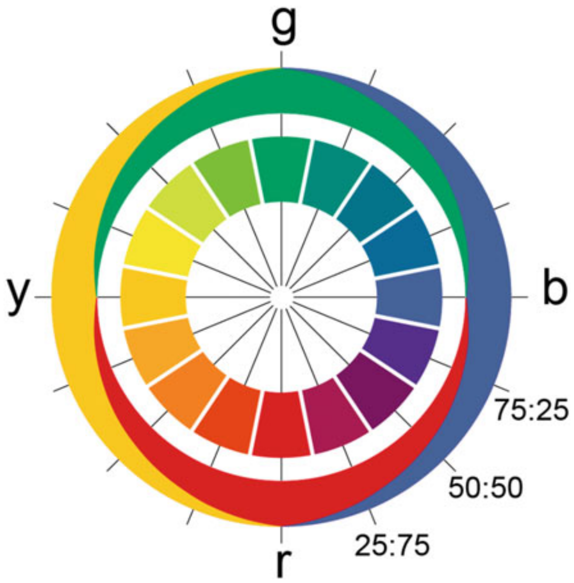

Fig. 43.1 Superimposed images of the conceptual mixture of the four hue fundamentals in different ratios and the resulting hue circle; derived from two images in Hering, 1878 [4]

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Chapter 44
von Bezold, Johann Friedrich Wilhelm 1837–1917

dpg-physik.de

Johann Friedrich Wilhelm von Bezold was born on June 21, 1837, in München where his father was a minister of state in the Kingdom of Bavaria. He studied natural sciences in München and Göttingen from 1856 to 1860. Already as a child, he was interested in painting, and during his studies at the University of Göttingen, he attended lectures in optics and the physiology of the sensory organs. In 1868, he was named professor of technical physics at the München Polytechnikum. His key

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research was related to lightning and its dangers as well as thunderstorms, their development and passage through the countryside. In 1885, he was offered a professorship in meteorology in Berlin. In this position, he organized the establishment of the system of weather information in Germany. He is considered the initiator of the field of thermodynamics of the earth's atmosphere. He was elected a member of the Prussian Academy of Sciences. Bezold passed on February 17, 1917, in Berlin [1].

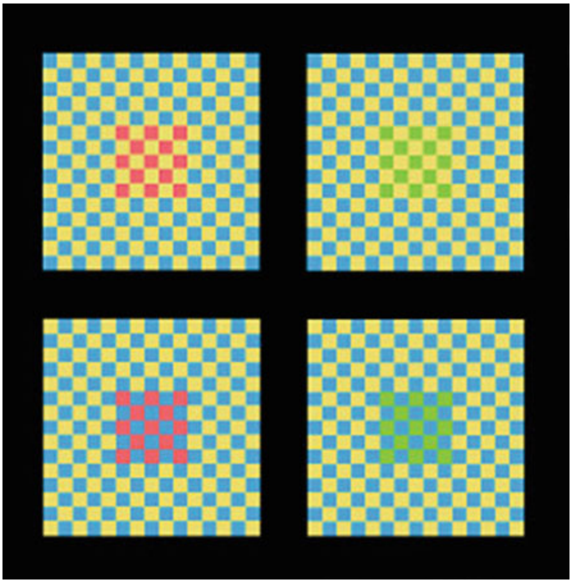
44.1 Bezold–Brücke Effect

Between 1873 and 1876, he published half a dozen articles on binocular vision, color mixture and presumed physiologically basic colors. It should be mentioned that during his adult time in München, he also was an art critic writing for several newspapers. In 1876, his book *Die Farbenlehre im Hinblick auf Kunst und Kunstgewerbe* (The theory of color in its relation to art and art-industry) was published, in the same year also in an English edition in the USA and one year later in a Russian edition. A revised second German edition was published in 1912. The book established von Bezold's broad reputation in the field of color and its connection to art.

In his scientific article "Ueber das Gesetz der Farbenmischung und die physiologischen Grundfarben" (On the law of color mixture and the physiologically fundamental colors), published in 1873, he reported experimental findings showing changes in apparent hue due to changes in luminance or lightness of the stimulus [2]. This was later also found to apply to the Munsell system where the location of the stimuli in the CIE chromaticity diagram usually differs as a function of lightness to a smaller or larger extent from one Munsell value level to the next, with only a few exceptions of hues. Over the years, the effect has been investigated multiple times by different methods with results differing somewhat by method as well as by observer. There are three wavelengths where the appearance generally does not change depending on luminance or lightness, ca. 470, 510, and 575 nm. The deviations are largest near the long-wave end of the spectrum. The three constant wavelengths coincide approximately with the average wavelengths of stimuli considered to represent unique hues. The effect had briefly been mentioned already in 1866 by the physiologist Ernst Wilhelm von Brücke (1796–1873). As a result, the effect became known as Bezold–Brücke Effect.

A second important observation by von Bezold was that the appearance of small stimuli surrounded by different color stimuli could change to surprising degrees. In more recent years, this effect has been exploited in numerous color illusion images. An example is shown in Fig. 44.1. In general terms, the effect is known as the Bezold color assimilation or Bezold spreading effect.

Fig. 44.1 Examples of the Bezold color assimilation effect. The reddish colored squares on the left side and the greenish colored ones on the right have on top and bottom identical stimuli [4]



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Chapter 45
Mach, Ernst Waldfried Josef Wenzel 1838–1916

Heliogravure by H. F. Juette, public domain

Ernst Waldfried Josef Wenzel Mach was born on 18 February 1838 in Chrlice, near Brno, currently in the Czech Republic. While Mach was a talented child, he had difficulties with classical languages, and his initial schooling was not trouble free. He began his schooling at the age of nine at a gymnasium, but he did not complete the curriculum. Mach received his education at home from his parents up to the age

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of 14. He was then enrolled at a piaristic school in Kroměříž. In 1855, he entered the University of Vienna to study mathematics, physics, and philosophy, and in 1860, received a doctorate in Physics. Upon completion of his inaugural dissertation (habilitation), he worked at the University of Vienna as a private associate professor.

In 1864, he accepted a position as Professor of Mathematics at the University of Graz and lectured on mathematics, physics, physiology, and psychology. During the years 1867–1895, he was professor of experimental physics at the Charles University in Prague. In 1879, he became the rector of the Charles University for one year. Mach met with Palacky and Purkyně during his stay in Prague and among other things became interested in visual and auditory perception and examined the air shock waves caused by fast-flying projectiles. His stay in Prague was, however, influenced by growing nationalism and anti-Semitism (Mach had many Jewish friends). Thus in 1895, he returned to Vienna and worked as professor of inductive philosophy.

In 1889, Mach endured a cardiac arrest that led to the paralysis of the upper part of his body. Nonetheless, he continued to propose experiments and publish his work. Ernst Mach died on 19 February 1916 in Vaterstetten, Germany.

Mach was interested in chemistry, physiology, and psychology and was a skilled experimenter. In addition to exact sciences, such as physics and mathematics, Mach was also interested in psychology and strived to unify these disciplines. He attempted to help establish psychophysics as a new discipline to determine the relationship between physical stimuli and sensations. He assumed it necessary to build upon psychology according to physical models in order to be able to develop psychophysics and explain the relationships between stimuli and percepts. This was in line with Gustav Fechner's efforts who was leading this endeavor at that time.

It should be borne in mind that nearly the entire focus of the empirical psychology in the nineteenth century was on perception, and mainly on visual and auditory aspects of perception. Relevant experimental psychology involved using specific coils or discs, which were compared against percepts of individuals. Mach's contribution in the field was most profound in the exploration of the physiology of visual perception. One of his experiments became later known as Mach's band effect. Nonetheless, Mach, even in his sixties, was not content on only indulging in experimental work. From a philosophical standpoint, he believed in the duality of the physical and the psychological and that they share a parallel course. He argued, however, that both sides of reality have their ontological basis in one perceived reality. This view corresponded with Mach's phenomenonalistic focus.

Mach's major contribution to science, however, was perhaps in the field of physics. He contributed to the overall paradigm shift in accepted hypotheses of his time. The most important work that best characterizes Mach's opinions in this field can be found in his book "Die Mechanik in ihrer Entwicklung" which was first published in 1883 [1]. In this book, he criticized the concept of Newtonian physics due to his view that it was unfruitful and outside the borders of perception. Mach also rejected atomic theory and considered it a product of theoretical physics. According to Mach, the atom was a conception for something that could not be defined by sensations and complicated the explanation of many phenomena. This work is considered a turning point in the evolution of physics in the nineteenth century. The most cited passages concern the criticism of Newtonian physics and classical mechanics. Mach criticized several sections of Newtonian physics based on the idea that a phenomenon should correspond to sensations (everything that is immediately accessible to us). In Newton's system, only reasoning based on direct observation of psychical reality was possible and justified, e.g., from observed collision between two objects forces could be assumed as physical variables allowing to predict the result of that collision. This opinion in the context of the representative epistemology was widely respected. For Mach, the sole basis of scientific research was based on sensations, and thus Newtonian reasoning of reality was seen as an embezzlement of proclaimed empirical foundations of science. For Mach's phenomenalism, judgments of objective physical reality were unjustified, metaphysical and did not belong to science.

Based on these views, Mach criticized a wide range of classical physical concepts such as force, causality, mass and most importantly absolute values, i.e., absolute space, time and movement. In Mach‘s concept, these were mere metaphysical constructs and unjustified extensions of empirical relationships outside the bounds of empiricism. Mach declaimed not only Newtonian absolutes, but also all absolute quantities of contemporary science such as the absolute thermal zero point or the absolute speed of light. He considered theoretical physics unfruitful, which went baselessly beyond the borders of experience. Against such physics he then placed physics based only on experience, i.e., in the context of his teachings describing the sensations, and mathematical description of their relationship. Mach remained opposed to theoretical physics throughout his life. From the beginning of the twentieth century, Mach's work was criticized by several scientists including those that were influenced by his work such as Einstein and Planck [2].

45.1 Mach Band Effect

One of the important visual perception discoveries made by Mach is now known as Mach's band effect. He observed and recorded this visual phenomenon in 1860s. The effect is observed in the vicinity of the boundaries that separate regions of differing illumination or tone. The result is the perception of bright or dark bands in the boundaries. The following example shows the effect of placing an identical set of five tonal bars next to each other, once with a side touching and then with some gap between them. The Mach band effect is visible in the right hand image where the bars are in contact. In this case, the brain exaggerates the difference between bars when they are touching and perceives the color of a physically uniform bar lighter where it touches a darker neighbor and darker where it touches a lighter neighbor. This results in increased perceived differences between the bars (Fig. 45.5.9).

This phenomenon can be explained based on the concept of visual receptive fields. In the following image, receptive fields are represented by a disk (+) and an

Fig. 45.5.9 Examples of the Mach Band Effect

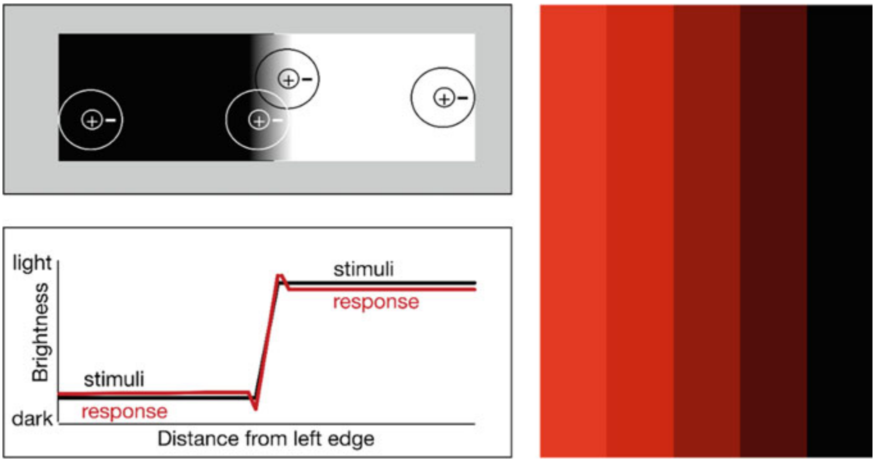

Fig. 45.5.10 The relationship between distance from edge and brightness of stimuli

annulus (-). The center of the disk is an excitatory area and the annulus an inhibitory area. The receptive fields in the uniformly white and uniformly black areas receive about the same stimulation in their excitatory centers and inhibitory surrounds. Therefore, the center excitations are in balance with the surround inhibitions. The receptive field over the bright Mach band gives a stronger response in the center because part of the surround is in the darker area. Therefore, it receives less inhibition from the surround than the center at the extreme left and right ends. The receptive field over the dark band receives more surround inhibition because part of the surround is in the brighter area. Therefore, the excitatory response is less and this results in perceiving that the area as being darker as shown in (Fig. 45.10). The effects of Mach bands have been investigated and described in much detail in F. Ratliff's book "Mach Bands" published in 1965 [3].

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Chapter 46
Abney, William de Wiveleslie 1843–1920

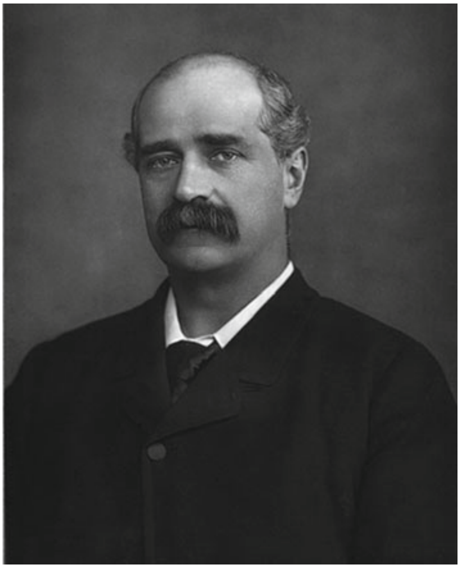

Image: Wikipedia

William de Wiveleslie Abney was an English scientist who made significant contributions to several fields of science including photography and vision science. He was a pioneering photographer with an interest in chemistry and was able to use these skills to advance knowledge in other fields that interested him, including astronomy. He married twice. In 1864, he married Agnes Matilda Smith with whom he had a son and two daughters. She died in 1888, and two years later, Abney married Mary Louisa Meade with whom he had another daughter. Abney died in December 1920 in Folkestone, England [1].

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He was the son of a clergyman, Rev. Edward Henry Abney and his wife Katherine Strutt and was born in Derby (England). His father was interested in photography and was a friend of the pioneering English photographer William Henry Fox Talbot. William Abney and his brother Charles also got interested in photography and eventually became the founding members of the Derby Photographic Society in 1884. William attended Rossall School and the Royal Military Academy in Woolwich. He was commissioned in the Royal Engineers in 1861 and served in India through 1867. After his return to England, he was posted to the Royal Engineering School at Chatham, where he was promoted to Captain in 1873, and retired from service in 1881.

Abney was elected a Fellow of the Royal Society in 1876 and continued his career as an independent scientific investigator until his death. He was knighted in 1900 by Queen Victoria in England and served in several official capacities in science and education. These included assistant secretary to the Board of Education in 1899 and Director of the Science and Art Department in the UK in 1900.

46.1 Abney Effect

Arguably, Abney's most significant contribution was in the field of photography. His introduction to photography at an early age gave him the impetus to examine, over the coming years, several related issues. His interest in photography was also encouraged during his service years at the Royal Engineers where he had the opportunity to offer a course in photography in Chatham. In 1871 and based on his lectures, he wrote a pioneering book, *Instruction in Photography,* which had its tenth edition published in 1900 [2]. In 1874, he traveled to Egypt to photograph the transit of Venus across the sun. He developed a dry gelatin photographic emulsion which he used in this expedition and which replaced "wet" emulsions. He also produced a book of photographs of historic temples at Thebes [3]. He wrote another book entitled *A Treatise on Photography,* which became a standard reference and also went into ten editions [4]. He discovered hydroquinone as a developing agent and silver bromide emulsions photographic printing on paper [5]. He is believed to have coined the term infrared. His knowledge of chemistry and his interest in astronomy resulted in developing an emulsion to capture the far-infrared solar spectrum in 1887 and the infrared spectra of organic molecules. Abney received the prestigious Rumford Medal from the Royal Society in 1882 "for his photographic researches and his discovery of the method of photographing the less refrangible part of the spectrum, especially the infrared region, also for his researches on the absorption of various compound bodies in this part of the spectrum" [6]. Abney's contributions to photography also include modifications to the reciprocity law (based on the works of Robert Bunsen and Henry Roscoe in 1862) that govern the relationship between the intensity and duration of light required for the reaction in light-sensitive material [7]. Based on his observations Abney reported deviations from, and suggested improvements to, the law in 1893 [8].

1. *Visual and color science*
   Abney was a pioneer in researching sunlight in the atmosphere. He examined the visible spectrum and the transmission of light in different atmospheric media. He carried out a series of experiments on chromatic photometry in the 1880s. He also became interested in psychological aspects of color vision and the perception of spectral lights. These works resulted in publishing a book entitled *Colour Vision,* published in several editions through 1913 [9]. Among the topics examined by Abney were general issues associated with perception of color, e.g., disappearance of hue sensations with increasing eccentricity in the peripheral regions of the retina; color vision theories; role of color in visual science; and color perception under varied illumination conditions. Abney was a supporter of the trichromatic theory and did not believe in the opponent-color vision model. He also investigated several visual phenomena, which are still not completely understood. The most well-known of these observations is called Abney's Law. This law describes that a compounded stimuli's luminance is linearly and additively related to the luminance of its components. Abney proposed that the law is also applicable to brightness; however, it has been found that this is incorrect [10]. In addition, Abney described changes in visual appearance of light in the visual field because of exposure to sudden illumination, such as those in explosions [11]. Abney's contributions also include the blur spot or "circle of confusion" in photography and microscopy and the invention of a camera for color photography.
2. *Abney effect*
   Abney discovered that perceived hue changes with increasing luminance of the stimuli. In other words, as the color becomes increasingly desaturated, it also changes in hue. The original article describing this phenomenon was published in Proceedings of the Royal Society of London, in 1909 [12]. The effect has since been known as the Abney effect. A simulation of this effect is depicted in Fig. 46.1. While desaturation of the color as a result of increased stimuli luminance can be relatively easily envisaged, a less intuitive effect is that of hue shift which as yet has not been satisfactorily explained. Abney decided to quantitatively examine these visual observations of color change. His investigation involved adding white light to mixtures of red, green, and blue primary as well as other lights. A single beam of light was split into two parallel beams

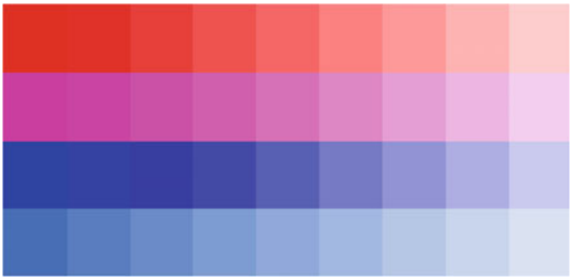

Fig. 46.1 A simulation of desaturation of colors by adding white light to illustrate the Abney effect

projected onto a white screen. One beam was desaturated with a predetermined amount of white light (equivalent to half of the luminosity of the colored light) while the other was kept intact. He noted that the addition of white light caused the colored light to shift, from red to yellowish red, from orange to yellow–green, and from green to blue–green, etc. He concluded from his observations that the hue shift was mainly due to red and green components of the white light and that blue did not contribute much to the effect. Abney examined the percentage composition and luminosity found in the different spectral colors as well as the white light source that was added to the colored beams and experimentally matched the shifted colors based on calculated proportions [12].

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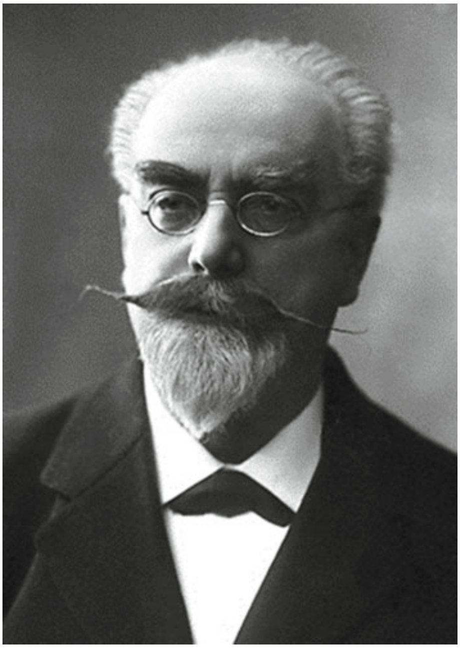
Chapter 47
Lippmann, Jonas Ferdinand Gabriel 1845–1921



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Jonas Ferdinand Gabriel Lippmann was a French inventor and physicist (born in Luxembourg) who created the first color photographs using what was certainly the first spectral imaging system.

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47.1 Lippmann Process of Full Color Photography

Lippmann's system of color photography was conceived in 1886 and then refined for several years due to the complex nature of its theory and implementation. The system works by placing a very fine-grain photographic plate in contact with mercury that acts as a mirror. Light waves pass through the emulsion, reflect from the mercury backing, and then create an interference pattern within the emulsion. The developed plate then has an interference filter built into it due to the properly spaced layers of silver in the emulsion (created by the interference pattern exposure). The plates are then viewed with directional lighting, and the observer sees the same wavelengths that were present in the scene—a spectral image reproduction. Lippmann presented the first color photograph using his system in 1891 and then presented several nearly flawless photographs made by Auguste and Louis Lumière created with the process. The process was difficult and time consuming and few have been able to replicate the stunning photographs. Lippmann's work certainly presaged modern photographic and holographic processes and he received the 1908 Nobel Prize in Physics for this work [1].

Despite having no formal education beyond high school, Lippmann ended up a full professor at the Sorbonne (University of Paris). He was a student at the École Normale, but failed the examination that would have qualified him as a teacher due to his penchant for concentrating only on the work that interested him and neglecting the rest. However, he was appointed to a government scientific mission to Germany where he was able to work with the likes of Kirchhoff and Helmholtz. In 1873, he invented the Lippmann capillary electrometer for precise measurements of extremely small electrical voltages. It served as the basis for early echocardiographs. Lippmann joined the Faculty of Science in Paris in 1878, became Professor of Mathematical Physics in 1883, and was later appointed Professor of Experimental Physics and Director of the Research Laboratory. He made many contributions in various fields of physics including, electricity, thermodynamics, optics, and photochemistry [2].

In addition to his Nobel Prize for the Lippmann process of full color photography, Gabriel Lippmann served as Marie Curie's thesis advisor at the Sorbonne and let her use his laboratory for her thesis work in radioactivity and helped her find other sources of support [1]. Lippmann died at sea in 1921 while returning from a voyage to Canada. There is no record of the cause of death.

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Chapter 48
Ladd-Franklin, Christine 1847–1930

Source feministvoices.com

Christine Ladd was born on December 1, 1847 in Windsor, CT. Her father Eliphalet Ladd and her mother Augusta Niles both came from distinguished New England families. Ladd attended Wesleyan Academy for two years, graduating in 1865. She then entered Vassar College from which she graduated in 1869. Her main interests were mathematics and science. For the next nine years, she taught these subjects at secondary schools in New York, Massachusetts, and Pennsylvania and wrote several articles on mathematics. In 1878, she applied to become a student in advanced mathematics at Johns Hopkins University in Baltimore, MD. Women

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were at the time not permitted in graduate studies but her unusual mathematical capabilities resulted in an unofficial exception for her. She completed the requirements for a doctoral title in 1882 but officially received the degree only in 1926. Her thesis was titled "The algebra of logic" and was included in a volume of studies on logic by the famed philosopher C. S. Peirce in 1883 [1]. In the year 1882, she married Fabian Franklin, a mathematics professor at Johns Hopkins. She continued to write articles on mathematics and also logic where she proposed an anti-logic model opposite to the classical syllogism in an article titled "The algebra of logic." It was considered a major achievement in its time. Her interest in color began when she investigated how points in space are dealt with by binocular vision.

In 1904, she finally was officially made a lecturer at Johns Hopkins University, but only for one course in each term: mathematics or logic in one term and vision/ color in the other. However, it represented a big step in the recognition of women in American academia. She continued to have papers published in her fields of expertise. In 1929, a collection of her most important papers on vision and color was published with the title "Color and color theories" [2]. In 1910, Ladd-Franklin and her husband moved to the city of New York where she lectured at Columbia University. There she remained active as a strong supporter of women's rights until the end of her life on March 5, 1930 [3].

48.1 Ladd-Franklin's Color Vision Theory

In 1891/2, she had the opportunity to work in the laboratories of the psychologist Georg Elias Müller (1850-1934) at Göttingen University and of Hermann von Helmholtz (1821–1894) in Berlin. There she also attended lectures by his assistant Arthur König. She began to contemplate the Young–Maxwell–Helmholtz theory on the one hand and Hering's on the other. As a result, she developed an evolutionary theory of color vision that combined to a degree both of these. In her theory, there are three stages of color vision: the most primitive one is black-and-white vision; the second stage adds yellow–blue, with the third adding red–green vision (Fig. 48.1). She presented this theory in 1892 at the International Congress of Psychology in London, with von Helmholtz, who thought highly of her, in attendance. It produced considerable discussion in the following years. In a manner of speaking, the sequence of the second and third stages remains valid, with her second stage due to dichromacy and the third to trichromacy.

She experimentally tested the Hering theory and in 1892 also found the fact that, in her disk mixture experiments, the achromatic appearance of a balanced red-green mixture to be different from that of the yellow–blue mixture.

In 1924, she authored the paper "The nature of the colour sensations" that was appended to Vol. II of the English translation of the third edition of Helmholtz's*Treatise on physiological optics*, as well as in her 1929 book *Colour and colour theories* that represents a historically important review of her knowledge and ideas about color vision [2].

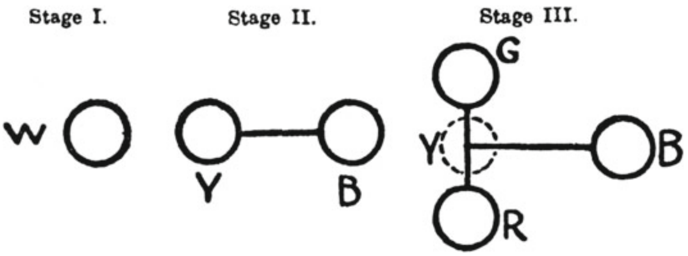

Fig. 48.1 Ladd-Franklin's schematic representation of the three evolutionary stages in her color vision theory. In Stage III, the Yellow mechanism of Stage II is split into Green and Red [2]

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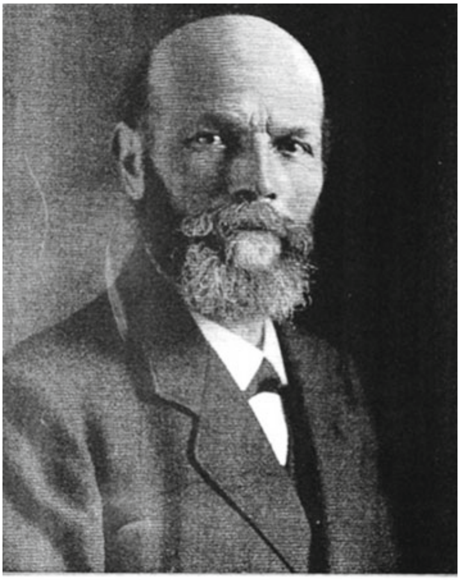
Chapter 49
von Kries, Johannes Adolf 1853–1928



J. v. Kries.

Source vonkries.de

Johannes von Kries was a German physiological psychologist, or what might now be called a neuroscientist, and student of Helmholtz. In color science, he is known as the father of chromatic adaptation models for his work on the coefficient theory of adaptation. He also made significant contributions to a variety of other fields including probability theory and the structure of the retina and human visual system.

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von Kries published profusely (in German, with few works translated to English) on topics such as blood flow in arteries, duplicity theory, chromatic adaptation, zone theory, probability theory, physiology, psychology, and history. For example, observations of the Purkinje shift led von Kries to postulate the existence of two separate visual systems, rods, and cones, also referred to as duplicity theory. It is well known that Helmholtz described the trichromatic theory of color vision and participated in a famous academic dispute with Hering, the main proponent of opponent-colors theory. It is less widely recognized that von Kries was among the first proponents of the so-called zone theory of color vision that allowed for trichromatic receptors (the cones) and opponent processing of the visual information. It is not surprising that von Kries is sometimes referred to as the "greatest German disciple" of Helmholtz. Considering that Helmholtz's students included the likes of Max Planck, Wilhelm Wien, Arthur König, A. A. Michelson, and Wilhelm Wundt, that is quite a statement.

In the second half of the nineteenth century, von Kries was applying probability theory to the evaluation of the effectiveness of new drugs. He realized that the computation of probability distributions depends on the classification of symptoms and pathologies into diseases, often very subjective data. Given that the important uncertainty was determined by the experimenters' definition of events, he developed the logical foundations of a probability theory where the subjectivity of mental representations impacts the assignment of numerical values to probabilities. Interestingly, with some distortion and misunderstanding, these ideas passed on to J. L. Keynes and formed the core of his economic theory. In his book on the topic, von Kries developed a highly original interpretation of probability, illustrating it to be both logical and objective [1].

49.1 Chromatic Adaptation

Returning to color science, von Kries' most recognized and long-lived contribution came from his works on the theory of chromatic adaptation (1902, 1905) in which he proposed the coefficient rule that lives on to this day as the von Kries coefficient law or simply the von Kries model of chromatic adaptation [2, 3]. Interestingly, von Kries did not write out the mathematical formula with which he is credited; he simply stated the theory in words. In MacAdam's translation of von Kries' [2] words:

> This can be conceived in the sense that the individual components present in the organ of vision are completely independent of one another and each is fatigued or adapted exclusively according to its own function.

Perhaps it should not be too surprising to realize that von Kries [2] himself foresaw that this model was too simple to explain all chromatic adaptation phenomena [2]. The next line after his description of what is now referred to as the von Kries model reads:

> But if the real physiological equipment is considered, on which the processes are based, it is permissible to doubt whether things are so simple.

Indeed, things are not so simple, but yet von Kries' theory forms the basis of all effective modern models of chromatic adaptation, including that embedded in the CIECAM02 system.

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Chapter 50
Ostwald, Wilhelm 1853–1932

de.wikipedia.org

Wilhelm Ostwald was born on September 2, 1853 in Riga, the capital city of Latvia, to German immigrant parents. He studied chemistry at the University of Dorpat (now Tartu, Estonia) where he received his Ph.D. in 1878 and lectured at the Polytechnicum in Riga. In 1887, he moved to the University of Dresden in Germany where he remained until his early retirement in 1906. He married in 1888, and he and his wife had five children. He was active in many fields, including philosophy; he is considered to be one of the founders of the science of physical chemistry and received the Nobel Prize for the discovery of chemical catalysis in 1909. Ostwald is the author of 45 textbooks and over 1000 articles. In his spare

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time, he was a talented painter. In 1905/06, he spent several months in the Boston area giving courses in philosophy, physical chemistry as well as techniques of painting at Harvard University, MIT, and the Lowell Institute, where he met Munsell and learned of the latter's early development of the Munsell color system. After he left the University of Dresden, the result of his lack of interest in lecturing students, he moved to his nearby country seat in Grossbothen where he spent the rest of his life primarily working on color theory, developed a large color order system and a theory of color harmony. Ostwald died on April 4, 1932 in Grossbothen [1].

50.1 Ostwald's Color Order System

Ostwald saw the place of the science of color in the total field of science to be in psychological science [2]. He was not only fully aware of the work of Maxwell, Grassmann, and Helmholtz, but was convinced that also Hering had made important contributions toward the understanding of color phenomena. His immediate predecessors had focused primarily on the relationship between lights and color experience. Ostwald made significant contributions to the understanding of object colors. His main contributions in the color field are briefly mentioned below.

Ostwald developed a color order system that combined psychological and psychophysical knowledge, resulting in *Grosser Farbenatlas* of 680 systematically ordered samples of 24 different hues, published in 1917/8 (Fig. 50.1). A version

Fig. 50.1 View of the double-cone model of Ostwald's color atlas

with 872 samples dyed on wool yarn was also produced. The largest system is the *Grosse Farborgel* (Large color organ) with 2510 samples in 24 hues. An American version of the Farbenatlas was published in the 1940s as *Color Harmony Manual* [3].

1. *Distinction between unrelated and related colors*
   Helmholtz and others of his time investigated color primarily in terms of spectral light. Ostwald demonstrated and made clear the difference between unrelated and related colors, the latter experienced from viewing objects in varying surroundings, including the existence of gray, brown, olive, and other colors in related form only [2].
2. *Non-linear relationship between wavelength differences and perceived Hue differences*
   Ostwald demonstrated the highly non-linear relationship when establishing the hue circle of his color atlas, showing that there are two spectral regions where perceived hues change rapidly as a function of changes in wavelength while near the beginning, middle, and end of the spectrum the frequency of change is much reduced [4].
3. *Farbenhalb/Vollfarben*
   Ostwald demonstrated that in case of object colors of highest saturation a relatively broad spectral portion (loosely termed *Farbenhalb*, half of the spectrum) of light is reflected, in contrast to spectral light. He used a graphic format with wavelength on the horizontal and reflectance between zero and one on the vertical axis. At the same time, he defined *Vollfarben* (full colors) as object colors of the highest saturation possible for a given hue, occupying spectral ranges with either one or two transitions in the spectrum. Full colors are the optimal object colors of a given hue at the lightness level at which they have highest saturation, varying by hue. In 1920, Schrödinger offered a mathematical proof of the concept of optimal object colors that included Ostwald's Vollfarben [5].
4. *Metamerism*
   In 1918, Ostwald demonstrated the existence of metameric object colors and introduced the term *metamerism* [4].

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Chapter 51
König, Arthur Peter 1856–1901

Public domain

Arthur Peter König was born in Krefeld, Germany on September 13, 1856. His father was a teacher; his mother died when he was 2 years old, and he was mainly raised by an aunt. König suffered from birth from congenital kyphosis and was physically handicapped. However, he was an excellent pupil. After graduating from gymnasium, he began a merchant's apprenticeship. Nonetheless, soon he was able to study at the Bonn and Heidelberg Universities and in 1879 at Berlin University where he formed a relationship with one of his professors, Hermann von Helmholtz. He obtained his Ph.D. degree in physics in 1882 and became an assistant to Helmholtz. He was named an associate professor in 1884 and in 1889 a full

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professor at the physical division of the physiological institute. His special duty was to lecture on physiological optics. Together with Hermann Ebbinghaus, he founded the *Zeitschrift für Psychologie und Physiologie der Sinnesorgane* (Journal for Psychology and Physiology of Sensory Organs) and was editor of two additional scientific journals. Together with Helmholtz, he edited the second edition of the latter's *Handbuch der physiologischen Optik* (Treatise on physiological optics), published after Helmholtz's death (in 1894) in 1896. Among other reasons, it is famous for containing a list of 7833 published articles on the general subject, accumulated by König. Several well-known psychophysicists passed through König's laboratory, among them Christine Ladd-Franklin. At the beginning of the twentieth century, König's health deteriorated and he died on October 26, 1901, at age 45. The successor in his position was Willibald Nagel [1].

51.1 Cone Spectral Sensitivity Functions

König published a number of papers on subjects related to physics but his most important contributions are those on physiological optics, a number of them co-authored by a student of Helmholtz, C. Dieterici. The articles have been conveniently collected by König and were jointly published in 1903 [2]. For some 50 years Helmholtz and Ewald Hering had been in a battle about color vision with the former quantitatively formulating and expanding on Young's three-sensor types theory and Hering, based on visual experience, proposing an opponent-color theory. Much of the work of König was to offer support for Helmholtz's theory.

Perhaps the most important of König's papers (together with C. Dieterici) were two describing the findings of their experiments determining the spectral sensitivity functions of the three implied cone types (Fig. 51.1) [3, 4]. They found that color-normal individuals varied noticeably in their results and that dichromats only had two such functions. In the figure, the functions V (violet) and R (red) are close enough for König and Dieterici to have single curves. This is different for the G (green) curve where K and D indicate the functions for each investigator. König interpreted the differences in the curves between 550 and 430 nm to be due to individual differences in macular pigmentation. The dashed curve is representative of the spectral sensitivity of the rod sensors. In their second paper, based on additional experimental data, König and Dieterici concluded that the three fundamental functions are sufficient to describe the basics of color vision and that in case of dichromatic observers either cones of the R or the G type were missing. For anomalous trichromats, they found that two fundamentals were identical with those of a color-normal observer while the third one is significantly different [4]. The data became known as the König fundamentals and were used for colorimetric calculations until, from experimental results by J. Guild and W. D. Wright, the CIE standard observer data were calculated in 1931.

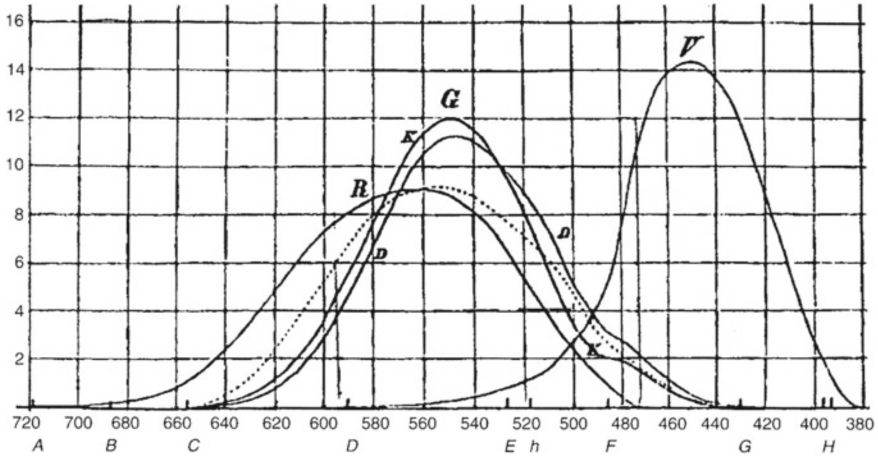

Fig. 51.1 Experimentally determined spectral sensitivity functions of the three cone types, identified as V, G, and R and that of the rods shown as a dashed line. The letters below the wavelength scale represent the locations of major Fraunhofer lines [2]

Other important investigations involve the determination of wavelength discrimination ability [5], experimental determination that Grassmann's laws of color mixture depend on light intensity [6], the dependence of Fechner's law on light intensity and to a degree on wavelength of comparison [7] and the perceived brightness of spectral hues at different light intensities [8]. An area of interest in the 1890s was the earlier identified visual purple discovered in 1877, then assumed to be the basis of color vision. Experiments by König showed that the light absorption of visual purple is in close agreement with the single sensitivity function of monochromats but different from the three functions of the normal trichromat [9].

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Chapter 52
Ives, Frederic Eugene 1856–1937

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Frederic Eugene Ives was an American inventor and scientist who made significant contributions to the field of colorimetry.

He was born on February 17, 1856, in Litchfield, CT to Hubert L. Ives and his wife Ellen. His father passed away when Frederic was still a child. He left school when he was 12 and began an apprenticeship as a printer at the *Litchfield Enquirer*. Photography and engraving became his hobby. At age 18, based on his reputation and without having a formal education, he was invited to run the photography laboratory at Cornell University in Ithaca NY where he stayed for four years, a key period in regard to his inventions. While at Cornell, he invented the halftone printing process for black-and-white photographs. In 1879, he got married and moved to

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Philadelphia where he established an association with a major manufacturer of woodcut engravings who was interested in photographic reproduction methods and Ives' halftone process. Until 1880 illustrations in books, magazines, and newspapers were largely based on woodcuts as well as lithography; by the turn of the century, the industry in the United States had mostly switched over to Ives' half-tone process.

Ives neglected to have the halftone process patented. However, for other inventions he was issued a total of 70 patents in his lifetime, many related to trichromatic halftone printing. He revolutionized color printing in books, magazines, and newspapers in a manner similar to that for black-and-white printing. Up to that time, the process in commercial use of color printing was lithography, with the image constructed from up to a dozen hand-made limestone or metal engravings used to print with differently colored inks. He regularly lectured on the subject of his inventions at Philadelphia's Franklin Institute. Circa 1890, he moved to New Jersey, outside New York. His son Herbert obtained a PhD degree from Johns Hopkins University in 1908. He was also active in the field of color science, publishing in 1915 an important article on the transformation of color-matching functions between different colorimetric systems [1].

52.1 Trichromatic Camera and Printing

In 1891, Ives printed his first "trichromatic" half-tones and in 1892 obtained a patent for what he called a trichromatic camera. In 1894, he obtained a patent for the Kromskop (Fig. 52.1), a stereoscopic version of a trichromatic camera. It had limited success and some years later Ives transferred the related patents to the Eastman Kodak Company. Two more significant inventions were the portable "colorimeter" and the "photometer," both patented in 1908. The former was used to measure and define color stimuli in terms of trichromatic designations, the latter to obtain measures for hue and intensity of lights.

The early trichromatic principle of color photography had been enunciated and demonstrated by J. C. Maxwell in 1855 with an image taken separately through red, green, and violet colored filters and developed as black-and-white positives on glass plates [2]. Light was projected in overlapping fashion through the three images and their related color filters onto a screen to generate the multi-colored image. The result was less than perfect and the process was soon forgotten but investigated again later by others, including Ives. He spent much time and effort to develop viable technologies for the method, including the "panchromatic" emulsions required to produce good quality color reproductions of scenes [3]. There were two steps to Ives' halftone color printing process: (1) Color separations were obtained by making successive exposures through colored filters onto film and halftone plates were made from these filtered exposures. (2) The three separations were printed onto paper, on top of each other in exact registration, with yellow, magenta and blue–green inks [4]. This process and further developments resulted in a revolution of the technical methods of printing colored images.

Fig. 52.1 Stereoscopic color image as viewed in the Kromskop, 1897. On the left are the B&W stereoscopic images for the three primary colors as used in the Kromskop. Top right is a digital recreation of the two stereoscopic versions of the image. On bottom right is an enlarged version of the image based on a photographic print made in the 1950s

In later years, Ives worked intensively on color cinematography, resulting in multiple patents. Ives died on May 7, 1937, in Philadelphia PA. A postage stamp with his portrait celebrating his invention of the halftone process was issued in 1996 (Fig. 52.2) [5].

Fig. 52.2 US postage stamp celebrating Ives' invention of the halftone printing process, 1996

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Chapter 53
Munsell, Albert Henry 1858–1918

Photograph from Munsell, 1905

Munsell was born on January 6, 1858, in Boston M.A. where his father was in the piano business. After high school, he attended the Massachusetts Normal Art School in Boston. In 1879, he studied Ogden Rood's influential book *Modern Chromatics*. In 1881, he was named an instructor and later a lecturer at this school, positions he held for 25 years. He was awarded a scholarship that made it possible

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for him to study from 1885 to 1888 at the Académie Julian and the École Superieure des Beaux-Arts in Paris and one year in Rome. After he returned, he was an active painter of portraits and seascapes. In 1889, he received a patent for an adjustable artist's easel. In 1894, he married Julia Orr, the daughter of a New York financier, with whom he had a son, Albert Ector Orr Munsell, and three daughters. Munsell died on July 28, 1918, in Brookline MA [1].

53.1 Munsell Color Order System

As a lecturer at the art school, Munsell became concerned with how to teach students about colors in a meaningful manner. In 1899, he developed a model of a balanced color sphere that, when spun rapidly, resulted in a gray appearance, thus showing a kind of color balance (see portrait above). He received a patent for it in 1900 [2]. Munsell met O. N. Rood, then professor of physics in New York, in 1899 showing him his color sphere, with Rood commenting positively on it. Simultaneously, Munsell concerned himself with the design of the interior of the color sphere. In April 1900, he sketched a hue circle based on the decimal system, with five primary, five secondary, and ten intermediate hues. It continues to be the basis of the modern system. Munsell, from his studies in painting, had a clear idea of lightness or value, as it was typically called in painters' circles. In 1901, he obtained a patent for a photometer he called a luminometer. It was manufactured in small numbers in the following years [3]. The basic question of using a logarithmic or a power root scale to relate the physical data of the luminometer to perceived lightness in his system was a question not fully resolved until after Munsell's death. In 1902, Munsell hand-plotted color intensity and lightness data for different pigments, earlier established by W. Abney, and realized that a sphere was an incomplete representation of perceived object colors. As a result, he began to name his color solid a "color tree." Having established a hue circle and a subjective lightness scale, he was aware that for completeness he needed to define a chromatic intensity scale. It is not established how he arrived at the term "chroma" for that purpose. In March 1902, he sketched a color solid based on the three attributes, as shown in Fig. 53.1 [4]. Samples were to be spaced according to perceptual differences, and Munsell began to establish such samples to fill limited hue pages. Munsell described the system in *A color notation*, first published in 1905 [5]. A first edition of the *Atlas of the Munsell color system* was published in 1907 containing eight charts of painted samples of ten different hues [6]. In the 1915 edition of the atlas, the number of samples was doubled. Munsell also introduced artist's tools based on his system: Munsell crayons and Munsell watercolors. As a painter, Munsell was interested in color harmony and he established nine principles based on his color solid [7].

Throughout the development of the system, he consulted with a broad group of scientists and artists and gave many presentations in the USA and in Europe. In 1917, he formed the Munsell Color Company to operate the business producing the

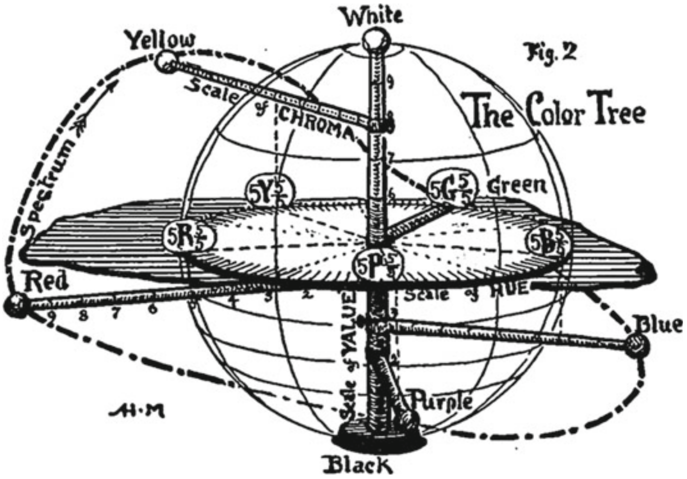

Fig. 53.1 Munsell's schematic depiction of the color tree [6]

atlas. After his passing, it was taken over by his son A. E. O. Munsell and other stockholders. At about the same time the National Bureau of Standards began to show interest in the system and supported sample measurement and expansion of the system. An enlarged edition with 20 hues was published in 1929 [8]. In the 1940s, extensive experiments were made under the auspices of the Optical Society of America resulting in the Munsell Renotations [9], colorimetric definitions of a revised version of samples of the atlas that continue to be the basis of the modern system. Munsell's system is perhaps the most important color atlas system yet developed.

The history of the development of the Munsell system has been described in more detail by Nickerson [10] and by Kuehni [11].

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Chapter 54
Luther, Thomas Diedrich Robert
1868–1945

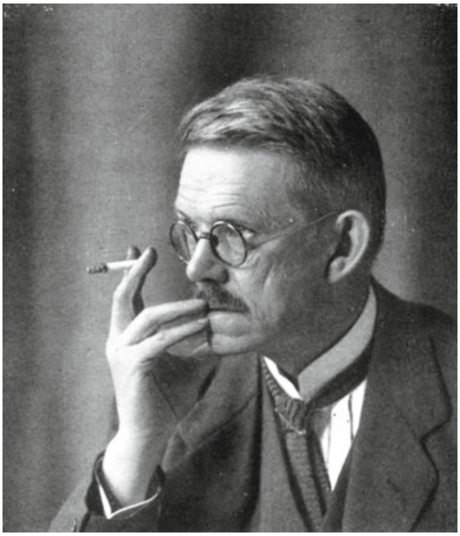

Image by U. Richter, ca. 1925

Thomas Diedrich Robert Luther was born on January 2, 1868, in Moscow to German parents. His father Alexander was a lawyer. Among his direct ancestors was Hans Luther (1492–1558), a late cousin of the reformer Martin Luther. From 1885 to 1889, he studied chemistry at the University of Dorpat in Russia. Toward the end of 1889, he was named assistant to the chemist F. K. Beilstein at the University of St. Petersburg. A serious illness in 1891 forced him to recuperate during the next two years. In 1894, he resumed studying chemistry, this time at the University of Leipzig where he received his Ph.D. degree in 1895. His primary educator there was Wilhelm Ostwald (1853–1931). In 1896, Luther was named an assistant to Ostwald at the Physical

R. Shamey and R. G. Kuehni, *Pioneers of Color Science*,
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Chemistry Institute of the University of Leipzig. In 1899, Luther submitted his habilitation thesis, titled "Equilibrium change between halogen compounds of silver and the free halogens caused by light," and obtained lecturer status. In the same year, he published the monograph C*hemical processes of photography*, a record of six public lectures he gave on the subject. In these lectures, he demonstrated, among many other things, the chemical reaction kinetics in layers or volumes of substances, a subject that occupied him for the rest of his life. He also was the co-author of the second edition of Ostwald's book on experimental methodology in physicochemical measurements in 1902. In the year 1900, he was named assistant director of the Ostwald Institute at the University of Leipzig. As colleagues, Ostwald and Luther were considerably different types. Ostwald did not like to have to lecture but published many papers and books. As a result, Luther was burdened with much of the lecturing activities at Ostwald's institute. Despite important work in many fields, he rarely wrote articles. In 1904, Luther was named a regular professor of physical chemistry at the University of Leipzig. Ostwald, wanting to just manage the Institute, was found to be neglecting his lecturing duties and resigned from his position in 1906, retreating to his country estate in Grossbothen, where he launched into his color research. In the same year, Luther was named director of the newly formed photochemical department. In the fall-out of Ostwald's departure, Luther found himself in a difficult position in Leipzig and in 1908 accepted an appointment at the Photographic Science Institute of the Technical University of Dresden, organized shortly before with the support of the local photographic industry (such as Zeiss). Luther remained there until his change to professor emeritus status in 1936, performing significant research in photographic and general physical chemistry and also concerning himself with the definition of color stimuli and color stimulus measurement. He was much admired by his students, among them Manfred Richter who later developed the DIN color order system. In 1909–1910, the well-known American photographer Imogen Cunningham (1883–1976) was a student of Luther, learning the technique of platinum prints. Luther remained in Dresden where he passed away on April 17, 1945, the last day of the Allied bombing runs on that city [1, 2].

54.1 Color and Spectrum

Luther's interest in color phenomena was the natural outcome of his activities related to the chemistry of color photography. He clearly distinguished between what he considered to be an objective definition of color stimuli and perceptual color phenomena. Most of his seminal paper "Aus dem Gebiet der Farbreizmetrik" (on color stimulus metrics) [3] was ready for publication in 1923 under the title "color and spectrum," as a contribution to a Festschrift for Ostwald in the *Zeitschrift für angewandte Chemie* (Journal of applied chemistry). However, the rabid inflation of the time prevented publication until 1927, as described in a footnote in the paper. His only other brief (2 pages) publication on the subject of color, from 1942, is concerned with practical application of the moment sum curve, developed in the 1927 paper.

1. *Colorimetry and optimal object color solid*

   The preliminary version of a trichromatic system of colorimetry had been worked on in Europe on basis of the visual sensitivity data, approximating cone responses, experimentally determined in Helmholtz's laboratory by Arthur König in 1892. Luther used these data to develop a number of different systems of colorimetry based on different parameters. Using the König functions, he also developed secondary colorimetric functions in reasonable agreement with Hering's four perceptually primary colors, yellow versus blue, and green versus red (purple), as shown in Fig. 54.1. Luther's functions were supported some 30 years later by the experimentally determined unique hue functions of Hurvich and Jameson. The red–green function has two transition points, while the yellow–blue has one. Using these, he calculated the first optimal object color solids. The version based on the vertical axis representing lightness is shown in two views in Fig. 54.2. A version of the object color solid calculated in a tristimulus space was published in 1928 by the Russian researcher Nikolaus Nyberg. The general designation of such solids became known as Luther–Nyberg solid.
2. *Luther condition*

   In his paper, Luther also proposed what became known as the Luther condition: Spectral sensitivities of the color layers in color film or of color filters used in color photography should duplicate or closely match the color sensitivities of the human visual system.
3. *Sensitometry*

   Luther, together with his former student Emanuel Goldberg (1881–1970), with input from other researchers proposed a German standard for the determination of what became known as film speed, a definition of its sensitivity. It was published in 1934 as DIN4512. In 1998, it was replaced with the corresponding ISO standard.

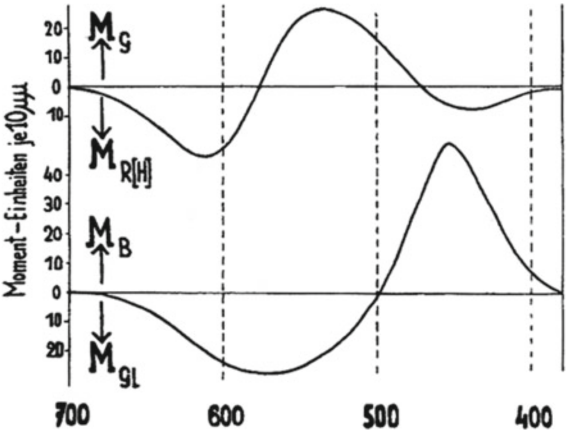

Fig. 54.1 Spectral functions calculated by Luther to represent a Hering-influenced colorimetric four-color system; on top the green–red, on bottom the blue–yellow function [3]

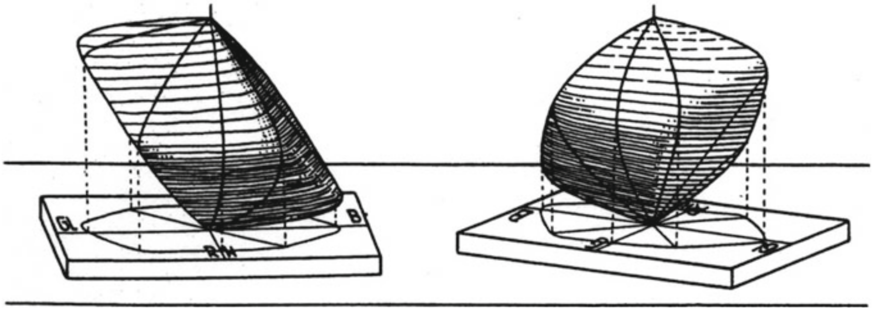

Fig. 54.2 Projective views of the optimal object color slid based on the functions of Fig. 54.1. The vertical axis represents lightness [3]

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Chapter 55
Macbeth, Norman 1873–1936

Artwork depicting Norman Macbeth Sr. on the ISCC Macbeth Award

Norman Macbeth Sr. was a pioneer in the art and science of illumination engineering and color and best known for inventing the Macbeth Illuminometer system in 1915 [1]. He was a British citizen born in 1873 in Canada and lived in New York, USA. He developed and patented the use of high- and low-color-temperature illuminants for testing metamerism [2]. With Ives, Macbeth developed and patented a circular slide rule for converting measurements of illumination and brightness. He passed away in 1936 in New York.

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55.1 Simulated Illuminants

In a 1994 paper, Cal McCamy described the development of daylight simulators by Macbeth [3]. A summary of the pertinent section should give the reader a good understanding of Macbeth's contribution to the field of illumination and color. In 1908, Norman Macbeth Sr. developed the "amber light" gaslight mantle. This gaslight was different from previous models because it emitted less green light and offered better rendering of complexion. He recognized the potential of the gas-filled tungsten-filament incandescent lamp, with a blue filter, for visual appraisal of color. Together with Gage, from Corning Glass Company, he developed a blue glass for filters to convert tungsten light to daylight [4]. He noted that artists and industrial color matchers preferred the light from a north window for color assessment, so Macbeth aimed to simulate daylight at a correlated color temperature (CCT) of at least 7000 K. To examine the performance of the glass filter, he used metameric specimens that matched under daylight but not under incandescent light. The resulting glass was called Corning Daylight Glass. Macbeth spent a significant amount of time to develop viewing booths and separate lamps and lighting fixtures for many applications. These included booths for medical examination, operating room illumination, artists' lamps, daylight lamps to evaluate merchandise in department stores next to the counter and luminaires for fitting rooms of apparel departments. He also published notes and guidelines [5]. Macbeth lamps were also used for cotton grading as early as 1919, and he patented an adjustable daylight reading lamp that was introduced for office and home use [3].

The viewing booths included auxiliary tungsten lamps operating at half voltage which produced light similar to that from the sun on the horizon, called horizon light. These were used as an alternate means of testing for metamerism. Because of significant differences between horizon light and north sky daylight, it was thought that specimens that matched under the two extremes of daylight would likely match in any phase of daylight or in incandescent light. This assumption proved to be fairly accurate but did not apply to fluorescent lights that came later. Macbeth also worked with Corning to develop a glass known as "Aklo" for less critical applications such as graphic arts and surgical lighting with a CCT of 3500–5000 K. In 1938, when daylight fluorescent lamps were introduced, Macbeth Jr. sponsored the development of special light fluorescent sources for general illumination, and in 1946, Macbeth Jr. introduced a viewing booth with daylight fluorescent lamps and incandescent lamps, known as the "Examolite." The viewing booths and luminaires were commonly used for critical evaluation of color in various sectors.

Macbeth began the experiments that led to the production of artificial daylight. He founded the Macbeth Arc Lamp Co. after inventing the illuminator but sold it in 1915 to create a new company, Macbeth Artificial Daylighting Co., in New York., which was the forerunner of the Macbeth Corporation. After Macbeth Sr. passed away, his son Norman Macbeth Jr. took over the affairs of the company and the subsequent developments in the field. The company grew quickly and diversified its products. In 1949, when it began producing measuring units that measured the pH

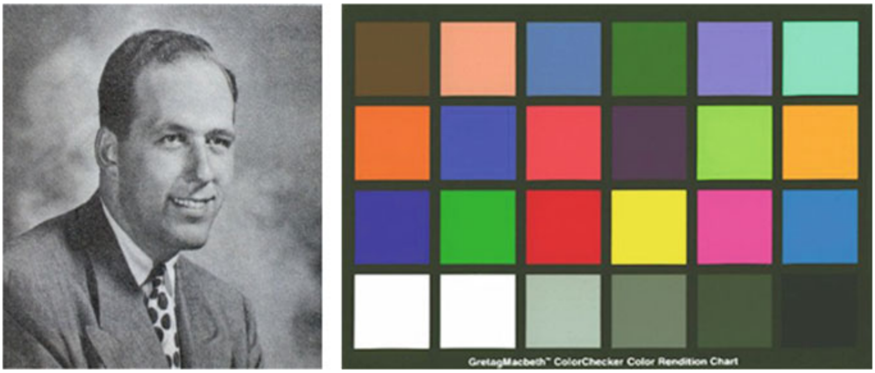

Fig. 55.1 Norman Macbeth Jr. (left) and Macbeth ColorChecker Color Rendition Chart

of solutions, it changed its name to the Macbeth Co. Macbeth merged with Kollmorgen Corp. in the mid-1960s. In 1988, a completely integrated color management company, the Macbeth Division of Kollmorgen Instruments Corp., was created [6].

The Macbeth Company merged in 1997 with Gretag to form the GretagMacbeth Company. Among the products developed by GretagMacbeth Company is a colorchecker introduced by McCamy, Marcus, and Davidson in a 1976 manuscript in the Journal of Applied Photographic Engineering [7]. The chart is a color calibration target, which consists of a cardboard-framed arrangement of 24 squares of painted samples (Fig. 55.1).

In 1967, Norman Macbeth Jr. established The Macbeth Award in memory of his father Macbeth Sr. The award is given by the Inter-Society Color Council to a member for important contributions to the field of color science [8]. A number of pioneers of color science who appear in this book have been the recipients of this award.

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Chapter 56
Luckiesh, Matthew 1883–1967

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R. Shamey and R. G. Kuehni, *Pioneers of Color Science*,
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Matthew Luckiesh (pronounced loo'kish) [1] was an American physicist who made significant contributions to the field of colorimetry. In his day, he was known as the "Father of the Science of Seeing" [2].

Matthew was born on September 14, 1883, in Maquoketa, Iowa, in a Roman Catholic family to John and Frances Root Luckiesh and grew up in Cleveland. He graduated from high school in Maquoketa in 1899 at the age of 15. His parents were supportive of him attending college, but he was asked to find a way to pay for it. Luckiesh learned to play the trombone and even joined a circus. Around 1904, he got a job with a band in California and also began to work for the Yellow Pine Mining Company assessing mining claims [3]. He returned to Maquoketa and entered Iowa State College (now Iowa State University) in the fall of 1905. He transferred to Purdue University the next fall, earning his way through college playing his trombone, and graduated in 1909 with a Bachelor of Science degree in electrical engineering. In 1911, he received a Master of Science degree from the State University of Iowa and in 1912 the degree of Electrical Engineering from Iowa State College (Iowa State University).

After graduation, Luckiesh returned to Cleveland to start work for the General Electric Lamp Division at Nela Park in 1910, where he pursued research on light and vision. He became director of Applied Science in 1919 and director of the Research Laboratory in 1924, a position he held until his retirement in 1949. Luckiesh was married to Frances Clark in Maquoketa in 1913 who passed away in 1925 [4]. He then married Helen C. Pitts in 1928, and they had two daughters. Matthew Luckiesh passed away on November 2, 1967, in Shaker Heights, Ohio [5].

56.1 MAZDA Lamps

Luckiesh was a prolific writer and published 28 books and about 860 scientific and technical articles, as well as 11 US patents between 1911 and 1960 [5]. He developed several theories on color and its physiological effect on people. During World War I and World War II, he studied camouflage and airplane visibility, and later invented artificial sunlight and germicidal lamps.

In general, Luckiesh was interested in determining the conditions under which optimal visibility was achieved and studied the relationship between light and seeing to design better types of lamps. One such lamp had a coiled tungsten filament and a blue glass envelope to approximate the color of average daylight (Fig. 56.1). These MAZDA daylight lamps were used in situations where accurate discrimination of the colors of objects was important. Another lamp design attributed to Luckiesh, around 1926–1927, involved a warm color temperature to create a mood. The color of the MAZDA flametint lamps resembled that of candlelight and the warmth of an open fire (Fig. 56.1). The lamps were often used in wall fixtures in hallways. Luckiesh was also involved in the development of colored lamps, the MAZDA photographic lamp and white bowl lamps. The last product

Fig. 56.1 MAZDA daylight and flametint lamps designed by Luckiesh [6]

attributed to him, about 1949–50, was a lamp design known as the 50-GA lamp, which was used in ceiling fixtures and was enameled to produce a soft-tone effect.

In his 1944 book, *Light, Vision and Seeing*, and in collaboration with Frank Moss, Luckiesh discussed the development of a "Visibility Meter" based on determining brightness/contrast. The device consisted of a pair of similar photographic gradient filters, which increased in density when rotated together before the eyes. The filters thus reduced the apparent brightness of the observed field while lowering the contrast between the object of view and its background [7].

Luckiesh studied the lighting situation in the private and executive quarters of the White House in 1933, and determined the lighting to be inadequate. He specified new lighting arrangements, which resulted in increasing the light levels by 25–50 times their original values. One year later, President Roosevelt invited Luckiesh to examine the lighting situation in the study rooms of the US Naval Academy in Annapolis. It was revealed that nearly 13% of the students that failed to graduate had defective vision despite having passed the vision test when they originally entered the program. Lighting was found to be inadequate and was therefore changed to include new portable lamps. Many universities and schools quickly followed suit [8].

Luckiesh was awarded an honorary Doctor of Science degree from Iowa State College in 1926 and Doctor of Engineering from Purdue University in 1935. He was the recipient of several awards and honors including the Distinguished Service Foundation of Optometry and the Illuminating Engineering Society, and the James H. McGraw Award for distinguished contributions to the advancement of the electrical industry [9].

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Chapter 57

Katz, David 1884–1953

Image source: University of Rostock, Germany

David Katz was born on October 1, 1884, as the seventh of eight children of his parents in Kassel, Germany, where he attended the local Realgymnasium. As a child and student, he became a talented amateur painter, interested in color and other sensory abilities. In 1902, he began studying at the nearby University of Göttingen. There he became interested in psychology taught by G. E. Müller. In 1906, he obtained a Ph.D. degree in psychology, physics, and philosophy, and in 1907, he assumed the position of assistant to Müller. In 1911, he was named a

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professor, based on his work on color phenomenology [1]. From 1914 to 1918, he was a volunteer soldier in the German Army. In 1919, he received an invitation from the University of Rostock to assume a then new professorship in psychology. In the same year, he married the psychologist Rosa Heine with whom he had two sons. Over the years, they both were active in a wide field of psychology, including that of children and animals and had a number of well-known students. In 1929, Katz was for a time a guest professor in Maine in the USA. Shortly after Hitler's move to power in 1933, Katz and his wife were officially retired from their positions. In the same year, Katz with the help of a colleague moved to England, followed a year later by his wife and sons. In 1937, Katz received an invitation to fill the first professorship in psychology in Sweden at the University of Stockholm. Here he was broadly active in many fields of psychology. In 1952, already retired, he received an honorary professorship from the University of Hamburg. On February 2, 1953, he died in Stockholm. Katz produced over 200 research papers and books, most in the general field of psychology [2].

57.1 Katz and Phenomenology of Color Vision

Beginning with his dissertation, Katz was specifically interested in the phenomenology of vision, including shape, structure, space, color, and movement, to the exclusion of related physics and psychophysics. He defined three appearance modes of colors: film colors, surface colors, and volume colors. Film colors are those experienced when looking into the black tube of a spectroscope and seeing spectral colors, having a slightly spongy appearance without having a specific location in space. Surface colors are those commonly referred to as object colors. Volume colors he defined as those of colored glasses or gelatins. An important concept in his work was the subjective gray we experience either with closed eyes in the absence of strong light or with open eyes in a completely dark room. Another one was the reduction screen, a black sheet of paper with a small hole through which a small section of a colored object could be viewed and the resulting film color appearance compared to the surface color without the screen. Katz and his students performed many experiments related to color appearance involving illumination changes, surround and shadow effects, monocular versus binocular vision, exposition time, color constancy and lack thereof, light and dark adaptation, color and depth contrast effects, the effects of chromatic illumination, to name a few. He introduced novel concepts, translated as "pronouncedness" and "insistence," to describe nuanced phenomenological color effects. A key subject was the problem of definition of the "true" color of an object. To measure phenomenological magnitudes, he used innovative disk mixture methodology.

In his book, Katz discussed his agreements and disagreements with other researchers and their findings, such as Hering and of his time K. Bühler, A. Gelb, E. Jaensch, J. von Kries, and E. G. Müller. An important psychological concept of that period was Gestalt psychology based on the idea that, as its primary formulator

M. Werthheimer expressed it, “the brain is holistic” by considering the total amount of information received. Together with self-organizing tendencies, this results in “the whole is greater than its parts.” Katz published a textbook on the subject in 1944, issued in several editions and multiple languages [3].

Katz’s book of 1911 was issued in a revised and updated version as *Der Aufbau der Farbwelt* (The constellation of the world of colors) in 1930 [4]. After he moved to London, a shortened, translated version was published in 1935 in England as *The world of colour* [5].

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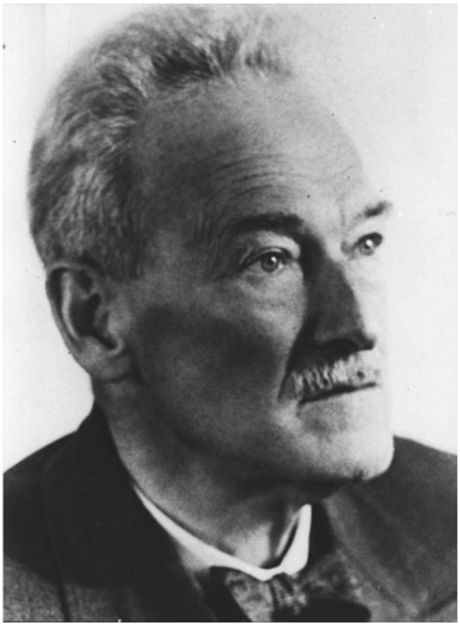
Chapter 58
Kohlrausch, Rudolf Hermann Arndt
1884–1969



Portrait © Jürgen Killmann and Universität von Tübingen, 1969

Arnt Kohlrausch was born on October 30, 1884, in Hannover, Germany, a member of an extended family of scientists from the early nineteenth century to the present. His father was professor of electrical technology at the Technical College of Hannover. Arnt Kohlrausch studied medicine at the universities of Marburg, München, and Rostock, graduating in 1911. In 1918, he became lecturer in physiology at the University of Berlin. In 1926, he moved to the University of

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Greifswald, today in the German province of Mecklenburg. In 1928, he became chair of physiology at the University of Tübingen, where he remained until his retirement in 1951. Kohlrausch was active in several fields of physiology. Perhaps his best-known work is *Körperliche und psychische Lebenserscheinungen* (Bodily and psychological phenomena of life) [1]. He also did research in visual perception and was one of the founders of the journal *Die Farbe* (Color). A peculiarity of low-level brightness perception, the *Kohlrausch-Knick* (bend) is named after him. It refers to a bend in the curve of absolute luminance threshold versus time during dark adaptation, the bend being due to the crossover of absolute thresholds of rods and cones at a certain time after light offset. The perceptual effect to an observer is that a very dim scene suddenly appears brighter as the rod sensitivity rises enough to dominate the visual signal. In English, it is known as the “rod-cone break.” Kohlrausch died on July 13, 1969 [2].

58.1 Helmholtz–Kohlrausch Effect

In 1923, Kohlrausch published an article *Über den Helligkeitsvergleich verschiedener Farben, Theoretisches und Praktisches zur heterochromen Photometrie* (comparing brightness of different colors, theoretical and practical aspects of heterochromic photometry) [3] in which he investigated in detail the effect of hue on perceived brightness, mentioned earlier by Helmholtz [4]. This was followed in 1935 by the article *Zur Photometrie farbiger Lichter* (Photometry of colored lights) [5]. As reported by Judd [6], in 1939, J. Urbanek and E. Ferencz introduced the term Helmholtz–Kohlrausch effect for the phenomenon, a term still in use today [7]. Figure 58.1 shows some examples. The six circles have luminance values identical to that of the achromatic surround. To most observers, the circles appear to various degrees, lighter than the gray.

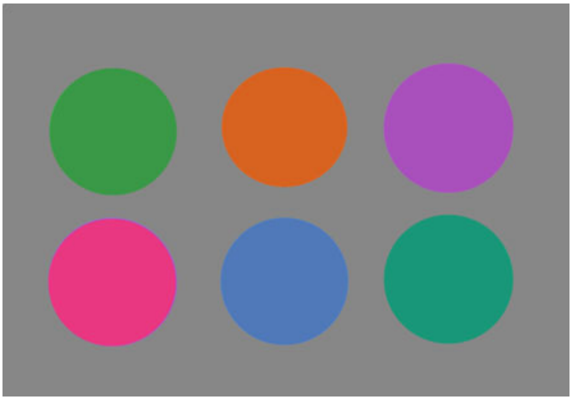

Fig. 58.1 Examples of the Helmholtz–Kohlrausch effect. All circles have the same colorimetric lightness values as the gray surround

Helmholtz used the term *glühend* (glowing) to describe the appearance of the chromatic colors compared to the achromatic surround. The strength of the effect varies by hue. Quantitative investigations of the Helmholtz–Kohlrausch effect (HKE) based on the CIE colorimetric system were performed by Wyszecki and Sanders in 1964 [8], the basis of the inclusion of the HKE in the lightness formula of the Optical Society of America Uniform Color Scales [9].

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Chapter 59
Priest, Irwin G. 1886–1932

Source: iscc22.wildapricot.org

Irwin Priest was born on January 27, 1886, in the small town of Loudonville, OH. He attended Ohio State University from 1904 to 1907 where he graduated with a BA degree. He obtained a position as a laboratory assistant, moving up to assistant physicist, at the National Bureau of Standards in Washington where he remained until his premature death on July 19, 1932, [1].

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https://doi.org/10.1007/978-3-319-30811-1_59

59.1 Priest-Lange Reflectometer

Early on at the National Bureau of Standards (NBS), Priest became interested in the subject of color. He soon was promoted to chief of the Colorimetry Section of the Optics Division of that organization. His main effort was to find a method by which color could be accurately defined in term of physically measurable quantities. A patent for a photometric device was issued to him in 1913 [2]. He invented a dispersion colorimetric photometer for measuring light sources and an apparatus to measure dominant wavelength, purity, and brightness of color samples, described in 1924 [3]. In 1920, together with E. Lange, he developed the Priest-Lange reflectometer, in use at NBS until the 1970s (Fig. 59.1). In the 1920s, as the result of the need for a reliable color specification system, Priest supervised and advised for work at NBS and the Munsell Color Company related to improvement and enlargement of the Munsell color atlas, resulting in a new edition in 1929. The early editions had only 10 hues; the 1929 edition was enlarged to 20 hues. This effort also resulted in a number of related publications [4]. An important effort of his was the calibration of hundreds of glass filters used at the time for color measurement at NBS. In 1927, an official NBS calibration scale, known as the Priest-Gibson scale, was set up for that purpose. Its main application was the definition of the color of vegetable oil, various kinds of which were produced in the USA. In 1913, he became an Honorary Lifetime Member of the American Oil Chemists Society for his work on oil color measurement.

Fig. 59.1 Priest-Lange reflectometer at the US National Bureau of Standards

A subject of interest to Priest was color saturation or purity, resulting in articles published in the Journal of the Optical Society of America [5]. An investigation of purity at the threshold level, together with his colleague F. G. Brickwedde, was presented at an OSA conference and published in 1938, guided by D. B. Judd [6]. Priest was also involved as the chief US representative in the CIE effort leading to the 1931 CIE standard observer [7]. He was president of the Optical Society in 1928/29. Priest authored and co-authored some 70 articles on color during his lifetime.

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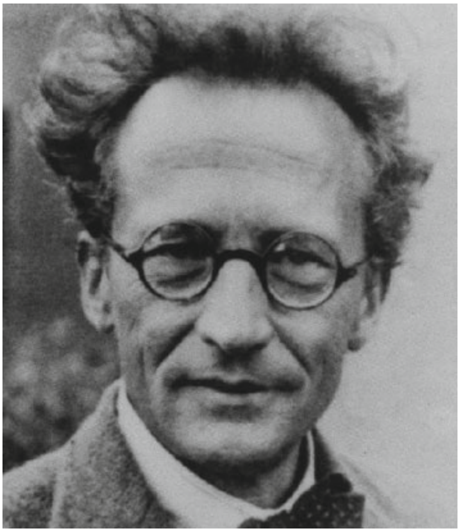
Chapter 60
Schrödinger, Erwin 1887–1961



Source krishnapath.org

Erwin Schrödinger was born in Erdberg, Austria, to a father of Austrian and a mother of mixed Austrian-English descent. He studied physics in Vienna under Franz Exner, whose assistant he became in 1911. He was influenced early by the writings of the German philosopher Arthur Schopenhauer resulting, among other things, in his interest in color theory. Three of his papers on color were written in Vienna after he concluded his military service in 1918 and before assuming a position at the University of Zürich in 1921. There he published six more papers on

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color and vision. His interest in color, which did not extend beyond his years in Zürich, apparently was due to his deep involvement with the works of Schopenhauer who in turn was influenced by Goethe.

In Zürich, Schrödinger did his most important work, on quantum wave mechanics, for which he shared with Paul Dirac the 1933 Nobel Prize in physics. In 1940, Schrödinger moved to Ireland, where he remained until his retirement in 1955. Then he returned to Vienna. Among his achievements is the thought experiment known as Schrödinger's Cat.

60.1 Color Theory

Schrödinger's main contributions to color theory include the following:

(a) He offered the first mathematical proof [1] of the theorem sketched by Wilhelm Ostwald that, under any illuminant, the object-color tristimulus locus is contained by a two-dimensional manifold generated by reflectances that are 1 or 0 at each wavelength and with at most two transitions between 0 and 1. Robert Luther later called these reflectances "optimal colors". The maximality of two transitions depends on the convexity of the spectrum locus, as is clear in his very brief proof: "*If a pigment has three transition points that in the chromaticity diagram are not located on a straight line, by moving the transition points its reflectance can be changed in a manner that results in a lighter pigment of the same chromaticity coordinates. Therefore, it cannot be optimal.*"

(b) He was the first to use differential geometry for color space, to import brightness as one of the space's coordinates, and to infer total color difference (in units of just-noticeable differences) through arc length along geodesics [2, 3].

(c) He was the first to offer a mathematically detailed connection of the Young-Helmholtz three-color theory and Hering's opponent-color theory [4], after Helmholtz offered such a concept in 1896 and von Kries that of a zone theory in 1905.

There are only very few [color] scientists whose portrait appeared on paper money. Goethe satirized paper money [Faust, Part 2, Act I, Scene 4], but did not appear on it. In 1983, Austria introduced a bank note featuring Erwin Schrödinger (Fig. 60.1).

Fig. 60.1 Schrödinger depicted on an Austrian bank note

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Chapter 61
Itten, Johannes 1888–1967

de.wikipedia.org

Johannes Itten was a Swiss expressionist painter, designer, and teacher, and one of the main pedagogical forces behind the Bauhaus in its earliest phase. Itten was born in Südern-Linden (Switzerland) on November 11, 1888. His 1961 book *The Art of Color* presented color theory in a simplified form that largely excluded scientific developments from the mid-nineteenth century onwards. His approach has permeated much subsequent teaching of color in the arts.

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He trained and practiced as teacher in Bern before studying under the abstract painters Eugène Gilliard in Geneva (1912) and Adolf Hoelzel in Stuttgart (1913–16). He then ran his own art school in Vienna until the director of the Bauhaus in Weimar, Walter Gropius, appointed him as one of its first teachers in 1919. Itten played a key role in the development of the "preliminary course" that would teach students the basics of material characteristics, compositions, and colors. However, conflict involving Itten's ambitions, his promotion of the eastern-inspired Mazdaznan sect, and his opposition to involvement in commercially oriented design, by which Gropius hoped to validate the state-funded Bauhaus in a hostile political and economic climate, prompted Itten to leave in 1923. He subsequently taught in the Mazdaznan community in Zurich (1923–26) before establishing an art and architecture school in Berlin (1926–34) and directing the Advanced Vocational School for Textile Art in Krefeld (1932–38). Itten then settled in Zurich, serving as director of the Museum and School of Applied Arts (1938–53), the Silk Industry Vocational School (1943–1960) and the Rietberg Museum (1949–56).

In his retirement, Itten published his main book on color theory, *The Art of Color*, in 1961 [1–3], and an account of his Bauhaus preliminary course, *Design and Form,* in 1963 [4]. Some of his ideas on color had appeared previously in the rare hand-printed *Tagebuch* of 1930 [5] and *Die Farbe*, an exhibition catalog from 1944 [6].

61.1 Color Star, Color Circle, and Color Sphere

At the Bauhaus, Itten taught color theory using a 'color star' of radiating tint and shade scales that he printed as a lithograph in 1921 [7]. The 12-hue scale derived via Hoelzel [8] from one Bezold had proposed as being perceptually equal, but was modified to align what Itten regarded as the warm–cool boundary (between yellow and yellow green) vertically. Unlike this 1921 scale, which placed yellow, "purple" (magenta) and cyan–blue in a symmetrical triad, Itten's post-Bauhaus color diagrams were all structured around a symmetrical triad of perceptually pure red, yellow, and blue primaries, producing an unequal hue scale with larger perceptual steps in the yellow–green–blue sector. Three secondary hues (orange, green and violet) and six intermediates (red–orange, yellow–orange, etc.) complete the circle. This change reflects Itten's adherence to the view, widely held in science until the mid-nineteenth century, that all object colors are mixtures of red, yellow, and blue. For a three-dimensional model, Itten ignored the quantitative systems produced by Munsell and Ostwald and used a simple sphere externally resembling the one published by Runge in 1810. This sphere places the strongest colors of all hues on the equator, with the result that the vertical dimension does not represent lightness consistently.

1. *Color contrasts*
   Hoelzel incorporated a broad range of sources into a system of seven or eight "contrasts" of color that were central to his teaching. Itten simplified Hoelzel's classification and language into a list of seven contrasts that is one of the most widely cited elements of his system: contrast, of hue, of light and dark, of cold and warm, of complements, of saturation, of extension, and simultaneous contrast.

2. *Subjective and "objective" color harmony*
   Itten encouraged exploration of the color preferences of the individual, but warned that this "subjective harmony" must often be subordinated to "objective" (though scientifically unexamined) laws. "Objective" harmony required balance of the three traditional primaries, which could be obtained (following Hoelzel) from complementary pairs, equilateral and isosceles triads, and rectangular, square, and trapezoidal tetrads in his 12-hue circle, but also by tilting these shapes in any direction within his color sphere. Balance also required that the three primaries be present in a set ratio that Hoelzel had derived ultimately from Schopenhauer, but which Itten misattributed to Goethe. Unbalanced, "discordant" combinations could, however, be used for expressive effect [9] (Fig. 61.1).

Fig. 61.1 Itten's Farbstern (color star, 12 hues each in six lightness steps beginning at white in the center, Ref. [1])

3. *Color expression*
   Itten also regarded color expression as involving objective rules and presented a system of “dictionary” meanings of colors and color combinations, in which complementary colors were expected to have opposite meanings, secondary colors were expected to combine the meanings of the primaries they “contain,” and meanings could be modified by contrast effects with surrounding colors [10].

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Chapter 62
Adams, Elliot Quincy 1888–1971

Emilio Segrè Visual Archives, Am. Inst. Physics, 2019

Elliot Quincy Adams was an American scientist born on September 13, 1888. He was the son of Edward Perkins and Etta Medora (Elliot) Adams from Cambridge, Massachusetts. He married Jane J. Pidgeon, and they had a daughter, Dora. According to Gilbert N. Lewis (1875–1946), known for the discovery of the covalent bond and his concept of electron pairs, Lewis dot structures and other contributions to valence bond theory, “the two most profound scientific minds,

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among the people he had known, were those of E[lliot] Q Adams and Albert Einstein. He also mentioned he would not think Adams would do much publishing." [1] Adams passed away in Cleveland on March 11, 1971, at the age of 82.

Adams studied chemical engineering at the Massachusetts Institute of Technology, worked under Gilbert N. Lewis, and in 1909 earned his bachelor's degree. The two would later team up again during Adam's Ph.D. studies. Elliot Adams had a scientific career that included government, industrial, and academic settings. After graduation, Adams took a position with the General Electric Research Laboratory in Schenectady, New York, where he worked and published a manuscript with Irving Langmuir, who would later become a Nobel laureate, on problems dealing with heat transfer [2]. In 1912, Adams supplied the simple mathematical formula that is used to describe the conduction–convection loss from an incandescent filament operated in a gaseous atmosphere, and the formula is still used by illumination engineers. In the same year, he moved to Berkeley, California, to continue his higher education at the University of California. In 1914, he earned his Ph.D. on "The Color and Ionization of Crystal-Violet" under the direction of Gilbert N. Lewis [3]. His interest in color remained a dominant theme in much of his later work albeit in a field quite different from his chemical studies. In a 1916 paper, he recognized that α-amino acids occur in neutral solution almost exclusively as dipolar ions (Zwitter ions) [4]. His idea was fundamental to the understanding of the behavior of amino acids and polypeptides.

He became an assistant and an instructor at Berkeley from 1914 to 1917, and during this period, he published papers with Lewis and others. In 1917, Adams moved to Washington, D.C., to perform research in the Color Laboratory in the Department of Agriculture (DOA). Adams's research in Washington resulted in several patents and journal articles dealing mainly with cyanine dyes as sensitizers for photographic emulsions. He also met Dorothy Nickerson at DOA, and later they developed the Adams–Nickerson (ANLAB) uniform color system in the 1940s. The system is an example of L-a-b color space providing three-dimensional color co-ordinates.

In 1921, his career moved him back to General Electric at Nela Park, Ohio, and he remained there until early 1950s, when he retired. At Nela Park, Adams studied a variety of subjects including "Fireflies, Phosphorus and Other Cold Lights" to "Physics in the Metal Industry" to descriptions of the fluorescent lamp. Adams published over 40 technical papers. Perhaps his most recognized effort was the book, coauthored with W. E. Forsythe, entitled "Fluorescent and Other Gaseous Discharge Lamps" [5].

62.1 ANLAB Model

He published a paper in 1923 in which he discussed a theory of color vision based on Hering and Helmholtz's models [6]. This was the basis for the subsequent work leading to his AB color space. Based on his research at GE, Adams proposed that amber minus green and green minus blue signals were the outputs of the visual system. His seminal contribution to color science, however, was in his 1942 paper, "X–Z planes in the 1931 I.C.I. system of colorimetry." [7] There, he suggested two models for perceptually uniform color spaces. One of the models was termed "chromatic value" which was the precursor of the modern CIELAB uniform color space; the other, called "chromatic valence," was the direct ancestor of the HunterLab color space, and provided the elements of today's CIELUV system. He used relatively simple transformations from XYZ of Munsell colors to obtain relatively uniform spacing of hue and chroma. Hunter made use of this approach in his opponent-color concept and obtained direct measures of opponency from the electrical outputs of the photocells in a circuit developed by Wilson of Westinghouse. This led to the direct readout of Hunter's original alpha–beta chromaticity co-ordinates and, later, to the a-b chromaticity dimensions. Adams also examined the effect of foveal vision on bright and dark surroundings, among other things.

Adams was a Fellow of the American Association for the Advancement of Science, American Physical Society, Mineralogical Society of America, and the Illuminating Engineering Society. His hobbies included work with Boy Scouts and the advocacy of Esperanto as an international language [1]. After his retirement from Nela, he worked with an ophthalmologist in the medical school of Case Reserve University, evidently to further knowledge of the physiology of vision. In 1941, he was presented the Silver Beaver Award by the Boy Scouts of America [1].

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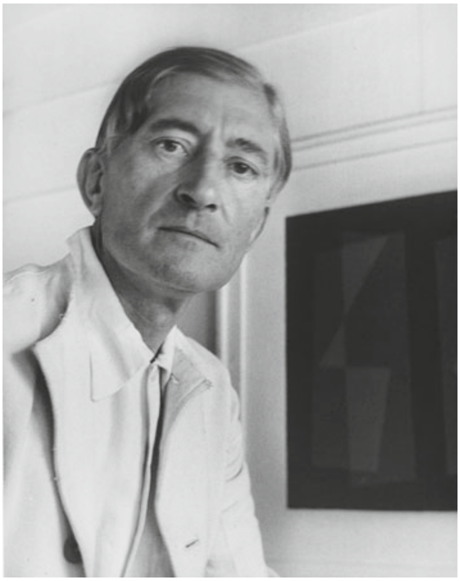
Chapter 63

Albers, Josef 1888–1976



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Josef Albers was born on March 19, 1888, into a Roman Catholic family of craftsmen in the industrial Ruhr district of Bottrop, Westphalia, Germany [1]. He was the only child of a house painter, Lorenz Albers. His Westphalian family tradition was crafts, blacksmiths on his mother's side, carpenters, and handymen on his father's side. He became an influential teacher, writer, painter, and color theorist—now best known for the Homages to the Square he painted between 1950 and

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https://doi.org/10.1007/978-3-319-30811-1_63

1976 and for his innovative 1963 publication “Interaction of Color [2].” He died at the Yale New Haven Hospital in 1976 at the age of 88.

Albers attended the Teachers College in Büren and became an instructor in several Westphalian primary schools from 1908 to 1913. He then decided to pursue formal art studies and enrolled at the Royal Art School (Königliche Kunstschule) in Berlin from 1913 until 1915. After finishing this program, he moved to Essen and Munich and continued to study art for the next four years. From 1916 to 1919, he worked as a printmaker at the vocational art school (Kunstgewerbschule) in Essen. In 1918, he received his first public commission for a stained-glass window for a church in Essen. In 1919, he went to Munich to study at the Royal Bavarian Academy of Fine Arts (Königliche Bayerische Akademie der Bildenden Kunst). In 1920, he enrolled as a student in the preliminary course (Vorkurs) of Johannes Itten at the Weimar Bauhaus and studied painting. He joined the Bauhaus in 1922 as an instructor in the basic design and experimented with glass paintings and stained-glass windows from broken bottles. He met his future wife, Annelise Elsa Frieda Fleischmann (1899–1994) in Weimar, Germany, in 1922 at the Bauhaus [3]. Josef and “Anni” Albers, who later became known for her elegant woven tapestries and fabric designs, were married in Berlin in 1925.

Albers was promoted to professor in 1925 when the Bauhaus moved to Dessau. The Nazis forced the school to shut its doors in 1933, and as a result, most of the artists dispersed and left the country including Albers who immigrated to the USA. He was offered a job as head of a new art school, in Black Mountain, North Carolina, in November 1933 where he remained until 1949. In 1950, Albers left Black Mountain and joined Yale University in New Haven as head of the department of design until he retired from teaching in 1958. He developed a reputation as a gifted and innovative teacher with unconventional ideas about the use of materials. According to one of his former students, Robert Rauschenberg, “Albers was a beautiful teacher, but an impossible person. His criticism was so devastating that I wouldn’t ask for it. But 21 years later, I’m still learning what he taught me.” [4] His theories of color relationships became the basis for art courses taught throughout the country.

63.1 Interaction of Color

Albers published “Interaction of Color,” which presented his theory that colors were governed by an internal and deceptive logic in 1963 [2]. The first edition was printed in only 2000 copies and contained 150 silk screen plates (Fig. 63.1). In this work, he discussed how for infinite variations on a single compositional theme-nested squares of color, gradations, harmonies, and contrasts affect the perceived appearance. He said, “Every perception of color is an illusion… . we do not see colors as they really are. In our perception they alter one another [5].”

Some considered his format of squares within squares as monotonous and repetitive, but he thought that the simplified geometric presentation was the way to

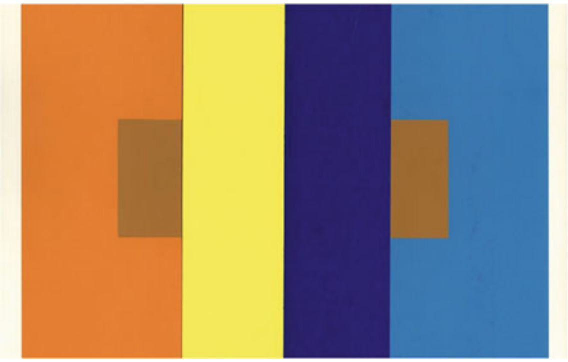

Fig. 63.1 Example plate from Josef Albers' Interaction of Color [2]

make colors "yield" their essence. "Just putting colors together is the excitement of it," he once told an interviewer. "The way green submits to blue, for instance, or vice-versa. What interests me is the way they marry, interpenetrate and produce the baby, the color that is their product together…. When you see how each color helps, hates, penetrates, touches, doesn't, that's parallel to life [1]."

To give his colors maximum intensity, he applied them—with few exceptions—unmixed, over a white Masonite ground, which he preferred to canvas because, he said, canvas "ran away from the touch." The perception of color—as conditioned by changing light, shape and placement—remained his abiding interest, and because he felt that form "demands multiple performance," he would work for many years on a single series, such as his "Homage to the Square."

Although Albers' book "Interaction of Color" is considered to be widely influential, it has been suggested that his general claims about the color experience and the system of perceptual education are misleading. In particular, his belief in the importance of color deception is likely related to a misconception about esthetic appreciation of color, in contrast to a better appreciation of the additive and subtractive color mixture, as well as the tonal relations of colors, simultaneous contrast, and the Weber–Fechner law [6].

In his last years, his paintings began to generate a substantial income, but he and his wife continued to live modestly. In 1971, his work was honored by a retrospective show at the Metropolitan Museum of Art, one of the few ever given to a living artist. In the same year, Albers founded the Josef and Anni Albers Foundation, [3] a nonprofit organization to further "the revelation and evocation of vision through art."

He was elected a Fellow of the American Academy of Arts and Sciences in 1973. As a teacher and theoretician as well as a painter, Albers had a wide influence on several generations of artists that extended into the realm of sculpture, architecture, and industrial design. Albers continued to paint and write, staying in New Haven with his wife until his death in 1976.

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Chapter 64

Guild, John 1889–1979

Photo courtesy of the Color Group of the UK

John Guild was a British scientist who worked at the National Physical Laboratory (NPL) at Teddington in England. Guild spent the majority of his professional life making outstanding contributions to the development of a wide variety of optical instruments and techniques [1].

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In the 1920s, he wrote several papers, published in the Transactions of the Optical Society, describing the fundamentals of colorimetry which have formed the basis of the discipline ever since.

64.1 Color-Matching Functions

He measured, for seven observers, additive matching results for the colors of the spectrum using beams of red, green, and blue light. This work, together with a similar study carried out by W. David Wright, with ten additional observers formed the basis of the international standard for measuring color, the CIE 1931 Standard Colorimetric Observer. The quality of this experimental work was so high that this standard, although now more than eighty years old, is still in wide use. Guild was largely responsible for making this work the basis of the international system of colorimetry that is still in use today. In collaboration with T. Smith, also of the NPL, he devised the transformation of the experimental results into the International Commission on Illumination (CIE) XYZ system that is the form in which the standard is used.

In spite of having played a key role in establishing the basis and original standard of colorimetry, after 1931 Guild transferred his interests to other areas of work and took little further part in the subject. However, he retained his interest in colorimetry and was instrumental in the formation of the Color Group in the UK where he was the second Chairman of the Group (1943–1945) and one of the first Honorary Members in 1966 [1].

Some of his more important and relevant publications pertaining to this field are listed.

- J. Guild, An equipment for visual spectrophotometry. *Trans. Opt. Soc.,* **26**, 74–94 (1924–1925).
- J. Guild, The transformation of trichromatic mixture data: algebraic methods. *Trans. Opt. Soc.,* **26**, 95–108 (1924–1925).
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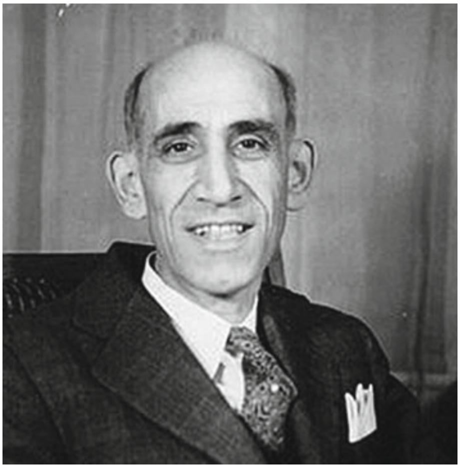
Chapter 65
Godlove, Isaac Hahn 1892–1954



colorantshistory.org

Isaac Hahn Godlove was born on June 13, 1892, in St. Louis, MO to Louis and Lillie Godlove. His father was a photographer working for the J. C. Strauss Studio in St. Louis. I. H. Godlove, one of the four children, studied at Washington University of St. Louis where he received a B.S. degree in 1914 and an M.A. degree a year later. At the University of Illinois, he received a Ph.D. degree in chemistry in 1926. For the next four years, he served as a director of the Munsell Research Laboratory, supervising the production of the color chips for the 1929 Munsell Book of Color. In 1923, Godlove married Esther Alice Hurlbut with whom he had a son, Terry Francis. Between 1932 and 1935, Godlove operated his own color consultant service. In 1935, he joined E. I. du Pont de Nemours in Wilmington, DE

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as a physico-chemist. In 1943, he joined General Aniline and Film Corp. in Easton, PA where he remained until his early passing on August 14, 1954.

One of his hobbies was the history of color in the history of humans. He wrote a book text, "The earliest peoples and their colors," on the subject but died before it got published. It is now available as a digital text on the Web site of the Inter-Society Color Council (www.iscc.org). As his son reported: "His interests were wide, his intellect keen, and he was most generous in sharing his wide knowledge of the physics and chemistry of color with those who sought his help… ." After his death, his second wife, Margaret Noss, established the ISCC Godlove Award in his memory, an award that is considered the highest honor given by the ISCC.

Godlove was on the Board of Trustees of the Munsell Color Foundation from its foundation in 1942 until his death. He was an active member of the Optical Society of America, the American Association of Textile Chemists and Colorists, and the Archeological Society of America. At OSA, he was for an extended period of time a member of its Colorimetry Committee and one of the authors of its report "The Science of Color (1953)." He was an active member of the Inter-Society Color Council for many years and its chairman in 1948–49 [1].

65.1 Munsell Neutral Value Scale

Godlove's initial involvement with color was at the Munsell Research Laboratory where, under the guidance of I. G. Priest at the National Bureau of Standards, efforts were underway to standardize the color samples of the Munsell color atlas and to expand their number so that it could be used as a reliable color reference system. The number of hues in the early versions of the atlas was limited to ten, with the resulting number of color samples being less than 200. In the 1929 enlarged edition, the number of hues was doubled to 20 requiring the generation of many new samples by disk mixture, matching their appearance with painted samples and measuring their reflectance to standardize their production. A related important article Godlove co-authored with A. E. O. Munsell and L. L. Sloan, published in 1933, was "Neutral value scales: Munsell neutral value scale (Fig. 65.1) [2]." This and other efforts eventually resulted ultimately in the cube root version of the CIE L* lightness scale.

The measurement of color stimuli, their specification, and the calculation of small color differences became his specialty in the color field. Another field of interest was fluorescent colors. Many brief articles on various aspects of color he authored can be found in the Inter-Society Color Council Newsletters of the period. Over his lifetime, he authored and co-authored 47 articles on a wide range of color subjects, usually of a practical nature. Three examples of articles published in the Journal of the Optical Society are as follows:

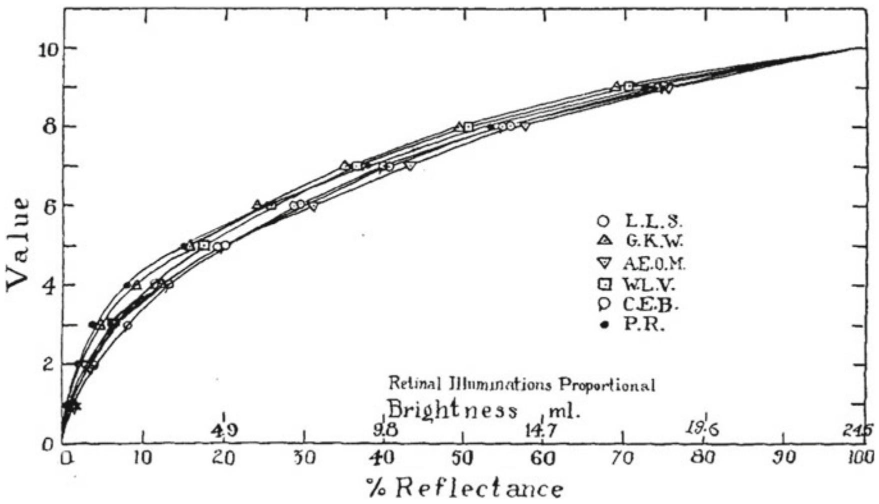

Fig. 65.1 Graph from Ref. [2] showing the results for six observers in experimentally scaling a value scale of gray samples

a. 1934: Comparison of Cobb's and Munsell Research Lab data on neutral value scales and equations describing them.
b. 1938: Some problems and methods of dyestuffs automatic spectrophotometry.
c. 1951: Color change from daylight to night light, calculated and observed.

Godlove was a contributor to the textbook *The science of color*, by the Colorimetry Committee of the Optical Society of America, published originally in 1953.

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Chapter 66
Hardy, Arthur Cobb 1895–1977

Emilio Segrè Visual Archives, Am, Inst. Physics, 2019

Arthur Cobb Hardy was born on July 24, 1895, in Worcester, Massachusetts. He was a physicist best known for his work with spectrometers and color analyzers. He co-authored a classic optics book with Fred H. Perrin entitled *The Principles of Optics*. After WWI Hardy worked at Kodak Research Labs and then transferred to Massachusetts Institute of Technology where he became chair of MIT's physics department, he passed away in 1977.

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https://doi.org/10.1007/978-3-319-30811-1_66

66.1 Hardy Recording Spectrophotometer

Hardy became the president of the Optical Society of America from 1935 to 36 and in 1935 filed a patent for the first recording spectrophotometer, a device for measuring and recording color values [1]. This device could detect two million different variations in object color and generate a record chart of the results. The patent was assigned to the General Electric Company of Schenectady, N. Y., which sold the first machine on May 24, 1935. It used a photoelectric device to receive light alternately from a sample and from a standard for comparison.

Together with Sherwood F. Brown and duVal Radford Goldthwaite, Hardy invented an Organ in 1931, described as a light piano. An account in "Modern Mechanix" in 1931 describes the device in which beams of light and a photoelectric cell produce completely new sounds based on light [3]. The heart of the "light piano" was a glass disk that had concentric sound tracks recorded into the medium photographically (Fig. 66.1). This disk rotated rapidly in front of a photoelectric cell. Light from a small lamp passed through the sound tracks, thereby generating currents in the photoelectric cell that were then amplified and fed into a loud

Fig. 66.1 Light piano, invented by Goldthwaite and Hardy [2]

speaker. The pitch of each note was determined by the number of wavelengths on each sound track.

As chair of MIT's physics department, Hardy created the Visibility Laboratory together with Seibert Duntley in 1939. It was focused on applying optics to such problems as camouflage, misdirection of aerial bombardment, target location, and visibility of submerged objects at sea.

In addition, his contributions include a number of articles in scientific journals including the Journal of the Optical Society of America where he discussed topics such as illuminating and viewing conditions for spectrophotometry and colorimetry, the size of a point source, non-intermittent sensitometers, the optical system of the oscillograph, and similar recording instruments, a recording photoelectric color stimulus analyzer, the errors due to the finite size of holes and sample in integrating spheres, the theory of three color reproduction, history of the design of the recording spectrophotometer, an analysis of the original Munsell color system, colorimetry by abridged spectrophotometry, Beer's law, photoelectric method of preparing printing plates, color correction in color printing, electronic method for solving simultaneous equations, atmospheric limitations on the performance of telescopes, and flux calculations in optical systems, among other topics.

Hardy was awarded the Edward Longstreth Medal in Engineering from the Franklin Institute in 1939 for his invention of recording spectrometer and the Frederic Ives Medal in 1957 for distinguished work in optics [3]. He also founded and directed the MIT Color Measurement Laboratory, which gave rise to a noted book, Handbook of Colorimetry in 1950.

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Chapter 67
Helson, Harry 1898–1977

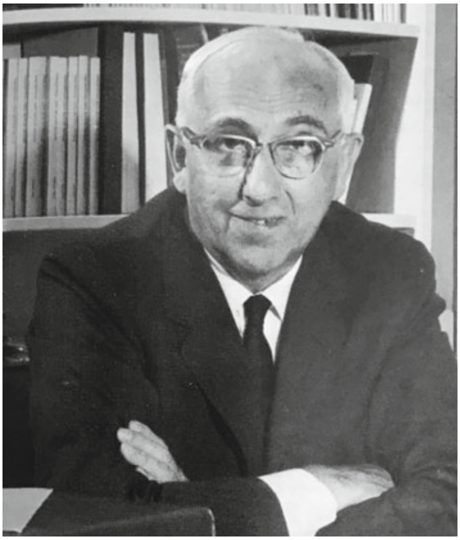

Photo courtsey of Psychology Department of Kansas State University, 1966, KSU Royal Purple Year book, p. 509

Harry Helson was an American psychologist and professor of psychology [1] who is best known for his adaptation-level theory. He was born on November 9, 1898, in Chelsea, Massachusetts in USA and died on October 13, 1977, in Berkeley, USA [1, 2]. His parents were Jewish immigrants from Eastern Europe. They separated and subsequently he lived with his mother until the age of ten. Helson then went to live with his father for a year, after which he left to live with his mother's friends

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until he was an adult [1–3]. He struggled with disciplinary issues in his early years in school.

Helson studied philosophy and psychology at Bowdoin College in Maine where he worked as a reporter for the college's newspaper and played the violin to fund his schooling. He continued his postgraduate studies in philosophy at Harvard University, but by his second year and after being introduced to Gestalt psychology, he decided to change his concentration to psychology. Helson completed his PhD dissertation on a critical review of Gestalt psychology in 1924 [4, 5]. He was married to Lida Anderson and his son, Henry, was also a professor at the University of California, Berkeley.

At the time, most of the original research on Gestalt psychology was in German. The publication of Helson's doctoral dissertation in the American Journal of Psychology in 1925 and 1926 served as an excellent introduction to Gestalt psychology in America.

Helson joined Kansas State University and was a professor from 1961 to 1968. There with his colleagues, he developed his adaptive-level theory of cognition. [6] While working in a photography darkroom illuminated in red, he noticed that the end of his cigarette was green. This resulted in several years of experimentation on the topic and the development of color conversion principles [5].

67.1 The Adaptation-Level Theory and Helson–Judd Effect

Most of Helson's work and research focused on the perception of color. Helson developed the adaptation-level theory of psychology. This theory states that an individual's basis of judgment of a stimulus is based on their prior subjective experiences as well as their recollections of how they perceived similar stimuli in the past and in different situations [5–7]. Helson also noted that stimuli may appear achromatic under monochromatic lighting and based on the mode of viewing and also the background. This finding led him to his recognition of how adaptation levels work in vision [3]. While this adaptation-level theory was initially based on his experiments involving vision, it can be applied to attitudes, sounds, light, and many other concepts.

In 1952 and together with Judd, he presented results of meticulous work on the subject of color constancy. They noted that lighter achromatic surfaces tend to take on the hue of the illuminant under which they are viewed and darker achromatic surfaces take on the complementary hue [8]. This became known as Helson–Judd effect.

He received American Psychology Association award for distinguished scientific contributions to psychology in 1962.

Kansas State University recognizes his contributions to the field through the Harry Helson Award, which is given to a graduate student for their excellence in scholarship and research in cognitive psychology [8].

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Chapter 68
Kubelka, Paul 1900–1956

Photograph from Kubelka Passport Application Documents, Michal Vik

Paul Kubelka was a Czechoslovakian chemical engineer whose many accomplishments include a theory of light absorption and scattering by a layer of paint. Kubelka was born in 1900 to Austrian parents in Czechoslovakia.

He was educated in the German language, attended elementary school in Kladno and secondary school in Brno and Prague. In 1918, he served half a year in the

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Austrian Army and began studies at the Technical University in Prague. In 1922, he passed his final examination as a chemical engineer. He then served seven months in the Czechoslovakian Army, where he soon commanded the military analytical laboratory.

After leaving military service, Kubelka collaborated with Werner Mecklenburg, the well-known colloid chemist, at Verein für Chemische und Metallurgische Produktion, in Aussig, Czechoslovakia. During this period, he worked on activated charcoal, resulting in patents and in the gas mask charcoal "G 1000." One theoretical investigation of this period earned Kubelka a Doctorate of Engineering in 1926. At this time, Kubelka married Margarethe Schönhöfer and they had two children.

In 1928, he led both the Inorganic and Analytic laboratories at his employer company. His laboratory investigated (among other things) high-temperature reactions, the preparation of pigments, and activated charcoal.

In 1931, Kubelka resolved to enter an academic career. Because of his publication on absorption and capillary condensation, he was nominated docent of the University of Prague. There he investigated the absorption of vapors by silica gel, which led to an exact method of measurement of surface tension of crystals. His work interested Fritz Haber and he expected to be nominated as professor at a German University. It was during this year that Kubelka published the famous paper with Munk [1], but he does not mention this in his autobiography.

In 1933, the situation was changed by the Nazi revolution in Germany. Kubelka refused to go to Germany, and had few choices in the rest of Central Europe, so he returned to technological contributions—soon founding the company Kubelka Schuloff & Co., which eventually changed to Dr. P. Kubelka & Co. The company established a research laboratory and later a small factory. Products such as the fungicide Cuprenox were successful. However, World War II disturbed this success and prevented the realization of other inventions. Furthermore, Kubelka was forced to change to German citizenship and then was ostracized by the Nazis. At the end of the war, his German citizenship was nullified, he was promised to regain Czechoslovak citizenship, and he accepted a position as research chemist at the Film Company at Cesky Brod near Prague, branch factory of the Aussig Combine (SPOLCHEMIE). There he worked out a new photomechanical emulsion and reorganized the testing system. Upon deciding to go to America, he was told that the Czech authorities intended to prevent him as a specialist from leaving the country. The only place to emigrate legally was to Germany. Through the date of writing of his autobiography, he then lived in Bavaria with his children, working on the optical theory of light scattering materials and thermodynamics of absorption and capillary condensation. His first wife had passed away during the war and In March 1947, he married Dr. Brigitte Gade.

After immigrating to Brazil in 1950, Paul Kubelka conducted further research to generalize his optical transfer theory to inhomogeneous layers [2, 3]. He passed away on June 23rd, 1954 in Rio de Janeiro, where he was Head of the Research Laboratory at the Brazilian Ministry of Agriculture.

68.1 Kubelka–Munk Theory

This theory, originally published in 1931 with Franz Munk [1], is the basis of much software that performs colorant-recipe prediction (colorant formulation). Whereas the 1931 theory assumed that light flows in one dimension (two fluxes, upward and downward within the layer), and in 1948, Kubelka derived the same equations (up to a factor of 2) assuming spherical scatter within the paint layer [2]. Later, he generalized the theory to inhomogeneous layers [3].

The main contribution of these articles was a closed-form function relating the reflectance R of a layer to two constants characteristic of small particles within the layer: the absorption coefficient K and the scattering coefficient S (both assessed in a unit thickness of the layer). If the layer is opaque, then the reflectance is a function of K/S; otherwise, R depends on K and S separately, as well as on the reflectance of the material behind the layer. The Kubelka–Munk analysis also includes equations for total transmittance of a translucent layer.

Although Kubelka and Munk independently developed their analysis for paint layers, the underlying theory originated with an astronomical motivation, starting with Arthur Schuster's 1905 paper [4] relating to transmission of light through clouds.

To render Kubelka–Munk analysis useful for colorant formulation, one needed the additivity principle described by Duncan in 1940 [5]. This principle says that the total absorption coefficient K of a layer is the concentration-weighted sum of the K-values of the components ($K = c_1 \ K_1 + c_2 \ K_2 + \ldots$) and similarly for S ($S = c_1 \ S_1 + c_2 \ S_2 + \ldots$).

Once the Kubelka–Munk theory, the additivity principle, and computer technology had emerged, colorant formulation was on its way. By 1958, Davidson and Hemmendinger introduced the analog Colorant Mixture Computer (COMIC), and this was quickly followed by dedicated digital devices, which in turn yielded to software packages that ran on general-purpose digital computers. The above discussion places Paul Kubelka's color-science contribution in historical context.

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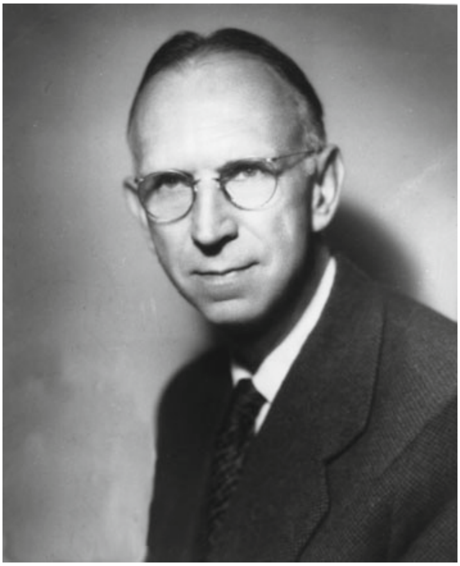
Chapter 69
Judd, Deane B. 1900–1972



Emilio Segrè Visual Archives, Am, Inst. Physics, 2019

Deane Brewster Judd was an American physicist who contributed to the fields of colorimetry, color discrimination, color order, and color vision. Born in South Hadley Falls, Massachusetts on 15 November 1900, he attended Ohio State University and received an A.B. in 1922 and an M.A. in 1923 [1]. He completed his Ph.D. in physics at Cornell University in 1926 with a dissertation on a quantitative investigation of the Purkinje afterimage. Judd demonstrated pioneering efforts in the

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use of psychology in colorimetric studies. He was a Munsell Research Associate in colorimetry at the National Bureau of Standards (NBS) in Washington in 1926.

In 1927, Judd joined the NBS, where he remained until his retirement in 1969 and subsequently continued as a guest worker. He was the USA's representative in colorimetry at eight meetings of the International Commission on Illumination (CIE) from 1931 to 1967 and thereby a key force in the development of the CIE standard system of colorimetry, e.g., 1931 and 1964 standard observers, standard illuminants B and C, daylight illuminants like D65, and definition of colorimetric purity [2]. Largely responsible for coining the term "psychophysics," he wrestled throughout his career with the relationship between color stimuli and color perception.

69.1 Colorimetric System and Color Difference

Judd introduced the concept of keeping luminosity and chromaticness separate in the CIE system. He was active in the colorimetric definition of color temperature and introduced the CIE colorimetric system to US industries. Together with D. L. MacAdam and G. Wyszecki, in 1964, he used principal component analysis to show that natural daylights are largely composed of three components from which daylights at any correlated color temperature can be defined (CIE method of calculating D-illuminants) [3].

In a series of papers in the 1930 s, Judd represented then available color scaling data first into a chromaticity diagram based on color-matching functions introduced by the Optical Society of America in 1922, then represented the resulting diagram in a Maxwell-type primary triangle, and finally embedding unit difference ellipses into the CIE chromaticity diagram. This work became the basis for the CIE u,v color diagram in 1960, slightly modified in the 1976 CIELUV color space. In 1939, he was instrumental in developing the NBS color-difference formula. When in 1947, at the suggestion of the U.S. National Research Council, the Optical Society of America (OSA) undertook to develop a perceptually uniform color space Judd became its chairman and remained in that position until 1968, when D. L. MacAdam assumed the chairmanship, with results published in 1974. One of the key findings was "that strictly uniform color scales of all kinds are not homologous with Euclidean space" to which Judd proposed a solution implemented in the OSA uniform color space [2].

1. *Systematic color names*
   The perceived need for systematic naming of colors resulted in 1939 in ISCC-NBS method of designating colors, based on the Munsell color system, with a revised edition published in 1955 [4, 5].

2. *Color constancy*

   Judd in 1940 and together with Helson and Warren in 1952 presented results of meticulous work on the subject of color constancy [6, 7].

3. *Miscellaneous*

   At NBS, Judd investigated impaired color vision, whiteness measurement of paper, opacity, and color stimulus measurement and developed a flattery index for artificial light sources. In 1951, he proposed a modification of the CIE 1924 luminous efficiency function $V(\lambda)$ below 460 nm that became known as Judd-modified $V(\lambda)$, not implemented in the CIE system but used in some vision research work [8]. In addition to his positions at the CIE, Judd was president of the Optical Society of America from 1953 to 1955 and of the Inter-Society Color Council from 1940 to 1944. He was president of the Board of Trustees of the Munsell Color Foundation from 1942 to 1972.

   In his homage, the International Color Association, AIC, instituted its Judd Award, a prize that since 1975 is bestowed every two years to persons who have made important contributions in color research.

   Judd was the author of one book [9] and more than 200 articles, 57 of which were reprinted as a volume by the NBS [2].

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Chapter 70
Nickerson, Dorothy 1900–1985

Dorothy Nickerson measuring the color of textile samples at the National Bureau of Standards, ca 1930, US Government

Dorothy Nickerson (August 5, 1900–April 25, 1985) was an American color scientist and technologist who made important contributions in the fields of color quality control, technical use of colorimetry, the relationship between color stimuli and color perceptions, standardization of light sources, color tolerance specification, and others. Nickerson was born and raised in Boston, attended Boston University in 1919 and Johns Hopkins University in 1923. Later, she continued her education at summer courses and university extensions at Harvard University, George

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https://doi.org/10.1007/978-3-319-30811-1_70

Washington University and the Graduate School of the U. S. Department of Agriculture. Her special interest was the science of color, then in significant development.

In 1921, Nickerson joined the Munsell Color Company as a laboratory assistant and secretary to A.E.O. Munsell who in 1918 had taken over the firm from his father. In 1922, the firm moved to New York and in 1923 to Baltimore. In 1927, she was offered a position at the US Department of Agriculture where she remained until her retirement in 1964. When she joined, color science and technology were without international standards and at the beginning of industrial use. Nickerson was instrumental in developing the technology and its use in agricultural and industrial settings.

Nickerson became the first individual member of the Inter-Society Color Council, founded in 1931. She was a lifelong member, received the Godlove Award, and had an award named after herself. She was a member of the US National Committee to the CIE and the International Association on Color where she received the first D.B. Judd AIC Award in 1975. Nickerson was a trustee of the Munsell Color Foundation since 1942, was its president from 1973 to 1975, and assisted in the transfer of the foundation to the Rochester Institute of Technology in 1983 where it helped fund the then new Munsell Color Science Laboratory. Nickerson was the author and co-author of some 150 papers and publications [1].

70.1 Color Quality Control of Agricultural Products

In the late 1920s, Nickerson worked on usage of disk color mixture to define the color quality of cotton and other agricultural products and the conversion of disk mixture data into the CIE colorimetric system [2].

1. *Standardization of light sources for color assessment and color rendering*
   In the later 1930s, a major occupation of her was the development of defined light sources for visual assessment of color quality. Later, she was also active in the development and promotion of standard methods for the definition of color rendering of lights [3].
2. *Munsell color system and its colorimetric definition*
   In 1940, a technical committee of the Optical Society of America began a study of the Munsell color system, improvements and extensions of the system and its definition in the CIE colorimetric system. Nickerson was an important participant in this effort. The final report of the committee was authored by S.M. Newhall, D. Nickerson, and D.B. Judd and its results are known as the Munsell Renotations [4], the specification of the aim colors of the current system [5]. Nickerson prepared plots of the Munsell color stimuli in the CIE chromaticity diagram that remain in publication today [4]. She also wrote an extended history of the Munsell system [6, 7].

3. *Color tolerance specification*
   In 1936, Nickerson published the first color-difference formula for industrial use, based on the addition of increments of Munsell hue, chroma, and lightness scale values. In 1943, together with Newhall, she published realistic representations of a three-dimensional perceptually approximately uniform optimal object color solid. In 1944, together with her assistant K. F. Stultz, she published a colorimetric color-difference formula, known as the Adams–Nickerson–Stultz formula, that in modified form eventually became the CIE L*a*b* color space and difference formula [8, 9].
4. *Color charts*
   In the mid-1940s, Nickerson was active in methods for assessing the color of soils, an effort that found its expression in the Munsell Soil Color Chart, still in use today. In 1957, Munsell issued the Nickerson Color Fan, a color fan for horticultural purposes (262 color samples in 40 hues, no longer produced). Working with D.B. Judd, the chair of the OSA committee that developed the OSA uniform color space, Nickerson, as a member of the committee, was also a contributor to that effort for over 25 years and wrote a detailed history of the development of the system [10].

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Chapter 71
Birren, Faber B. 1900–1988

http://sewsitall.blogspot.com/2016/08/who-was-faber-birren.html

Faber Bernard Birren was an American author, historian and consultant on color theory [1]. He was born in Chicago, Illinois, on September 11, 1900, to artistic parents, Joseph P. Birren, a successful landscape painter and a native of Luxembourg, and Crescentia (Lang) Birren, who was a skilled pianist and had two siblings. He is credited as the originator of the Occupational Safety and Health Administration (OSHA) colors. He consulted for the private, public, and governmental sectors and has also been credited as having established the profession of color consultants in 1936. Birren married Wanda LaVerne Martin who was

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supportive of her husband's endeavors, and they had two daughters, Zoe and Fay. Birren was not an institutional academic, however, together with his wife he conducted a significant amount of research on the subject of color, and organized and made it accessible to a wide public. Faber Birren died on December 30, 1988, in Stamford, CT, USA.

Birren attended the Art Institute of Chicago while in high school and then studied color theory at the University of Chicago, planning to emulate his father [2]. Having conceded that he fell short on artistic talent, he left the University after two years but did not lose the interest in color that he had developed while studying the subject under Walter Sargent. He began working for a local bookseller and publisher in 1921 at the printing and graphics end and started to collect books on color and to write on the subject. In 1929, he set up a shop in his native Chicago. When the Depression came, he moved to Manhattan, 500 Fifth Avenue where his office kept sales records on color trends in paints, wallpapers, textiles, plastics, home furnishings, etc., and his business flourished and became an industrial color consultant [1]. Businesses desperate to stay alive were willing to apply the art and science of color trade. This was the period in which The Saturday Evening Post covers, formerly black and red, went polychromatic and Technicolor was born. He provided consultancy to various businesses on the use of color. He was interested in all aspects of color including color theory, masterworks by the most noted color theorists, human perception and experience of color, ancient philosophical views on color, religious connotations of color, applications in art, and the latest scientific discoveries pertaining to color. He collected over 600 books on the subject.

In 1971, he established a depository at Yale University's Art and Architecture Library together with an endowment for books on color. The "Faber Birren Collection" has grown from his initial donation of 177 books into one of the most comprehensive collection of its kind in the world, with over 2000 items.

71.1 OSHA Colors

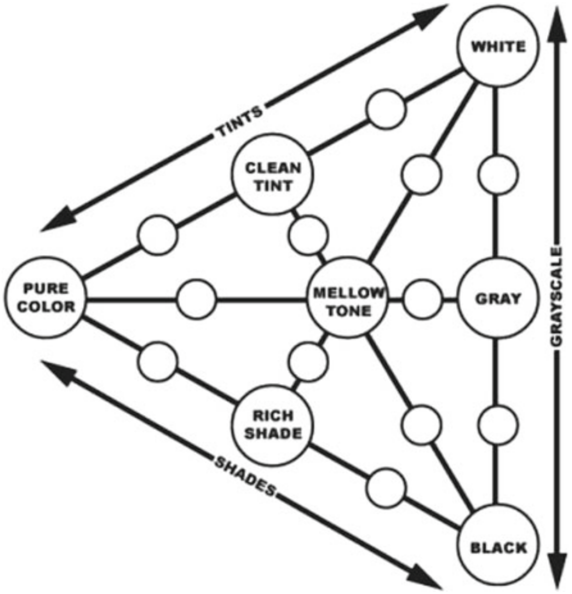
Birren was a prolific author and published several books on color including *Principles of Color*, *Color Perception in Art*, and *Creative Color*. By the time of his death, he had written some 250 articles and 28 books [2 revised editions, and 3 Colorizer color charts]. These works are widely used for color education in art in the United States and abroad. Additionally, he resurrected and republished the largely forgotten works (sometimes at his own expense) of Jakob Le Blon (1725), Moses Harris (c. 1769), Michel-Eugène Chevreul (1854), Thomas Sully (1873), Edwin Babbitt (1878), Ogden Rood (1879), Albert Munsell (1921), and Wilhelm Ostwald and Johannes Itten. He also contributed to Lanier Graham's The Rainbow Book (1975). He began publishing articles on color in 1924; his first book *Color in*

Vision was published in 1928 [2]. In 1934, he established his own company and worked as an industrial color consultant, advising clients on the psychological effects of color on safety, employee morale, productivity, and sales [3]. *The Story of Color, from Ancient Mysticism to Modern Science* (1941, revised 1963) was a brave and pioneering attempt to piece together, in chronological order, many centuries of humans applying color in myths, arts, therapy and sciences into an inexpensive and readable text [4]. Birren's *History of Color in Painting* (1965, a large-format book of 370 pages), is another pioneering attempt to chronologically link together the principal milestones in the evolution of color in the fine arts [5].

Birren was interested in the relationship between color, perception, and emotions and had strong opinions on the matter. In one of his books, *Color Psychology and Color Therapy* [6], he noted that, compared to emotionally responsive individuals, introverts are affected less by colors and concluded that human perception of color, and not the colors themselves, influences human feelings, thoughts, and emotions. In another book, entitled *Color and Human Response* [7], Birren discussed the historical influence of color on human life. He noted that while color had many symbolic religious and societal uses in ancient times, its psychological importance persisted in the modern times in homes, offices, schools, and even hospitals. He then made recommendations for certain colors to be used in different spaces in order to achieve the appropriate desired effect. His recommendations included the functional use of color, especially in hospitals and schools such as changing wall and interior colors to reduce visual fatigue, and using bright colors on machinery to reduce accidents [3]. Birren was a firm believer in the therapeutic effect of bright colors on the mentally troubled and thought they distract attention from the self. He noted that violent criminals can be calmed, at least temporarily, by confinement in rooms painted cerise, but said there are hues to be avoided such as yellow-green since it has connotations of sickness. However, he also noted that chromatic taste is personal and highly subjective [8].

His color theory postulates that warm tones are more preferable by both artists and viewers. Birren felt that artworks that include tints, tones, and shades (e.g., Leonardo da Vinci's works) instead of pure colors only were more harmonious and thus pleasing to the eye. The relationship between these attributes is shown in Fig. 71.1. He coined the phrase "perceptionism" to describe the effect of environmental conditions on human perception of color. In *Creative Color* [9]. Birren details how the perception of luster, iridescence, and luminosity can be created with careful combinations of color. He also includes discussions of chromatic light, chromatic mist, and luminosity in mist. He showed, with examples, that skilled artists can present a work that leads the viewer to perceive transparency, solidity, highlights, shadows, and texture. Birren also discussed the association between senses, such as sight and taste, known as synesthesia in another book, *Creative Color: An Approach for Artists and Designers* [10]. Birren's theories are still studied by those interested in color, especially architects, artists, and designers.

Fig. 71.1 Tints, tones, and shades of colors



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Chapter 72
Rushton, William A.H. 1901–1980

moviespictures.org

William Albert Hugh Rushton was a British neurophysiologist who made important contributions to our understanding of color vision and perception. He is perhaps best known now for his development of the principle of univariance.

Rushton was born in London on December 12, 1901. He entered Cambridge University as a medical student in 1921 and obtained a degree in physiology in 1925. He received a Ph.D. degree in 1928 working under Prof. E.D. Adrian for his

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research investigating the flow of current in and around nerves to determine the portion of the current responsible for excitation. As a result of this work, he won the Stokes Studentship at Pembroke College in 1929. He spent two years at the Johnson Foundation in Philadelphia before returning to a Research Fellowship at Cambridge University. He went to University College Hospital in 1931 to study clinical medicine before obtaining a lectureship at Cambridge University in 1935 after which he produced a prodigious body of work; he published 37 papers on nerves with four colleagues over 25 years and 147 papers on vision with 27 colleagues over a period of 30 years. Upon retirement, he spent some time at Florida State University as a Distinguished Research Professor. He was awarded the Royal Medal of the Royal Society in 1970 and continued to publish articles until he died in 1980. He passed away on June 21, 1980, in Cambridge, England, and is buried at the Trinity College Chapel.

72.1 Nervous Excitation and Principle of Univariance

Rushton laid the groundwork for the establishment of the modern theory of nervous excitation and propagation by his quantitative analysis of the temporal and spatial factors involved in electrical excitation [1, 2].

He developed techniques to measure the visual receptors in vivo and made important contributions regarding the distribution of receptors in the retina, the action spectrum of bleaching, and the spectral characteristics of bleaching [3–5].

By 1955, Rushton had evidence of visual receptors at the fovea in normal and color-blind subjects. He obtained evidence of two receptors in the medium-long wavelength spectrum in color normals and demonstrated that protanopes and deuteranopes were each lacking one of these [6, 7].

In the early 1960s, Rushton developed an analytic anomaloscope to study color vision. Using this instrument, observers would match a pure spectral light with an additive mixture of red and green in variable proportions [8].

Rushton published two papers in *Scientific American* and gave several notable didactic lectures. In a review lecture at the Physiological Society (London), he described the principle of univariance that “the output of a receptor depends upon its quantum catch but not upon which quanta are caught.” Many of the laws of color mixing are a direct consequence of this principle. He also reintroduced the cone-forming color triangle, first put forward by Maxwell, as an alternative to the usual representation of color space developed by the CIE [9].

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Chapter 73
Stiles, Walter Stanley 1901–1985

M. Alpern [1]

Walter Stanley Stiles, OBE, FRS, was a physicist and mathematician who made significant contributions to the field of colorimetry and visual science. He was born on June 15, 1901, in London to Elizabeth Catherine and Walter Stiles, and due to the abundance of this family forename, W. S. Stiles was known as "Stanley" throughout his life to family and friends. His mother died in 1919 from a ruptured appendix at the age of 42, and his father retired from the Metropolitan Police in

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1920 as a Superintendent at the age of 54 [1]. Stanley Stiles died on December 15, 1985, at his home in Richmond, Surrey.

Stiles attended Burlington (Preparatory) School and St. George's Higher Grade School. In 1912, he entered the Polytechnic Day School, London, as a student of the Technical Secondary School. In 1918, he won an Andrews Entrance Scholarship (Science) to University College, London and started as a Chemistry student but after one year switched to physics under the influence of Professor Porter. He left University College in 1922 and contemplated whether to continue his higher education in mathematics, medicine, or physics. He decided to study mathematics at St. John's College, Cambridge. Due to poor health and financial problems, after three terms and having completed no postgraduate research, Stiles left Cambridge and became lecturer in physics and mathematics in the Municipal College, Portsmouth, in the spring of 1923. After a year, he joined the Royal Naval Signal School in Portsmouth as a Junior Scientific Officer. There he developed a sensitive audio-frequency amplifier for electrode signaling. In 1925, he transferred to the National Physical Laboratory (N.P.L.) of Great Britain in Teddington, where he remained until retiring in June of 1961. In his first year, he worked on thermionic emission and on general photometric problems.

Stiles was created OBE (Officer of the British Empire) in 1946 for his wartime work on visibility, visual search, and the defensive use of dazzle. He was elected to the (British) Royal Society in 1957 and was awarded the Tillyer Medal of the Optical Society of America in 1965. He served as General Secretary of the Commission Internationale de l'Éclairage from l928 to 1931, was Chairman of the Color Group of Great Britain from 1949 to 1951, and was President of the (British) Illuminating Engineering Society from 1960 to l961.

73.1 Stiles–Burch Observer

Stiles' earlier work with B. H. Crawford introduced the concept of veiling glare, a subject of particular importance in street lighting and other applications of illuminating engineering. His name is perhaps best known in the Stiles–Crawford effect, the reduction in sensitivity of the retina as the angle of incidence of the light becomes increasingly different from normal.

In the late 1950s, he spent much time and effort in constructing a visual colorimeter for redetermining the color-matching functions of the average observer. This work, involving measurements on over 50 observers, provided the major basis for what became the CIE 1964 supplementary standard colorimetric observer for field sizes of 10°. The study also included experiments with a two° fields which confirmed the validity of the CIE 1931 standard colorimetric observer, apart from the well-known deficiency in sensitivity at the short-wavelength end of the spectrum. This work also addressed the phenomenon of rod intrusion: the fact that in fields of 10º size, some input from the rods can be added to that of the cones.

Much of his later work was devoted to the study of increment thresholds: the magnitude of the just noticeable amount of a stimulus of one wavelength when superimposed on a uniform field of another wavelength. From these studies, he identified a series of basic visual mechanisms, which he identified as π mechanisms, the significance of which has been a matter for considerable discussion.

Toward the end of his life, he collaborated with Gunter Wyszecki in the writing of *Color Science*, *concepts and methods, quantitative data and formulas,* published by Wiley in 1967, with a second edition in 1982. This work still provides an enormous amount of useful data and information on color science.

He was dedicated to traditional psychophysical experimental methods, regarding it as very necessary to avoid arguments founded on introspective descriptions of sensations, which he regarded as notoriously difficult to interpret correctly. He therefore had no contact with the area of magnitude estimation pioneered by S. S. Stevens and further developed subsequently by other workers in color science.

Stanley Stiles was interested in languages and learned Hebrew, Danish, Italian, German, and French. As a lecturer, he was clear and authoritative with a commanding demeanor. As a man of great intellect and prodigious experience in color science, he was always willing to help others in the field who approached him for help. His interests included mathematics, reading, and painting. The following short list includes some of Stiles' publications.

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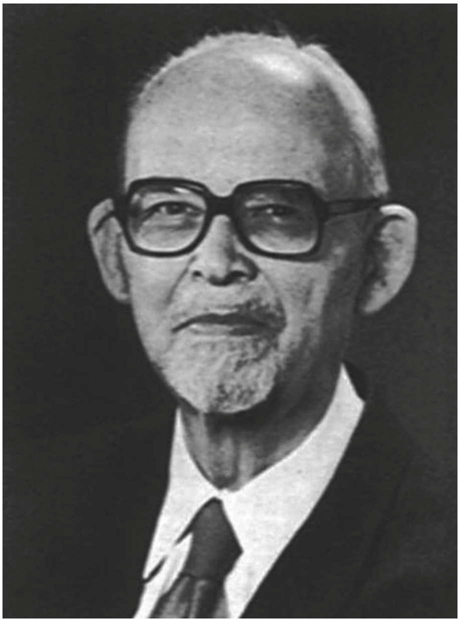
Chapter 74

Richter, Manfred 1905–1990



Source Manfred Richter

Richter was born on August 7, 1905, in Dresden, Germany, where he studied technical physics under Robert Luther at the Technical University from 1924 to 1933. The subject of his doctoral dissertation was Goethe's *Farbenlehre* as related to scientific problems [1]. In 1927, as an assistant in the department of color research of the German Institute of Textile Research and following Helmholtz's assistant Arthur König, he developed an international bibliography of publications

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in color science, an effort he continued until the mid-1950s [2]. In 1934, he began work in the laboratories of the lamp manufacturer OSRAM in Berlin. In 1943, he transitioned to the Materialprüfungsanstalt (Office for testing of materials, later named Bundesanstalt für Materialprüfung (BAM), where he remained until 1962 and where he organized a color research laboratory. In 1941, he was asked by Deutsches Institut für Normung (DIN, German institute for industrial standards) to develop a standard color system and atlas, an effort that kept him occupied for an extended period. It is known today as DIN6164. He was also a professor at the Institut für Lichttechnik (Institute for lighting technology) of the Berlin Technical University. In 1949, he was a founding member of the Fachnormenausschuss Farbe (FNF, Color standards committee) [3]. He was a leading member of Deutsche farbwissenschaftliche Gesellschaft (DfwG, German society for color science, founded in 1974) and a leading force for the journal *Die Farbe* (1951–2003). He was a member of the directorial board of the International Association of Colour (AIC) and active in several research committees of the International Commission on Illumination (CIE). His passing on April 20, 1990 was the result of a traffic accident.

74.1 Din6164

Richter's plan for a standard color system and atlas was that it needed to be based on well-supported colorimetric data, thereby not limited to colorants involved. A starting point was Ostwald's color atlas and the Luther–Nyberg color solid. The system was to be perceptually uniform. As perceptual parameters, he selected hue (T), saturation (S), and degree of darkness (D). Lacking a satisfactory colorimetric model of hue scaling he proceeded to experimentally determine a constant saturation contour in the CIE chromaticity diagram separated into 24 perceptually equal hue differences. He then scaled saturation from the neutral point to the spectral limit into up to 16 levels. The darkness scale D is based on logarithmic scaling of the relative brightness value scale proposed in 1928 by S. Rösch. It has a value of 0 for white and 10 for black. A schematic cross section of the system is shown in Fig. 74.1.

Atlases were published in 1960/1962 with matte samples and 1978/1983 with glossy samples. Figure 74.2 shows a 3D model of the system. As its name indicates, DIN6164 is a German industrial standard system.

In 1940, Richter published a book on color science, with the cooperation of I. Schmidt and A. Dresler, that presented the subject in at that time likely the most comprehensive and detailed fashion [2]. Given the Second World War, it was never translated into English. In 1976, he published *Einführung in die Farbmetrik* (Introduction to color metrics) [5].

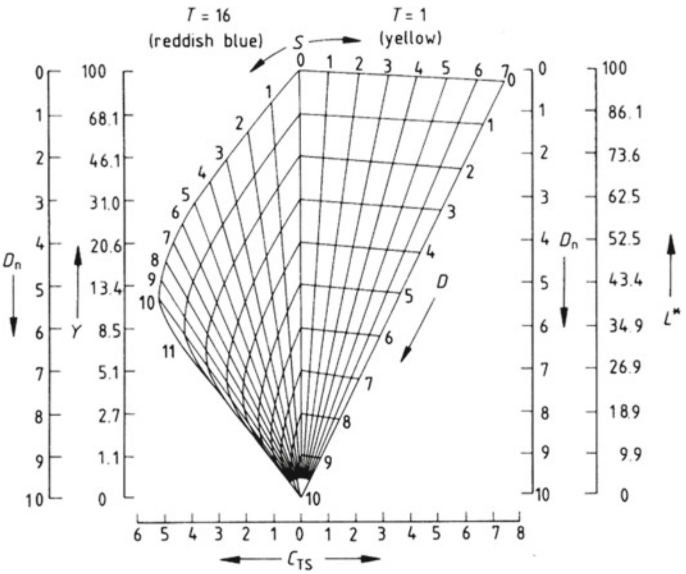

Fig. 74.1 (Left) Schematic representation of the samples of hues T1 and T16 in the S, D diagram [4]

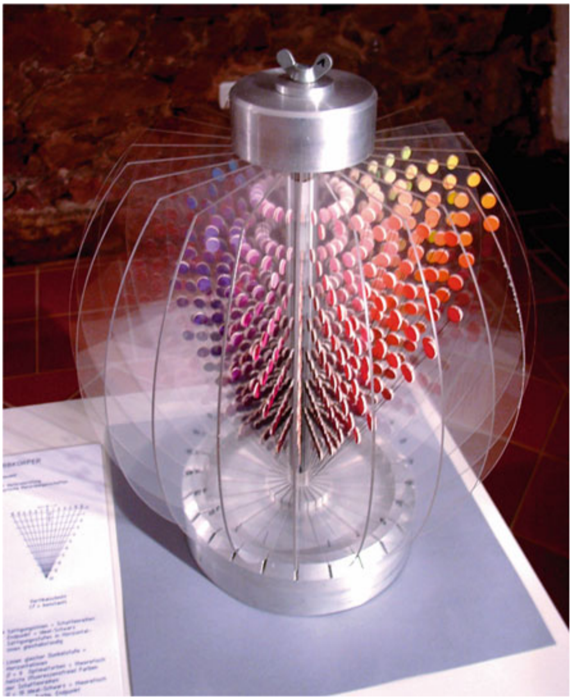

Fig. 74.2 (Right) 3D representation of the samples of the DIN6164 system [4]

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Chapter 75
Stevens, Stanley Smith 1906–1973

thefamouspeople.com

Stanley Smith Stevens was an American experimental psychologist perhaps best known in the world of color science for introducing the psychophysical power law and for collecting data on brightness perception as a function of adaptation. He was even more well known in the general field of experimental psychology and

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psychophysics for many accomplishments in acoustical psychophysics, his important publications, and founding of the Psycho-Acoustic Laboratory at Harvard University.

Among Stevens' written contributions to the field are the extensive, and immensely praised, *Handbook of Experimental Psychology* [1], that provides much information remaining useful more than half a century later and the book *Psychophysics* [2], that was published posthumously after final editing by his wife. It, too, remains a useful reference on the subject. Among the topics described is the hierarchy of mathematical scales (nominal, ordinal, interval, and ratio) in psychophysics, something else developed by Stevens.

Stevens was an undergraduate student at the University of Utah and then transferred to Stanford University where he completed his degree in an undetermined field since the variety of courses he took was so extensive. He then was accepted at the Harvard Medical School, but chose to enroll in Harvard's School of Education to avoid the medical school's $50 fee and organic chemistry requirement and still have access to Harvard's resources. At Harvard, he was transformed by a course on perception taught by E. G. Boring, became Boring's unpaid research assistant, and earned a Ph.D. in Philosophy by the end of his second year there. After some more studies in physiology and physics, he was appointed an instructor in the Psychology Department, where he remained until his death. In 1962, Harvard University agreed to appoint Stevens as a professor of Psychophysics in honor of the field founded by G. T. Fechner.

One of Stevens' most notable papers was titled "To honor Fechner and repeal his law," published in Science in 1961 [3]. In it, Stevens summarized psychophysical scaling data for a variety of perceptual stimuli (e.g., brightness of light, loudness of sound, hotness of heat, pain of electric shock) and illustrated that they all could not possibly follow the logarithmic relationship between stimulus and perception predicted by Fechner's Law. Instead, all of his data could be well described by power functions with various exponents, which depend on the type of perception being scaled. This new relationship is known as the psychophysical power law or Stevens' power law. One technique used to establish the power law that Stevens developed is known as cross-modal matching. In these experiments, observers match perceived magnitude of one stimulus (e.g., brightness of light) with another (e.g., loudness of sound).

75.1 Stevens Effect

Stevens' work on brightness is well known in color science and led to the description of a color appearance phenomenon as the Stevens Effect. This work, published in 1963 by Stevens (no relation) and Stevens, examined the effects of light and dark adaptation on the perception of brightness [4]. Scales of brightness were obtained using magnitude estimations (Steven's hallmark) and showed that the contrast of brightnesses increases with increasing adapting luminance (exponent in the power increases). Therefore, as Stevens showed, when the level of lighting increases, dark colors look darker and light colors lighter.

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Chapter 76
Crawford, Brian Hewson 1906–1991

Image from Brian Crawford obituary, written by D. A. Palmer, published in the newsletter of The Colour Group (Great Britain), Volume 17, Number 1, February 1992

Brian Hewson Crawford was a British physicist who made important contributions to the science of vision, colorimetry, lighting, and color rendering. He was born on March 26, 1906, in Hornsey, London, to Andrew Crawford and Marian Hewson (Fairweather) Crawford. He was married to Margarethe Bettina “Marga” Nagel, who was a native German from Darmstadt. He died on May 5, 1991, in London, England.

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https://doi.org/10.1007/978-3-319-30811-1_76

Crawford went to University College London, graduating with first-class honors in physics at the age of 19. After a brief spell at the Rodenside Laboratory of the photographic company, Ilford, he joined the staff of the National Physical Laboratory (NPL) in 1927.

He continued to work in the conservation department of the National Gallery long after officially retiring from NPL. He also made investigations on color in the laboratories of the University of Edinburgh, the Paint Research Association, Imperial College, and the Institute of Ophthalmology. He went on publishing original papers until the age of 79, thus refuting the idea that scientific research is only for young people.

Crawford's interests were very wide and included languages, painting, and music. His attitude to life was well illustrated by his remark after breaking his wrist in a fall from a bicycle that it had reset at a more convenient angle for playing the viola. While not one to hanker after honors, he was proud of his Doctorate of Science from the University of London and his Newton Medal from the Colour Group (Great Britain), of which he was a past Chairman and Honorary Member.

76.1 Crawford–Stiles Effect and Other Contributions

Joining the NPL in 1927 resulted in a most fruitful association with Walter Stanley Stiles, under the beneficent aegis of John Walsh. A brilliant series of papers followed in the *Proceedings of the Royal Society,* on such new topics as equivalent backgrounds, increment thresholds, and above all, in 1933, the directional sensitivity of the retina to light and color. These *Stiles–Crawford effects* [1] comprise the reduction of brightness (the first kind) and the change of hue and saturation (the second kind) of stimuli entering the periphery of the iris compared to stimuli entering the center of the iris. These effects were discovered during attempts to build a visual photometer based on pupillometry. The then "usual assumption that the apparent brightness of an object is proportional to the pupil area" was soon demolished.

Such serendipity was characteristic of both scientists, but important discoveries fall only to those who deserve them. Crawford would say that you only had to search about in any field and you were bound to find out something interesting. No doubt, this was so in his case. His 1947 *Proc. Roy. Soc.* paper on "Visual Adaptation in Relation to Brief Conditioning Stimuli" [2] is not obviously inspired by temporary blinding effects of gunfire flashes during the Second World War, but that was how "Crawford Masking" was discovered. This is the effect whereby a bright stimulus can be perceived prior to a later less bright stimulus.

It is interesting to compare and contrast the large-field colorimeters, which Stiles and Crawford had each constructed in adjacent laboratories. Stiles' machine was workshop-built to the highest NPL precision and endowed with such facilities as a meteorology station of hygrometers, barometers, and thermometers, to monitor changes in the refractive index of the air. Crawford's apparatus belonged to the string and sealing wax tradition, with corks for nonslip knobs and strips of graph paper for scales. Both instruments served their respective purposes admirably.

Perhaps, one explanation of the successful early partnership and later divergence was a creative tension between opposite natures. To draw an analogy from art, Stiles' science was classic; like Nicolas Poussin, he had neglected nothing. Crawford was romantic; he was fond of quoting Maxwell's dictum that it is always worth playing a trombone to a petunia at least once, you never know what might happen. But Crawford could work to the highest NPL precision and accuracy when required, as he did in determining the average scotopic spectral response of the human eye, by recording scotopic brightness matching; this led to the international standard for spectral luminous efficiency for scotopic vision (the $V'(\lambda)$ function), which forms the basis of the present CIE definition. Not least was the difficulty of eliminating the effects of minute amounts of stray light and simultaneously discrediting data produced by several investigators who had not been so careful.

He also showed that color-matching functions made when matching monochromatic stimuli were different from those made when matching white stimuli. An explanation of this phenomenon is still awaited.

Crawford's last years at NPL were occupied with a study of the color rendering properties of artificial light sources, and he made a great breakthrough in convincing suspicious experts in art galleries and hospitals that certain fluorescent lamps were suitable for their exacting requirements. Typical of Crawford was his finding that combinations of tungsten filament lamps and "Radar Blue" fluorescent lamps could imitate almost perfectly any phase of natural daylight. The resultant equipment was essential in providing a transportable reference illuminant for the darker corners of the Victoria and Albert Museum and the Sheffield Royal Infirmary.

With the kind permission of the Colour Group (Great Britain), this account is based largely on the obituary written by Dr. D. A. Palmer and published in its newsletter, Volume 17, Number 1, February 1992.

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Chapter 77
Wright, W. David 1906–1997

Image courtesy of R. W. G. Hunt

W. David Wright was a British physicist and color scientist who made very important contributions to colorimetry and visual science. In fact, he is generally regarded as one of the fathers of colorimetry as it is practiced today. David Wright was born on July 6, 1906, in England and died on June 4, 1997, in England [1].

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Wright graduated at Imperial College, London University in 1926. He was a Medical Research Council student at Imperial College from 1926 to 1929, and in this period, the spectral color-matching properties of ten observers were measured. He received his Ph.D. in 1929 and a D.Sc. in 1937.

He was a Research Engineer at Westinghouse Electric and Manufacturing Co., Pittsburgh, USA, 1929–30, where he undertook early research on color television, long before even black-and-white television was a practicality. The color television system in use today uses Wright's work as the basis for the reproduction of color. On his return to England, at Imperial College, he became a Lecturer and Reader in Technical Optics, 1930–1951, and Professor of Applied Optics, 1951–73. He was a Research and Consultant Physicist to Electrical and Musical Industries, 1930–1939. He became Kern Professor of Communications at the Rochester Institute of Technology, USA, from 1984 to 1985.

77.1 Color-Matching Functions

W. David Wright had a number of interests, which included optics, vision, photometry, colorimetry, color perception, color applications, and color paintings. He supervised a succession of research students in color science, many of whom subsequently held senior positions in academia and industry.

Wright's most important research work was the measurement, for ten observers, of the way in which the colors of the spectrum are matched by beams of red, green, and blue light added together. This work, together with a similar study carried out by John Guild (at the National Physical Laboratory at Teddington, England, with seven additional observers), forms the basis of the international standard for measuring color established by the Commission International de l'Éclairage (CIE). The quality of this experimental work was so high that the standard, although now more than eighty years old, is still in universal use.

Wright's work on color was the result of funding that was made available by the Medical Research Council to Imperial College for studies pertaining to color in 1926. Prior work on color at Imperial College had been done by Sir William Abney and Wright initially used the same laboratory that Abney had used in 1877. Abney's influence is also evident in the concept behind Wright's colorimeter, which used prisms to generate the color-matching primaries.

Wright's researches also led, for the first time, to definitive descriptions of the main types of color deficiency (color blindness). His book *Researches on Normal and Defective Colour Vision*, published in 1946, summarizes the results of his research on color vision. He also wrote the book *The Measurement of Colour*, the four editions of which provided a widely used practical guide to colorimetry from 1944 to the present time. His leisure interests included an appreciation of paintings, as well as religious service and church activities. Wright's books and key publications include as follows:

- The Perception of Light, Blackie, 1938
- Researches on Normal and Defective Colour Vision, Kimpton, 1946
- The Measurement of Colour, Hilger, 1944 (2nd ed. 1958, 3rd ed. 1964, 4th ed. 1969)
- Photometry and the Eye, Hatton, 1950
- The Rays are not Coloured, Hilger, 1967

He also authored about 80 original papers, mainly dealing with color and vision. Wright received numerous awards and was a member of several professional bodies, which included:

- The Physical Society Thomas Young Oration, 1951
- Honorary D.Sc. City University, 1971
- The AIC (International Colour Association) Judd Award, 1977
- Honorary D.Sc. University of Waterloo, Canada, 1991

He also provided public and professional service, which included as follows:

Founder of The Physical Society Colour Group, 1941
Chairman, The Physical Society, Colour Group, 1941–43
Vice President, The Physical Society, 1948–50
Secretary, International Commission for Optics, 1953–66
Chairman, The Physical Society Optical Group, 1956–59
President, International Colour Association (AIC), 1967–69
Chairman, The Colour Group (Great Britain), 1973–75

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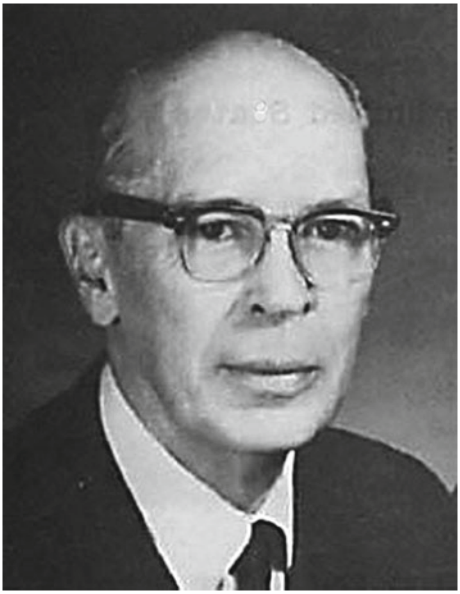
Chapter 78
Evans, Ralph Merrill 1908–1974



ISCC.org

Ralph Merrill Evans was born in 1908 in Massachusetts. After schooling at the Phillips Academy in Andover, MA, he attended Massachusetts Institute of Technology from which he graduated in 1928 with a B.S. degree in optics and photography. He worked briefly for Kodak Corporation, moving on to Twentieth Century Fox Film Corporation in New York in 1929 where he worked in research and quality control until 1933. He returned to Kodak where he became supervisor in the color process development department. In 1945, he was named superintendent

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of the color control department and in 1953 director of the Color Technology Division. Some years later, a reorganization at Kodak resulted in Evans being placed in charge of the Photographic Technology Division, a position he occupied until his retirement in 1970. Evans died on Jan 29, 1974 [1].

Evans was convinced that better understanding of color perception would result in improved color photography and printing, and he proposed the hiring by Kodak of young researchers with new ideas about color to do color perception research. Among these were Dorothea Jameson and Leo Hurvich who did research work at Kodak from 1947 to 1957.

Evans published some fifty scientific and technical articles on color and photography, and he is the inventor or coinventor in 17 patents. He was an active member of several color- and photography-related societies, including the Inter-Society Color Council where he was given the Godlove Award in 1959 [2]. He was well-known for his presentations at conferences that always included cleverly prepared slides to illustrate key points. Evans also authored and co-authored four books related to the subject of color. His 1948 book *An introduction to color* was considered a path-breaking text on color perception at the time, describing many color perception phenomena and illustrating them with color plates. It covers also some issues related to color photography and the effect of different light sources on the outcome in the photographic image. Two of his books specifically covered the subject of color photography: *Principles of color photography* (1953) and *Eye, film and camera in color photography* (1959). His final book *The perception of color* was published posthumously in 1974 with the help of his colleague and co-researcher Bonnie K. Swenholt. It is an updated and more specialized text on color perception that addresses the effect of surrounds of different kinds on the appearance of an object in detail [3].

78.1 The G_0 Function

In his later years, Evans became more and more interested in the appearance of color stimuli under specific conditions, such as unrelated and related, and in the latter case the relationship between the luminance of the surround stimulus and that of the central test stimulus. Based on experiments, he concluded that against a white surround of a certain luminance, colored test stimuli have a grayish appearance that diminishes steadily as its luminance increases up to a point where the apparent grayness disappears. With further increasing luminance of the test stimulus begins to have a fluorescent (or fluorent) appearance against the surround that increases as the luminance increases. Evans found the zero-grayness point to vary across the spectrum as a function of dominant wavelength (Fig. 78.1).

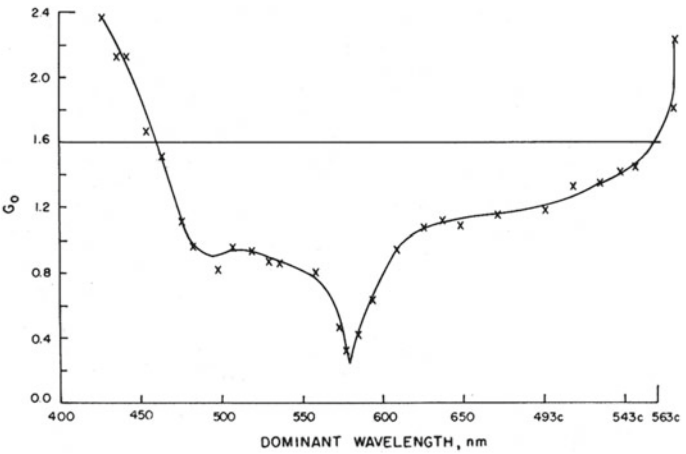

Fig. 78.1 Evans' G_0 function across the spectrum in terms of dominant wavelength, achromatic surround at 100 mL, observer RME [3]

He gave fluorence the name "brilliance" and the perceptual parameter ranged from full grayness to zero-grayness. He concluded that chromatic stimuli have five independent variables: hue, saturation, lightness, brilliance, and brightness. Evans' G_0 concept has become a component of various color appearance models. It represents the finding of an aspect indicating how complex color appearance is and that attempting to constrain it to three dimensions is not realistic.

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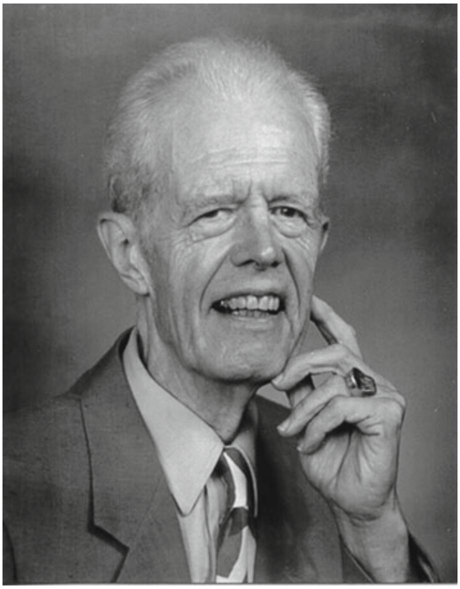
Chapter 79
Hunter, Richard Sewall 1909–1991



Inter-Society Color Council

Richard Sewall Hunter was born in Washington, DC, in 1909, to Herbert F. Hunter and Susie Isabel Sewall. He was a pioneering leader in the field of appearance evaluation and measurement. His childhood was spent in Washington where he graduated from the McKinley Technical High School in 1927 [1]. At age 18, he joined the Colorimetry and Photometry Section of the National Bureau of Standards as a minor laboratory apprentice under the energetic Chief Irwin Priest. During his employment at the National Bureau of Standards (NBS) and over a ten-year period, he attended evening classes at the George Washington University and graduated in

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1937 with a major in psychology and a minor in physics. He married Elizabeth Caroline Landman, and they had two children. At the NBS, he designed a visual reflectometer and presented his work at a Technical Association of the Pulp and Paper Industry (TAPPI) meeting. In the pursuing years, he met with Deane Judd and was encouraged to build the first multi-purpose reflectometer in 1938, which was later commercialized by the Gardner Laboratories [2]. He passed away just before finishing the final draft of the third edition of his work *Color and Appearance Standards* in December 1990.

79.1 Laboratory Color Scales

He is, perhaps best known for conceiving the "laboratory" color scales, which in a modified form are still used in the color industry worldwide. His scaling system, originally described in alpha–beta chromaticity coordinates and, later, the a–b chromaticity dimensions, which became known as the HunterLab, consisted of three, attributes: "L" for lightness, "a" representing the degree of red–green, and "b" denoting the blue–yellow content of a given color. This was considered to be easier to comprehend than the previously devised XYZ scale by the CIE. The work was published by the National Bureau of Standards in a circular in 1942 [3, 4]. The concept was based on research by E. Q. Adams at the General Electric Company, who earlier in 1923 had indicated his notion that two signals summed up by the amber minus green and green minus blue were the outputs of the visual system. Later on, Hunter incorporated this opponent-color concept in his colorimeters, which generated a direct readout of this scale.

In 1946, he became Chief Engineer of the Henry A. Gardner Laboratory in Maryland where he designed and developed a number of instruments for the measurement of color and gloss. The need in the paint industry for a gloss meter provided the initial stimulus that directed Hunter's interest toward geometric attributes of appearance.

In 1952, he formed his own company, Hunter Associates Laboratory, Inc. (HunterLab), which is currently located in Reston, Virginia. His wife joined his company to manage the business aspects of the company and over the years helped him in various capacities. Hunter designed various instruments for different clients including one to measure tomato puree for USDA Grade A rating, a citrus colorimeter for grading frozen orange juice for the Florida Citrus Commission, gloss meters, a distinctness of image meter, an online colorimeter, and other color and appearance measuring instruments. In 1956, he received a large order from Procter and Gamble to build twenty-five colorimeters, and thus, HunterLab became a manufacturing firm and moved to Fairfax, VA and, then in 1979 to Reston.

Hunter was a creative scientist and developed and described measurement procedures that correlate with visual assessments of appearance. Hunter's achievements during his career included the book *The Measurement of Color and*

Appearance, published in 1975, which was revised and republished in 1987 as well as over one hundred manuscripts. He served as President of the Inter-Society Color Council from 1972 to 1974 and concentrated on solving the complex interrelations between appearance sensations ascribed to spectral characteristics and those generally classed as geometric [5]. He used a patterned or half-silvered mirror for visually comparing two fields of view, and the concept was used many years later in the development of a signaling mirror to aid in the rescue of downed military and civilian aircrews and passengers. His collaboration with Dorothy Nickerson also led to the development of the Nickerson–Hunter photoelectric colorimeter for grading cotton.

He assisted the American Society for Testing and Materials (ASTM) in developing appearance standards dealing with paints, plastics, metals, textiles, and others. He began the work in ASTM publication—Compilation of Color and Appearance Standards which was first published in 1984, and then again in 1987.

He received many recognitions including the ISCC Godlove Award ('91 posthumously); The ASTM Award of Merit (1961); ASTM Fellow; The Bruning Award of the Federation of Societies for Coatings Technology (1962); The Richardson Award from the Optical Society of America (1970) [6]; Fellow of the Optical Society of America; and The ISCC Macbeth Award (1976). The ASTM Color and Appearance Committee created the annual Richard S. Hunter Award in his honor.

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Chapter 80
Land, Edwin Herbert 1909–1991

wikimedia.org

Edwin Land was born on May 7, 1909, in Bridgeport, CT, to Harry and Martha Land. He was educated at Norwich Free Academy in Norwich, CT where he graduated with honors. He spent one year at Harvard University studying chemistry, dropped out and moved to New York City. He educated himself at the New York Public Library and experimented after hours at a Columbia University laboratory where he invented the Polaroid J sheet, an arrangement of microscopic

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crystals on a plastic sheet filtering out certain kinds of polarized light, used for example in sunglasses. He obtained a patent for it in 1929. He returned to Harvard where he concentrated on chemistry and physics. He and a partner formed a company that produced polarized sheets, named Polaroid Corporation in 1937. During World War II, the company developed new kinds of night vision goggles and a system that could reveal enemies in camouflage uniforms. When in New Mexico in 1944, Land's three-year-old daughter Jennifer asked him why the camera he used could not immediately produce an image. This got Land to think about such possibilities, and early in 1947, the Polaroid Model 95 camera and the related Type 40 Land film producing black-and-white images began to be offered on the market. The system soon became a big success.

In 1963, Polaroid began to produce a color camera and film, the Polacolor system. A fully automatic color system, SX 70, was introduced in 1972. The success of the Polaroid systems lasted until the introduction of digital cameras. Land's interest in the phenomena of color vision began already in the 1930s.

In the years after the War, Land continued to cooperate with the US Federal Government, being involved in the development of the U2 spying plane. In 1982, Land retired from the Polaroid Corporation and began to spend much time on the subject of color vision. He also established the Rowland Institute for Science in Cambridge, MA, associated with Harvard University, where research in many advanced fields was and is conducted.

Land was listed on 535 patents as inventor. He received some 20 honorary Ph.D. awards, including one from Harvard. He obtained the Presidential Medal of Freedom from the US Government in 1963 and became a member of the Royal Society in England. He obtained 15 awards from various organizations, including the Optical Society of America. Land died on March 1, 1991, in Cambridge, MA [1].

80.1 Retinex Color Vision Model

Already in 1959, Land published an article in Scientific American, titled "Experiments in color vision" [2]. There he described experiments that point to higher complexity of the color vision system in case of complex stimulus patterns than demonstrated for simple patterns: a test sample in a simple surround. He made black-and-white transparent slide images of complex scenes containing many different colored objects, one generated through a red filter and the other through a green one. Then he projected them overlapping onto a screen, with the light source for the one made through the red filter being long-wavelength light and the other one broadband colorless light. The conventional expectation is that the appearance of the projection is only in various levels of redness. However, surprisingly, the projected image had nearly normal appearance, with blue, green, yellow, and other perceived color present. He experimentally evaluated the appearances with many different combinations of projector lights resulting in varying outcomes but usually multi-colored appearances. As he commented, “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.” Using only two chromatic primaries (or one with an achromatic one) in this projection experiment of complex images does not result in reproduction of equal chromatic quality as three chromatic primaries, but its surprising results have as yet not been fully explained.

Land continued working in the field of color appearance and in 1964 proposed the “retinex” (derived from *retina* and *cortex*) model, a mathematical model to predict the influence of surrounding color fields on the appearance of a test field. It was described in a lengthy article in Scientific American in 1977 [3]. Land used what he called Mondrian images, the name based on somewhat similar paintings by the Dutch modernist painter Piet Mondrian. Land demonstrated that, depending on the local illumination and its surrounding patches, a patch in a Mondrian could have significantly different appearances even though the light reflected from it was identical (Fig. 80.1). An important contributor to Land’s effort was his cooperator J. J. McCann.

Land’s retinex theory resulted in criticism from other color researchers who showed that his effects were more limited than claimed and that a number of findings had been shown by previous workers. Two-primary color reproduction did not receive any practical application. The broad issue of mathematically modeling color appearance, initiated in 1906 by J. von Kries, continued to be and still is

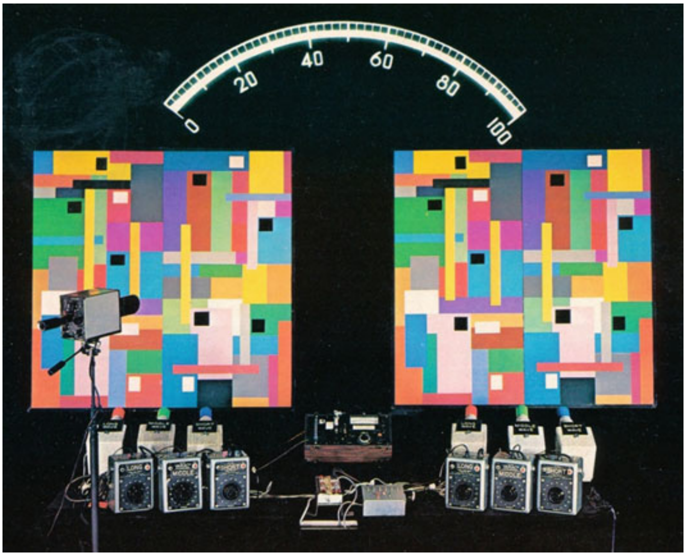

Fig. 80.1 Image of land’s experimental setup for his Mondrian experiments

addressed, resulting in several appearance models [4]. An important current example of a color appearance model is the CIECAM02 model first published in 2004 [5].

In Fig. 80.1, two “Mondrian” images are displayed, each one having three projectors with their output individually controllable in regard to spectral power and luminance. On the left is a telescopic photometer with which the reflected light from each area of the images can be separately measured, with the results projected onto the scale above the images. Illuminating radiation can be adjusted for different color fields so that the reflected light is identical, even though the appearance of the fields varies broadly, such as white, red, blue, or green [3], (reproduced with permission).

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Chapter 81
MacAdam, David L. 1910–1998

Emilio Segrè visual archives, Am, Inst. Physics, 2019

David Lewis MacAdam was an American physicist and color scientist who made important contributions to colorimetry, color discrimination, color photography and television, and color order. David MacAdam was born in Philadelphia, PA on 1 July 1910 [1].

MacAdam grew up in Philadelphia, attended Lehigh University for a B.S. degree in 1932, and in 1936 received a Ph.D. in physics from MIT. Under Prof. Arthur C.

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Hardy, he originated the first course in color measurement and assisted Hardy in the preparation of *Handbook of Colorimetry* and *the Science of Color*.

Upon graduation, MacAdam joined the research laboratories of the Eastman Kodak company in Rochester, NY, from where he retired as a Senior Research Associate in 1975. Subsequently, he was named Adjunct Professor at the University of Rochester, Institute of Optics where he remained active until 1995. At Eastman Kodak, among many other things, he helped to establish the theoretical basis for color photography, including color masking as compensation for unwanted dye layer absorptions [2].

While still studying, MacAdam published in 1935 two papers in which he offered a geometric proof of the optimal-color theorem and calculated the optimal object color solid raised over the CIE chromaticity diagram, using the newly established CIE standard observer and illuminant C and A data from 1932 [3, 4].

81.1 MacAdam Ellipses

One of MacAdam's best-known contributions was in support of technological color control. Assuming that the basis of color-difference perception was the statistical error in matching the appearance of a given color stimulus, he conducted an extensive experiment with one observer, the result of which was expressed in the CIE chromaticity diagram in form of statistically derived ellipses, published in 1942 [5]. However, the resulting Friele–MacAdam–Chickering color-difference formula proved less effective in predicting perceived color differences than formulas derived on other bases. In attempting to convert the ellipses to circles of equal size, MacAdam encountered the non-Euclidean nature of psychophysical color space.

1. *Instrumentation and computation*
   In the mid-1940s, MacAdam pioneered the use of computers in colorimetric computations, established Hardy's reflectance spectrophotometer as a reliable industrial measuring instrument, and invented a tristimulus integrator as an accessory.

2. *Principal component analysis of daylight*
   With Deane B. Judd and Günter Wyszecki, MacAdam performed the first principal component analysis of phases of daylight of various correlated color temperatures, demonstrating that they can be represented as linear combinations of a limited number of spectral components [6].

3. *Optical Society of America Uniform Color Scales*
   MacAdam was a leading member of the committee of the Optical Society of America that in 1947, at the suggestion of the US National Research Council, began work on a perceptually uniform colorimetric model of the color solid. Upon the retirement of its first chairman D. B. Judd, MacAdam was elected

chair. The result of the committee's work was published in 1974 as "Uniform Color Scales," [7] with OSA publishing a related color atlas with 558 samples in 1977.

MacAdam was a major contributor to OSA's 1953 book *The Science of Color* [8]. His interest in the history resulted in publication in 1970 of *Sources of Color Science*, [9] a compilation of 26 seminal papers on color science, from Plato to LeGros Clark, several translated for the first time into English. In 1981, he published *Color Measurement: Theme and Variations*, a presentation of fields of color science in which he made important contributions [10]. He also authored some 100 peer-reviewed journal articles.

MacAdam was president of the Optical Society of America in 1963 and editor of the Journal of the Optical Society of America from 1964 to 1975. He was active in the Inter-Society Color Council and the Commission Internationale de l'Eclairage (CIE). He received honors from many societies, including the Frederic Ives Medal of the Optical Society of America in 1974.

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Chapter 82
Hurvich, Leo Maurice 1910–2009

dla.library.upen.edu

Leo Maurice Hurvich was born in Malden, Massachusetts on September 11, 1910. He obtained his undergraduate and doctoral degrees (1936) from Harvard University. He remained at Harvard as a researcher until 1947, investigating distance perception with his future wife Dorothea Jameson and others, a subject of particular interest during the Second World War. The couple (they married in 1948) was invited by Ralph Evans of Eastman Kodak to join company's color technology

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division as research psychologists to study color perception. In 1957, they moved to New York where Hurvich assumed the position of chair of undergraduate psychology at New York University. The next step was a move to the Psychology Department at the University of Pennsylvania in Philadelphia where he remained until his retirement in 1979. He was a fellow of the New York Academy of Sciences and, among other things, a member of the National Academy of Science. He and his wife were recipients of the 1972 Distinguished Scientific Contribution Award of the American Psychological Association. Hurvich remained active in the field of color until the end of the century. He died in New York on April 25, 2007 [1].

82.1 Experiments on Opponent-Color Vision Theory

Hurvich and Dorothea Jameson published some 95 papers on many aspects of color science. Over the years, they broadly investigated the perceptual aspects of hue, saturation, and brightness of colors. In 1981, Hurvich published his book *Color vision* that was an influential, wide-ranging text on the subject [2].

In the mid-twentieth century, Hurvich and Jameson became interested in Hering's theory of four primary hues. In 1955/1956, they published four articles on various quantitative aspects of an opponent-color theory, followed in 1957 by a summary article "An opponent-process theory of color vision." These efforts and the English translation in 1964 of E. Hering's *Grundzüge der Lehre vom Lichtsinne* (1905) as *Outlines of a theory of the light sense* [3] made Hurvich and Jameson the main proponents of their generation of an opponent-color theory of color vision. As described and illustrated in Hurvich's *Color vision*, a complex optical apparatus made it possible for observers to establish objective experimental data determining how much of a stimulus representing a unique hue it took to cancel the color appearance of a second opposing unique hue. While there was inter-observer variability in the results, a general picture emerged (Fig. 82.1).

The locations of the unique hue stimuli were determined to be approximately 475 nm for blue, 500 nm for green, 580 nm for yellow, with red located near the end of the spectrum. The general idea of an opponent-color process was also supported by neurological results indicating the presence in the brain of color-opponent neurons. However, it has become evident that the human visual system has a more complex neurological basis. Multiple mathematical models of the opponent-color theory based on cone sensitivity or color-matching functions have been developed by various authors since that time. A neurophysiologically supported model is still lacking at this time.

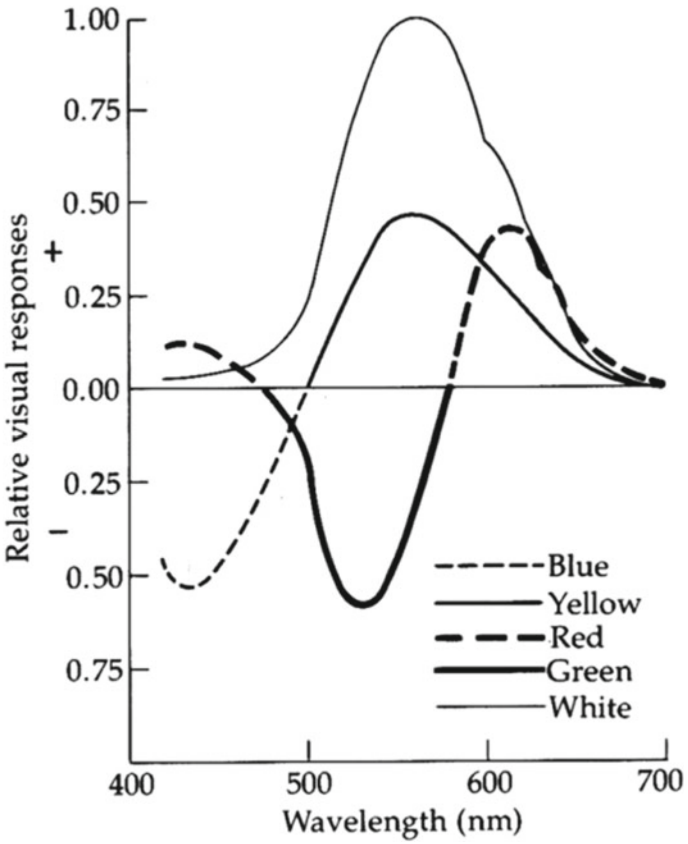

Fig. 82.1 One observer's chromatic and achromatic (White) spectral responses in terms of unique hues [2]

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Chapter 83
Hemmendinger, Henry 1915–2003

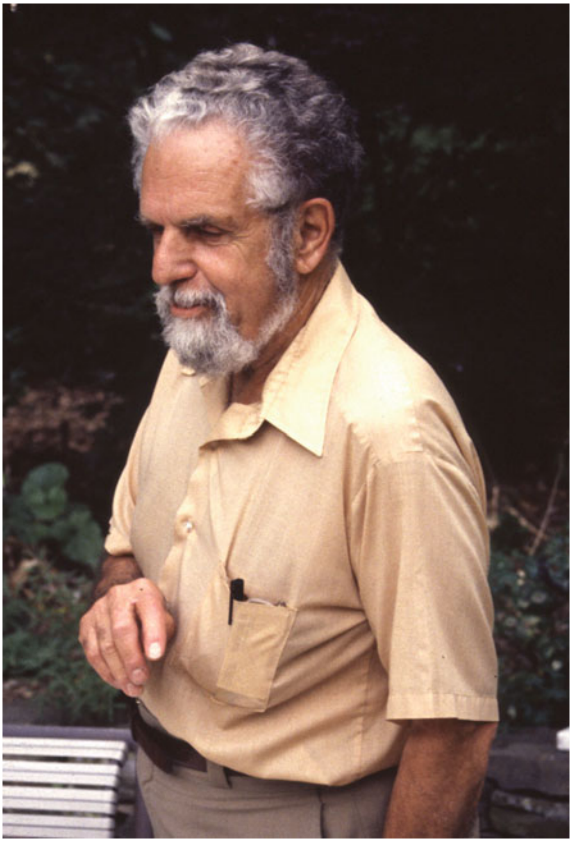

Image courtesy of Robert Hirschler

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Henry Hemmendinger, an eminent authority in color science and standardization, was a pioneer in computer-directed colorant formulation and also was for many years the sole source of transfer standards for aligning the measurements of US spectrophotometers nationwide.

Born in Bernardsville, NJ, Henry studied at Harvard and Princeton, from which he received a Ph.D. in astronomy in 1939 under the direction of Henry Norris Russell. His career as a physicist working in color measurement, specification, and control spanned the last half-century, first in a partnership, Davidson and Hemmendinger, and later as a consultant operating Hemmendinger Color Laboratory from his home. He was a widely recognized authority on color science, a member of international committees, and recipient of numerous honors, such as the Godlove Award from the Inter-Society Color Council and Honorary Membership in the Council. Henry was a member of the American Society for Testing and Materials, a fellow of the Optical Society of America, and a lifetime member of the US National Committee of the CIE.

Hemmendinger's career focused on quantifying performance errors in colorimetry, incurred by photometric equipment and also by human observers. He brought to bear a deep knowledge of how spectral reflectance curves can aid in the formulation of products with desirable appearance attributes. He was also a leader in understanding metamerism, the situation where multiple objects have the same tristimulus values, have different spectral power distributions but have the same color appearance for the standard observer.

Henry worked to establish and to publish methods for precision spectrophotometry of reflecting materials. He devoted himself to getting good practice and good standards into the hands of industrial colorimetrists, a task in which his contribution has been compared to that of Deane Judd at the National Bureau of Standards. For many years, he was the sole US supplier of calibrated colored materials used to evaluate the performance of color measurement instruments. He presented numerous papers on this subject and was a leading expert on spectrophotometric precision and accuracy [1].

83.1 Colorant Mixture Computer (COMIC)

Hemmendinger contributed to many technological innovations, especially in collaboration with Hugh Davidson, with whom he founded D&H in 1952. In the 1950s, Davidson and Hemmendinger became pioneers of computer-directed colorant formulation. As attested by Hemmendinger:

> In 1958, Davidson & Hemmendinger Inc. introduced the COMIC (Colorant Mixture Computer), the first practical computer for finding a mixture of dyes or paints to match a given sample. An analog computer that solved a set of simultaneous equations and that was later replaced by digital computer programs, the COMIC helped bring automation to the colorant industry [2].

In addition, Davidson and Hemmendinger evaluated the reflectance curve shapes for candidate formulations for the Munsell Book of Color, to ensure good color constancy under change of illumination. They used their studies to embody the Munsell system in glossy paint. That was a significant achievement: Current embodiments are nowhere near as color constant. Many photographic products today are designed based on the rules they developed for the glossy Munsell Book of Color. Davidson and Hemmendinger also developed the D&H Color Rule, a device to gauge the extent of observer metamerism. This rule was for a long time viewed as indispensable in teaching the principles of observer metamerism.

In 1970, Henry founded the Hemmendinger Color Laboratory (HCL), devoted to the preparation and distribution of spectrophotometric and colorimetric color standards. In 1994, Hugh Fairman joined Henry as a partner in HCL and until 2015 operated the company out of Tatamy, PA.

In addition to these contributions, Henry fruitfully combined his areas of expertise. For example, he used metameric pairs as a tool to assess instrument performance.

Colleagues and former employees remember Henry as a fine human being and as a vigorous and generous mentor, freely sharing his knowledge and wisdom. Rigorously honest in his scientific and personal life, Henry always searched for the truth, and when he found it he spoke up with all due tact but unambiguously.

Besides pursuing scientific work, Henry was a passionate gardener who created a small oasis at his Princeton home, as he had previously done in Belvidere, NJ. He was interested in plant propagation and worked with a local garden club to cultivate the rare blue gentian flower.

Selected publications by Henry Hemmendinger:

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Chapter 84
Allen, Eugene M. 1916–2005

Image courtesy of Robert Hirschler

Eugene Allen was born on November 7, 1916, in Newark, NJ to Celia and Mitchell Kaplan. He attended Columbia College in New York, receiving a bachelor's degree. He transferred to Stevens Institute of Technology where in 1944 he received a master's degree in mathematics while working at the military research facility Picatinny Arsenal in Dover, NJ. In 1952, he obtained a Ph.D. degree in chemistry from Rutgers University while working, under the guidance of E. I. Stearns, in the Research Department of American Cyanamid Corp. in Bound Brook, NJ, then a textile colorant manufacturer using the latest technologies in colorant quality control. In 1967, he became director of the color science laboratory at Lehigh

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University's Center for Surface and Coatings Research from which he retired in 1982.

In 1967, Allen received the Armin J. Bruning Award from the Federation of Societies for Coatings Technology for his efforts in regard to the introduction of color measurement and colorimetry into that business group. He was named a Fellow of the Optical Society of America and in 1983 received the Inter-Society Color Council of America's top honor, the Godlove Award. His colleagues at Lehigh University considered him to be a Renaissance man "always reaching for wider connections between science, arts and humanities." Allen died on January 18, 2005 [1].

In the late 1950s, Allen's main interest was to establish a clear understanding of the mode of operation of fluorescent whitening agents and how their whitening efficiency could be objectively evaluated [2].

84.1 Digital Colorant Formulation

Allen's primary efforts related to color resulted from the introduction in 1958 of the Davidson and Hemmendinger COMIC (colorant mixture computer), an analog computer for matching reflectance functions of dyed or painted samples with related colorants, a technology that replaced centuries-old color matching by trial and error. Familiar with the technical limitations of analog computers, Allen developed a set of basic mathematical equations for color matching, using matrix algebra and the Kubelka–Munk equations for use in a digital computer. Small digital computers, such as IBM's 1130 with input via punched cards, began being introduced at the time. Allen's equations were published in 1966 and became an important basis for widespread industrial use of digitally based computer colorant formulation [3, 4]. Allen proposed matching algorithms for both one- and two-constant Kubelka–Munk data, the former for dyes and the latter for pigments.

The matching procedure is relatively complex. Among the variables are the reflectance function of the standard to be matched, the reflectance functions of the colorants to be used for matching at various concentrations as well as their price, and the reflectance function for the substrate material. An initial solution is then calculated together with the resulting theoretical reflectance function of the match. The tristimulus values for the reference and the match functions are calculated and compared in regard to color difference. If the calculated match formula is not sufficient, the formula undergoes an iteration process until the tristimulus values are sufficiently close, or the colorant combination is abandoned. Of sufficiently close formulations metameric and color constancy indices as well as cost are calculated for a final decision as to which formula is to be used.

1. *Metamerism*
   An important issue in colorant formulation is color metamerism and in particular, metamerism related to small differences in the color vision properties of observers. In 1969, Allen described a mathematical methodology to quantify it and proposed a statistically derived "standard deviate observer" based on the statistical standard deviation in color-matching functions of observers with normal color vision [5]. The standard deviate observer was later incorporated into the CIE colorimetric system.

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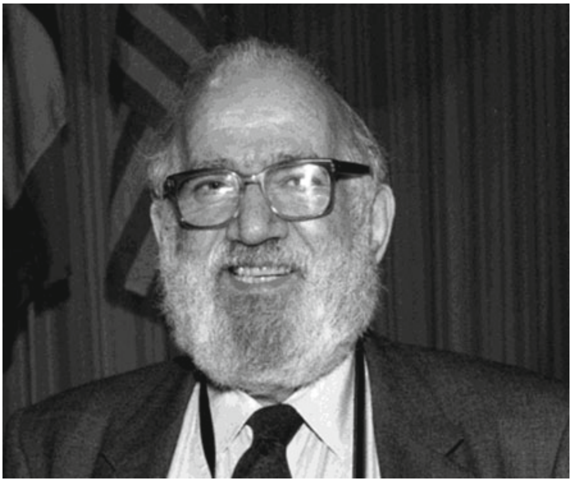
Chapter 85
Saltzman, Max 1917–2001



Donation by M. Saltzman

Max Saltzman was a chemist, educator, and scholar. As a steadfast member of the color community in the USA, he often mentored colleagues with thoughtful and generous encouragement, resulting in him having a profound influence in the field of color science in both industry and the art community.

Saltzman received a B. S. degree in chemistry from the College of the City of New York in 1936. In this early period, he worked in the field of medical instrument research and during the war years was in civilian service with the Chemical Warfare Service. Following the war, he settled into his first career in color by joining Harmon Colors, which later became Allied Chemical Corporation, where he worked in various research and management capacities for 26 years. As a native

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New Yorker, he lived in the city and reverse-commuted to New Jersey for this entire period.

At Harmon, he became an expert in pigments, dyes, and resins by identifying the colorants, making objective color measurements, defining criteria for selection of colorants for specific applications, and use of computers for color matching. We can see his interest and influences through the organizations which he joined: The American Chemical Society, the American Association of Textile Chemists and Colorists, the Inter-Society Color Council, the Society of Plastic Engineers, the Optical Society of America, the Society of Dyers and Colourists (UK), the Colour Group (Great Britain), the Dry Color Manufacturers' Association, and the Federation of Societies for Coatings Technology.

85.1 Color Education

During this time, Max realized there was a need for academic and industrial training in color technology. He encouraged Dr. Walter Bauer, Dean of the College of Science at Rensselaer Polytechnic Institute to establish a new research laboratory at RPI and to recruit Dr. Fred W. Billmeyer, Jr., to run the undergraduate and graduate program in color science and to expand it to include summer short courses for people from industry. The very popular textbook, *Principles of Color Technology* by Fred W. Billmeyer and Max Saltzman [1] went through two editions during this period (1966 and 1981) and followed Max's teaching principles of going back to the basics for a thorough understanding of the issue [2]. Max served as an adjunct professor for most of the 20 years the Rensselaer Color Laboratory was in existence.

Upon retiring from Allied Chemical in 1973, Max left New York moving to the west coast where he found time to follow one of his other major interests: the study and identification of ancient dyestuffs in textiles [3–9]. He began by establishing a color identification laboratory in the Institute of Geophysics and Planetary Physics at the University of California. His research led him far and wide, for example, he traveled to Peru to collect authentic samples of dyes used in ancient Peruvian textiles. This soon led to his second career in the area of conservation of historical textiles and other objects. He became active in the American Institute for Conservation of Historic and Artistic Works and the International Institute for Conservation of Historic and Artistic Works. In 1984, he was invited to present the George L. Stout Memorial Lecture, a prestigious honor from the American Institute for Conservation of Historic and Artistic Works. When the J. Paul Getty Conservation Institute was established, Max became a consultant there.

Although often working behind the scenes with individuals, Max Saltzman became an internationally recognized authority in the field of color science, receiving the Armin J. Bruning Award (1969) and the Inter-Society Color Council

Macbeth Award (1986). Among his many recognitions and awards, the Inter-Society Color Council also honored Max Saltzman's lifetime of contributions by bestowing on him the 2001 Godlove Award. Sadly, he died before the ceremony to receive the award.

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Chapter 86
Davidson, Hugh R. 1918–2010

Donation by H. R. Davidson

Hugh R. Davidson is best known for his work in computer color matching and for his educational seminars, but he also has many accomplishments in the areas of instrumental developments for industrial color control, color differences, and color-order spacings.

After graduating from high school in York, PA, Hugh took a year off and toured the far West of the USA returning to the East to attend Lehigh University in the fall

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Adapted from an obituary in the ISCC News #446 (Jul-Aug 2010).

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of 1937. He graduated from Lehigh in 1941 with a Bachelor of Science in Electrical Engineering, and joined the Office of Naval Research for the duration of the War where he was involved in development of automatic gunfire control and targeting for submarines.

Around 1954, he developed the first automatic tristimulus integrator and attached it to the GE-Hardy spectrophotometer. This provided for the first time a quick way of obtaining tristimulus values, which until that time had been obtained by counting squares under a plotted curve.

86.1 Computer Color Matching

With Henry Hemmendinger, at Davidson and Hemmendinger, he painted the first glossy edition of the Munsell Book of Color and supplied it to the Munsell Color Company. There he also developed COMIC, an analog computer, which proved to be the first computer dedicated to making computer-assisted color matches. The COMIC utilized an oscilloscope as a display. On the oscilloscope appeared 16 dots that represented the standard spectral curve to be matched. The pigments to be used were characterized at each of the 16 wavelengths by a plugboard that was inserted in the machine to provide the absorption characteristics of the formula for matching. The user adjusted the concentrations of the ingredients with knobs until a match was achieved, and then, the concentrations were read from the knobs.

Later, the COMIC II accomplished the same task digitally using Kubelka–Munk two-constant theory. A COMIC machine presently resides in the Smithsonian Institution in Washington, DC as an example of a special-purpose computer from the earliest days of electronic computation.

Shortly, after introducing COMIC II, Hugh and Henry published the first paper fully explaining Kubelka–Munk two-constant color-matching theory. This was some eight years before Eugene Allen's now well-known two-constant paper. Also at Davidson and Hemmendinger, Hugh developed the first color rule that used painted panels to display the series of metamers in the rule. About this time, Hugh undertook, with E. Friele, a very large study of the relative accuracy of the various color-difference equations then in use.

Later on his own at Davidson Colleagues, Hugh developed digital software for computer color matching to run on mini-computers and later personal computers. Hugh developed the pigment plan for and painted the samples of the Optical Society of America's Uniform Color Scales when an OSA committee chaired by David MacAdam produced that atlas [1]. Hugh has had over 40 papers published in such journals as *Journal of the Optical Society of America*, *American Dyestuff Reporter*, *Color Engineering*, *Journal of Chemical Education*, *Industrial and Engineering Chemistry*, *Journal of Coatings Technology*, and *Color Research and Application* [2–6].

From the early 1950's until around 2001, Hugh held week-long seminars in color education, directed mostly to the subject of computer color matching. He is estimated to have taught 2500 students in this period, and must, therefore, be near the top of the list of color-science educators who have the largest number of student-classroom hours.

In 1966, Hugh won the Bruning Award of the Federation of Societies for Coating Technology. In 1988, he won the Millson Award of the American Association of Textile Chemists and Colorists, and in 1977, the Inter-Society Color Council's most prestigious award, the Godlove Award. Hugh was made an Honorary Member of the Inter-Society Color Council in 2001.

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Chapter 87
Billmeyer, Fred Wallace, Jr., 1919–2002

Image courtesy of Robert Hirschler

Fred Wallace Billmeyer, Jr., was an American chemist who contributed through industrial research and academia to the developing fields of polymer chemistry and color science during the second half of the twentieth century.

Billmeyer was born on August 24, 1919, in Chattanooga, Tennessee. In 1941, he received a B.S. in chemistry from the California Institute of Technology. Then he received a Ph.D. in physical chemistry from Cornell University in 1945, after studying the measurement of molecular weights by light scattering under Nobel Laureate Peter Debye.

His professional career can be divided into two major parts, focusing first on industry and then on education. Upon graduation, he joined the Plastics Department

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of E. I. DuPont de Nemours & Co., Wilmington, Delaware, where he remained for twenty years. There he worked on various aspects of polymers. Instinctively an educator, he published *Textbook in Polymer Chemistry* (1957) and *Textbook in Polymer Science* (1962), which went through three editions and was also published in Japanese. These books helped to create the academic discipline of polymer science. He served as a visiting professor in Chemical Engineering at Massachusetts Institute of Technology for the 1960–1961 academic years. Billmeyer increasingly became involved with the growing field of color science. At the University of Delaware, he supervised his first graduate color science student, Joseph Atkins, whose 1964 Ph.D. thesis was on the Absorption and Scattering of Light in Turbid Media.

In 1964, he retired from DuPont to join academia full time as a Professor of Analytical Chemistry at Rensselaer Polytechnic Institute (RPI), Troy, New York. At RPI, he taught and directed research in both polymer and color science and directed the Rensselaer Color Measurement Laboratory until he became Professor Emeritus in 1984. During his time at RPI, he not only taught and mentored undergraduate and graduate students, but also, with Max Saltzman, initiated summer courses in color science for people from the industry. His influence on the field of color science was extended throughout the USA by over 1000 people from diverse fields attending these summer programs.

87.1 Principles of Color Technology

To extend his commitment to education, he undertook two other major projects while at RPI. In 1966, Billmeyer continued his collaboration with Saltzman, publishing *Principles of Color Technology*. Their two editions of this textbook became widely acclaimed throughout the industrial world as the primary introduction to color science. A third edition entitled *Billmeyer and Saltzman's Principles of Color Technology* (published in 2000) by Roy Berns is still widely read. Also with Richard Kelly in 1975, he published *Entering Industry: A Guide for Young Professionals*.

The second project was creation of an academic journal for color science. After supporting two unsuccessful attempts at journals of color engineering and science, in 1976, he initiated the journal *Color Research and Application*. Billmeyer was the founding editor and served in that position until 1986. His approach of involving national color organizations, beginning with the Canadian Society for Color, the US Inter-Society Color Council, and the Colour Group (Great Britain) and later others throughout the world, has contributed to the success of this English-language journal published by John Wiley & Sons as it continues to be published.

Many of Billmeyer's scientific contributions throughout the years fall into the category of light scattering and the application of turbid medium theory to the formulation and shading of colored materials. Beginning with the basic theory of Beer's law, he programmed a digital computer to calculate the concentrations required to produce a given transparent color by mixing soluble dyes [1]. Next, with Beasley and Atkins, he expanded two-flux Kubelka–Munk theory to a four-flux turbid medium theory [2], which became known as the BAB Theory for colorant formulation. From there, he continued development of the BAB to apply particularly to paint systems [3] and expanded that further to coatings with goniometric characteristics [4, 5]. He further developed practices for determining the optical properties needed to be used in the turbid medium theory and multi-flux theory [6–9].

Billmeyer was a versatile and prolific communicator; his contributions were not limited to turbid medium theory. Two other areas that should be mentioned here are the characterization of fluorescent materials [10, 11] and use of color difference equations in manufacturing [12]. His involvement within the many professional organizations and collaboration with other scientists throughout the world influenced most areas of color science. In particular, his more than 350 published articles discussed polymer characterization and diverse aspects of color. His 13 books were focused on teaching in clear, concise language the scientific principles necessary for the industrial use of polymers and color to enhance our lives.

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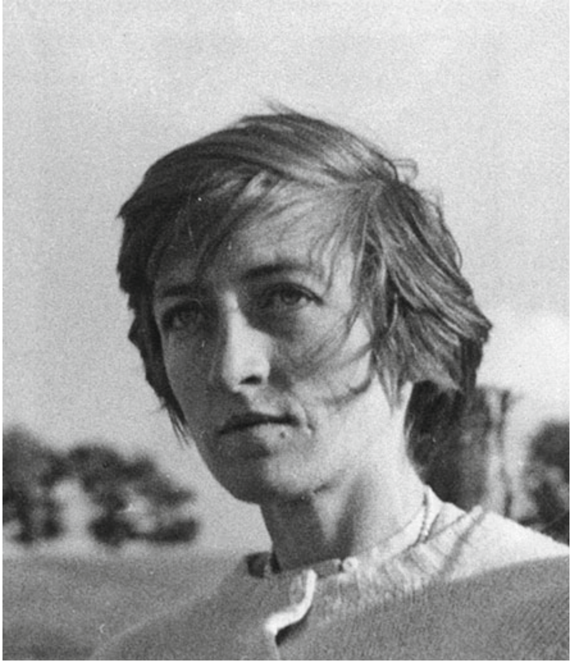
Chapter 88
Jameson, Dorothea 1920–1998



all-about-psychology.com

Dorothea Jameson was born November 16, 1920, in Newton, M.A. Her father was educated in electrical engineering as well as law. Her mother taught her to believe she could achieve whatever she wanted to do. Her early education was in small private schools for girls. She then attended Wellesley College and also attended by her older sister. She began concentrating on psychology but soon became interested

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in brain mechanisms behind psychological processes. In 1941/2, with the US's entry in the Second World War, she became involved in a project investigating factors affecting the judgment of distances, a joint project between Wellesley and Harvard. A Harvard researcher in the project was Leo M. Hurvich. After graduation, Jameson became a research assistant at Harvard. In 1948, she married Hurvich. In 1947, Jameson and Hurvich were invited by Ralph M. Evans who was the department head of color control at Kodak to join the company; the main subject of their efforts to be a better understanding of the perception of color that might result in better color photography. In 1957, they moved to New York City, she into a research job at New York University, he as a professor of undergraduate psychology. They remained there until 1962. The next move was to Pennsylvania State University's Department of Psychology and Institute of Neurological Sciences. Due to prevailing rules at the time, as a woman, she could not be named professor until 1975 when she became a University Professor of Psychology. By that time, she had authored and co-authored (mostly with her husband) some 80 papers, the majority on the subject of color, a number that reached the mid-nineties by the end of her life. During her life, she also showed much interest in color in art, resulting in a number of articles on that subject. As a member of the National Academy of Sciences, she served on several committees and boards of that organization. She was also the recipient of multiple awards, among them the 1987 Helmholtz Award of the Cognitive Neuroscience Institute, the Godlove Award of the Inter-Society Color Council, and the Dean B. Judd Award of the Association Internationale de Couleur. After retirement, she and her husband moved back to New York where she died on April 12, 1998. The close cooperation between her and her husband in research and life is considered exceptional [1, 2].

88.1 Hue Cancellation Experiments

Jameson and Hurvich's joint interest in color opponency began in the early 1950s. In 1955, they published several articles describing their findings from quantitative studies of the relationship between light stimuli and the perceptual results in terms of hue, saturation, and brightness from the point of view of an opponent-color theory. The key quantitative methodology they used is hue cancellation (Fig. 88.1). The theory was supported in a general way by the finding of neurons with opponent characteristics in the brain of monkeys. However, more recent data indicate that the neural processes of color vision are much more complex than assumed at the time. In 1964, they published together with their English translation of Ewald Hering's 1905 book in which he proposed an opponent-color theory in opposition to Helmholtz's trichromatic theory [3].

Work that she performed independently dealt either with the physiology of vision or with modern art.

At NYU, she operated a fish laboratory in which she and a student developed data demonstrating a degree of color vision in goldfish [5]. Another project

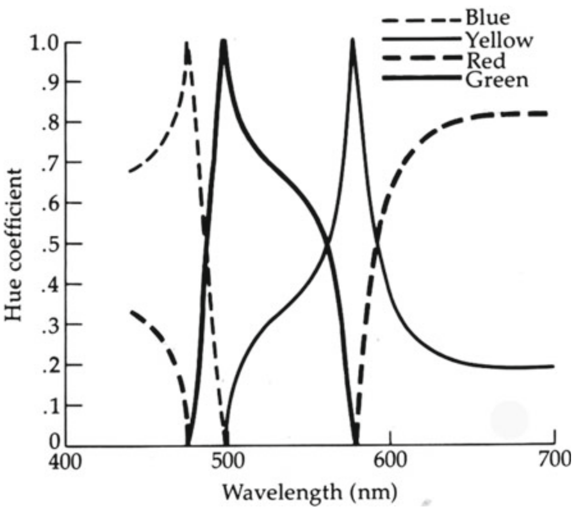

Fig. 88.1. Hue coefficients or relative content of colors of spectral wavelength in terms of four primary hues (unique hues) represented by light of wavelength 475 nm for blue, 500 nm for green, 580 nm for yellow; the stimulus for red complementary to green of 500 nm is a non-spectral purple. At each wavelength, the coefficients of the two primaries involved add up to 1.0. The data are representative of an average observer [4]

involved investigating the activities of retinal cell types that integrate information gained by cone cells. Examples of work related to art are her 1989 article "Color in the hands of the artist and eyes of the beholder" [6] and the joint article with her husband "Contrast to assimilation: in art and in the eye" [7].

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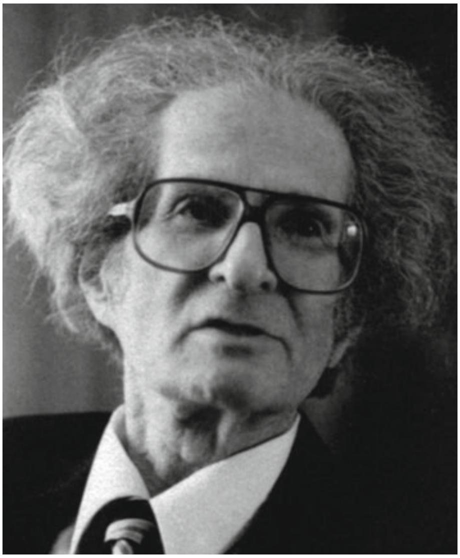
Chapter 89
Cohen, Jozef B. 1921–1995



Donated by J. B. Cohen

Cohen was born in Brookline, M.A on July 21, 1921. He attended grade and high schools in Brookline and obtained an undergraduate degree in psychology from the University of Chicago. He moved on to Cornell University where he got involved in the psychophysics of color. In 1945, he graduated with a Ph.D. in psychology. After spending a year in S. S. Stevens' laboratory at Harvard University and three years as a faculty member at Cornell, he moved in 1948 to the University of Illinois where he became a full professor in 1969 and a professor emeritus in 1991. Between 1946 and 1949, he worked mainly in the field of color, as can be judged by his publications.

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After an intermission, this subject was again his major interest in the mid-late 1960s. In 1974, he was the author of the article “Psychology” in the fifteenth edition of the *Encyclopedia Brittanica*. In the 1980s, Cohen began cooperation with his colleague W. E. Kappauf on what he named fundamental color metamers, the major color-related concept of his career. Cohen died on August 18, 1995 [1].

89.1 Principle Component Analysis of Reflectance Functions

A key and novel effort of Cohen was his principal component analysis of the reflectance functions of 150 Munsell color chips in 1964 where he found that the first three components accounted for over 99% of variability in the reflectance functions. This effort resulted over the next decades in a widespread principal component analysis of broader ranges of reflectance functions both of natural and artificial nature [2].

The nature of color stimulus space became of particular interest to him in the mid-1970s. In the early 1980s, together with his colleague W. E. Kappauf, he described a mathematical method to decompose a reflectance or a spectral power function into two components, a concept introduced by G. Wyszecki in 1953: the fundamental function and a metameric black function. These points are located in a related orthonormal space Cohen named the fundamental color space (Fig. 89.1).

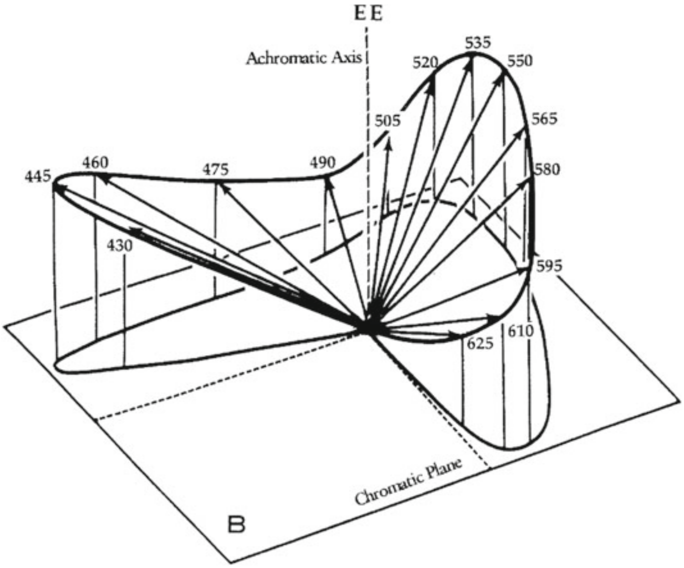

Fig. 89.1 Rendering of Cohen’s fundamental color space, with the locations of the spectral color vectors and the equal energy vector shown [1]

This concept was not accepted well by some key color scientists of the time. It gained wider traction from Cohen's 1988 article in *Color Research and Application* "Color and color mixture: scalar and vector fundamentals" [3].

A key component of the calculation of the fundamental metamer is what Cohen named "matrix R", $R = A\ (A'A)^{-1}\ A'$, where A is a matrix representing three color-matching functions on an orthonormal basis. If N is any given spectral power distribution function, he found that its fundamental metamer N^* is calculated $N^* = RN$. Cohen showed that a CIE tristimulus value-based color space is far from orthonormal, but there is as yet evidence neither for nor against the idea that the human color vision system has an orthonormal basis.

The broadest representation of Cohen's work is found in his posthumously published book *Visual color and color mixture* of 2001 [1]. Since then, it has been shown that there are other mathematical methods possible to calculate fundamental metamers. While he only hinted at a possible connection between the fundamental space and perceptual color space, it is clear that solid evidence for such a conclusion is lacking, as the relationship between stimulus and perception remains to a substantial degree unknown and is, in any case, very complex as demonstrated by color appearance models. In the last two decades of the twentieth century, his findings provided much new insight into the nature of color stimuli.

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Chapter 90
Indow, Tarow 1923–2004

Image courtesy of Robert Hirschler

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Tarow Indow was born in Tokyo, Japan, on August 22, 1923. He attended Keio University where he obtained a Ph.D. degree in psychology in 1959, together with an annual award for excellence. While working on his thesis, he had an opportunity to spend some time at Princeton University where he was introduced to the concept of multi-dimensional scaling, a concept he later applied to color stimuli and percepts. He was an instructor at Keio beginning in 1948 and, after obtaining his Ph.D. became a professor of psychology. From 1963 to 1966, he was a research fellow at Harvard University's Laboratory of Psychophysics under the guidance of S. S. Stevens. During 1971 and 1972, he was a visiting member of the Institute for Advanced Study at Princeton University. After returning to Japan, he was a lecturer at Tokyo University. He returned to the USA in 1977 as a professor of psychology at the University of California, Irvine, from where he retired in 1993. Beginning in 1981, he was also an adjunct professor at the Rensselaer Polytechnic Institute in Troy, NY. After his official retirement, he continued to be an active researcher at UCI until the end of his life [1].

Indow was a member of the executive committee of the International Color Association (AIC) from 1970 to 1981, its president from 1973 to 1979, and in 1989 received the Deane B. Judd-AIC Award for his contributions to color science. In 1986, he was named a fellow of the Society of Experimental Psychologists. He was a member of the editorial board of the Journal of Mathematical Psychology, indicative of his joint interest in both fields, from 1974 until the end of his life. Indow died on September 22, 2004, following hospitalization for a throat and lung disorder [1].

90.1 Global Structures of the Visual Space

Indow had a fascination with the mathematics of psychological findings. Based on extensive research, he published ca. 100 articles and six books in Japanese and in English some 80 articles authored or co-authored by him and three books. His primary interest was in the implicit global structures of the visual space relating to its geometry, as well as of color perceptions. Examples of the former are a 1988 article "On geometrical analysis of global structure of visual space" [2] and his 2004 book "Global Structure of Visual Space [3]."

In regard to color, some typical examples are the 1988 paper "Multidimensional studies of Munsell color solid [4]," "Color differences and principal hue vectors in the Munsell space [5]," and "Estimating physical reflectance spectra from human color matching experiments [6]." How to develop a metric that relates mean perceptual color differences to stimuli, taking into account the various conditions of viewing, surround and illumination, was another problem that fascinated him. Figure 90.1 shows an example of a chromatic diagram of the Munsell hue/chroma plane with the sample placement established by multi-dimensional scaling, with constant chroma samples connected by roughly circular lines and constant hue samples by approximately radial lines [7].

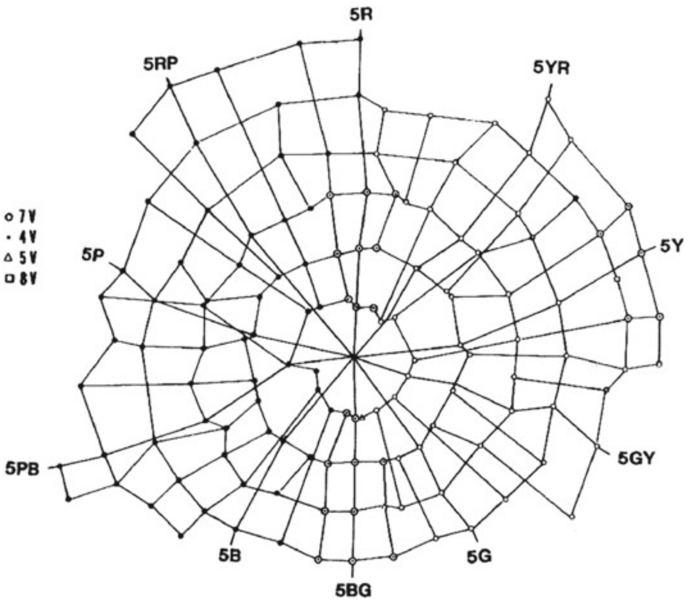

Fig. 90.1 Example of a chromatic diagram of the Munsell hue/chroma plane

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Chapter 91
Boynton, Robert M. 1924–2006

From Optical Society of America, Obituaries

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Robert M. Boynton was born on October 28, 1924, in Evanston, IL. He attended Amherst College in Massachusetts where he received an undergraduate degree. At Brown University in Providence, RI, he received in 1952 his Ph.D. degree in psychology. Soon after, he became an assistant professor of psychology at Rochester University, NY where, in 1963, he founded their Center for Visual Science. In 1974, he moved to the University of California San Diego where he remained until his retirement in 1991, in his final years being the associate dean in the Office of Graduate Studies and Research.

Boynton was the recipient of the OSA Tillyer Medal in 1971, the Frederick Ives Medal in 1995, and the Prentice Medal of the American Academy of Optometry in 1997. In 1981, he was elected a member of the National Academy of Sciences. After his retirement, he concentrated on his hobby, research of baseball, writing articles such as "Three Hours Instead of Five: Playing a 2000 World Series Game at the 1948 Pace" published in the journal "Grandstand Baseball Annual." Boynton died on September 4, 2006 [1].

91.1 Boynton MacLeod Physiological Color Space

His key activities revolved around experiments providing new information concerning the neurophysiological processes involved in vision and specifically color vision in the eyes and the brain. He is perhaps best known for his book *Human color vision* of 1979 published in a second, revised edition, co-authored by P. K. Kaiser, published by the Optical Society of America in 1996 [2]. He had a variety of additional research interests, including physiological optics, light adaptation and temporal sensitivity.

In 1968, Boynton and Kaiser developed the minimally distinct border criterion as a third important one in the quantitative assessment of luminance, in addition to flicker photometry and motion photometry. Boynton was interested in developing a psychophysical, colorimetric system based on cone sensitivity functions. In 1972, together with his colleague D. I. A. MacLeod, he proposed a Luther-inspired chromaticity diagram based on normalized cone response functions, with the two axes being $L/(L + M)$ or $M/(L + M)$ and $S/(L + M)$, a system in better agreement with biological facts than the CIE chromaticity system [3]. Figure 91.1 shows the related chromaticity diagram. While widely used in scientific efforts it has not replaced the CIE standards in technology.

During his academic career, Boynton authored and co-authored at least 35 important articles on human color vision. From 1982 to 86, he was also the chairman of the board of editors for the journal Vision Research.

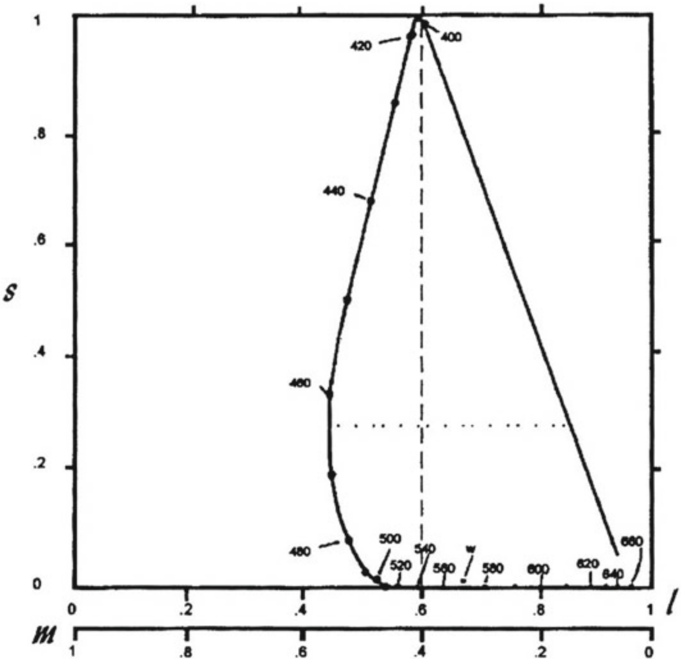

Fig. 91.1 Cone excitation isoluminant chromaticity diagram of the MacLeod and Boynton physiological color space

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Chapter 92

McCamy, Calvin S. 1924–2017

Obituary, The Frederick News-Post

R. Shamey and R. G. Kuehni, *Pioneers of Color Science*,
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Calvin Samuel McCamy was an optical scientist who contributed greatly to color technology and standardization, most notably in useful monographs, test hardware and methodologies, and closed-form approximations. Calvin McCamy was born on September 22, 1924 in St. Joseph, MO. He was in the US Navy (1942–1947), attaining the rank of Lieutenant, junior grade (j.g.). He received B.S. in Chemical Engineering and an M.S. in Physics at the University of Minnesota and taught mathematics there (1947–1950). He taught physics and did early research in colorant formulation at Clemson University (1950–1952). He lived in Edgewater, MD, with his wife, Mabel and passed away on November 12, 2017 in Frederick, MD [1].

At the National Bureau of Standards (1952–1957), McCamy established principles of fire detection in aircraft engines, discovered the mechanism of fire extinguishment by dry chemicals, and studied the hazards of liquid oxygen. As Chief of the Photographic Research Section and then the Image Optics and Photography Sect. (1958–1970), he conducted research on precise measurement of light transmission and reflection, image structure, satellite photography, photography at extreme reduction, optical information theory, optical filters, color perception, and preservation of microfilms. He designed hands-on experiments for the US Science Exhibit at the Seattle World's Fair. In particular, he published a monograph based on the theory of light-balancing filters for camera exposure of color films [2].

In 1970, he and wife Mabel moved to Wappingers Falls, NY.

92.1 Macbeth Color Checker Color Rendition Chart

McCamy was employed by the Macbeth Corporation where he served as Director of Research (1970–72) and Vice President for Science and Technology (1972–89). As Vice President for Research of the Macbeth Division of Kollmorgen (1970–1990), McCamy conducted research on optical design, precise transmission measurements, color measurement, optical filter design, simulation of daylight, geometric attributes of appearance, densitometry in photography and color printing, color order systems, color standards, and related mathematics. He designed the Macbeth ColorChecker Color Rendition Chart$^{\text{TM}}$ [3] used internationally to evaluate color imaging systems of all kinds. He also invented an annular illuminator [4] that would ensure azimuthally uniform illumination (hence, more reproducible measurements) in a 45/0 spectrophotometer.

McCamy was a member of the National Research Council. At the request of Congress, in 1978, he analyzed photographs and X-rays related to the assassination of President Kennedy and testified before the House Select Committee on Assassinations. His method of identifying images of firearms is used routinely by the FBI.

McCamy was active in national and international standardization of photography, color printing, and color science since 1957, chaired committees of the American National Standards Institute, the American Society for Testing and Materials, the International Commission on Illumination (CIE), and the

International Organization for Standardization (ISO). He wrote the spectral specifications for optical character recognition for the banking industry and the Universal Product Code for the grocery and other retail industries.

He was on the Advisory Board of the Munsell Color Science Laboratory at the Rochester Institute of Technology, and was Adjunct Professor at Rensselaer Polytechnic Institute. He was President of the Kollmorgen Foundation and trustee of the Munsell Foundation, both of which awarded doctoral scholarships in color science. He presented seminars on color science around the world, fourteen in Brazil alone.

McCamy published over a hundred scientific papers on color, notably a closed-form approximation to Munsell value [5] and correlated color temperature [6], simulation of daylight [7], and metamers for testing daylight simulators [8]. He was an officer or board member of several scientific societies. He was elected fellow of the Optical Society of America, Society of Photographic Scientists and Engineers, Royal Photographic Society of Great Britain, Society of Motion Picture and Television Engineers, and the Washington Academy of Sciences and has been honored for his lectures. He was elected Honorary Member of the Inter-Society Color Council and the Hong Kong Society of Dyers and Colorists, Life Member of the U.S. Committee of the CIE, and member of the New York Academy of Sciences. He received the 1997 Armin J. Bruning Award of the Federation of Societies for Coatings Technology and the 1999 Godlove Award of the Inter-Society Color Council.

McCamy was a consultant in color science since 1990. His avocations included photography, astronomy, and playing a 240-stop digital organ he built. His compositions include songs, a string quartet, and a circus March “Clown Alley,” which is played on the calliope at the Barnum and Bailey Circus.

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Chapter 93
Wyszecki, Gunter 1925–1985

Courtesy Mrs. Ingeborg Wyszecki

Gunter Wyszecki was a German–Canadian mathematician/physicist who made important contributions to the fields of colorimetry, color discrimination, color order, and color vision [1]. He was born in Tilsit, East Prussia, Germany (today Sovetsk, Russia) in 1925. He attended the Technische Universität Berlin where he obtained a Dr.-Ing. degree, with a dissertation on normal and anomalous trichromacy [2]. In 1953, he was awarded a Fulbright Scholarship and for a year joined Deane B. Judd at the Colorimetry and Photometry section of the U. S. National

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Bureau of Standards in Washington DC. In 1955, Wyszecki joined the National Research Council of Canada in Ottawa where he became the leader of its Optics Section in 1960 and Assistant Director of the Division of Physics in 1982, and where he remained until his untimely death from leukemia on June 22, 1985.

Wyszecki is best known for his scientific contributions to and leadership in the International Commission on Illumination (CIE). He was a chairman of its Colorimetry Committee from 1963 to 1975, vice president of the organization from 1979 to 1983 and its president from 1983 until his death. During this period, the CIE made many important recommendations in colorimetry, remaining valid today, such as 1 nm tables of the color-matching functions of the two CIE standard observers and the standard illuminants A and D65, addition of integrating-sphere reflectance factor measurement as a recommended measuring geometry, the 1964 (U*V*W*) and the 1976 CIELAB and CIELUV uniform color space and color-difference formulas, and others.

93.1 Metameric Black

Wyszecki introduced the important mathematical concept of "metameric blacks," psychophysical definitions of blacks with tristimulus values 0, 0, 0 that, within limits, can be added to a spectral reflectance to form various possible metamers having an identical set of tristimulus values under a given light [3]. With W.S. Stiles, he also developed mathematical methods to calculate by various methodologies the number of possible metamers for given chromaticities, peaking at the achromatic colors [4].

1. *Wyszecki seven-field colorimeter*
   In 1965, Wyszecki developed the seven-field colorimeter with which an observer can view with both eyes one or more of seven hexagonal fields, each with separately controllable RGB sources, achieved with filtered light and mixed in an integrating sphere. It was successfully used in many different research projects.

2. *Color-matching and color-difference matching*
   The MacAdam color-matching error ellipses of 1942 (1 observer) were extended in 1957 to 12 observers by Brown. In 1971, Wyszecki and Fielder determined color-matching error ellipsoids for three observers [5]. The latter two investigations demonstrated the considerable variability by the observer. The seven-field colorimeter was also used for a novel color-difference matching experiment in which three fields were displayed, and the observer had to adjust the third field, so that its brightness matched the brightness of preselected colors

with equal luminance in two fields and its chromaticity resulted in identical perceived differences between the colors in the triangular arrangement [6].

3. *Heterochromatic brightness matching*
   Wyszecki and co-workers added important experimental data to the luminance of equally bright appearing stimuli. Many chromatic stimuli, when compared to achromatic ones of the same luminance or luminous reflectance appear to be lighter or brighter, to be "glowing," an effect known as the Helmholtz–Kohlrausch effect [7].

4. *Publications*
   Wyszecki authored or co-authored 86 scientific papers and three books. The first book, *Farbsysteme,* was published in Germany in 1960 [8], describing various color order systems. He co-authored together with D. B. Judd the second and third editions of the latter's *Color in Business, Science and Industry*, the third edition published after the passing of Judd [9]. He was the lead author, together with W. S. Stiles, of the monumental *Color Science: Concepts and Methods, Quantitative Data and Formulae*, with editions in 1967 and 1982 [10]. The second edition remains in print today as a highly important source of information in the field of color science.

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Chapter 94
De Valois, Russell L. 1926–2003

Property of Karen K. De Valois

Russell De Valois was born on December 14, 1926 in Ames, IA, to missionary parents with whom he spent much of his early years in India. In 1947, he received a degree in zoology and physiology at Oberlin College in Ohio and in 1948 an MA degree in psychology. At Oberlin, he also was a player and for a year the coach of the soccer team. He moved on to the University of Michigan where, in 1952, he received his Ph.D. degree in physiological psychology. De Valois obtained a Fulbright scholarship and as a result spent time at Freiburg University in Germany. There he met a group of postdoctoral fellows working in the laboratory of the

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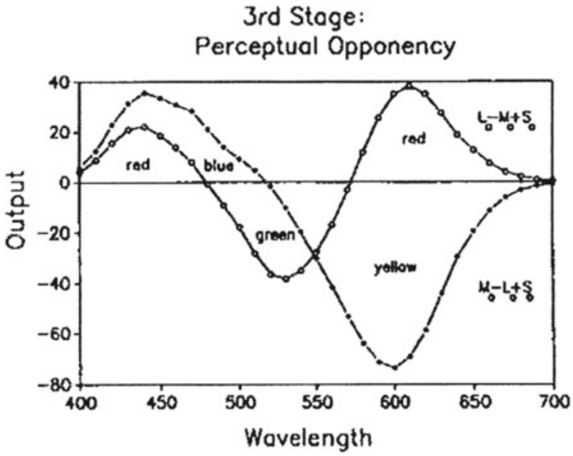
neurophysiologist Richard Jung (1911–1986) on the visual cortex of cats, inspiring in him his lifelong interest in the neurophysiology of vision. He encountered a paper proposing that activities in the lateral geniculate nuclei of the brain might be the biological basis for Helmholtz' theory of color vision. When returning to the USA, he was offered a position at the newly installed Kresge Institute of Ophthalmology at the University of Michigan in Ann Arbor. After five years, he moved to Indiana University where he remained until 1968. There, together with students like I. Abramov and G. Jacobs, he worked on a neural version of the opponent processing model of color vision. From Ann Arbor De Valois transferred to the Department of Psychology of the University of California, Berkley, teaching and conducting research until his death as the result of a car accident on September 20, 2003. One of his partners in research was his wife Karen K. De Valois, with whom he cooperated on several research papers and the book "Spatial vision" (1988). De Valois described his major interest as "the physiological and anatomical organization underlying visual perception" [1].

94.1 A Multi-stage Color Vision Model

Like D.H. Hubel and T.N. Wiesel, De Valois was one of the pioneers of establishing relationships between neurobiological activities related to vision in the brain and the corresponding visual experiences in consciousness. Publications on the subject began in 1958, with a 1960 article titled "Color vision mechanisms in the monkey" [2]. In the mid-later 60 s, the activities in the lateral geniculate nuclei became the focus of investigation. In the 1970s, De Valois and his team investigated the response of single cells in regard to wavelength, saturation, and intensity discrimination. The question of the representation of spatial vision in the brain resulted in joint research between De Valois and his wife Karen and the joint publication of a book on the subject [3]. In the early 1990s, the couple became interested in the question of how to model the classical findings of Hering and Helmholtz with activities beginning in the retina and proceeding in the brain. The effort resulted in the joint 1993 article "A multi-stage color vision model" [4]. The model was built on the earlier ideas of D. Jameson and L.M. Hurvich who in 1955 had proposed a two-stage model [5]. The De Valois realized that the responses of opponent-color cells in the lateral geniculate nuclei were not in agreement with implicit perceptual performance and developed a more complicated four-stage model in general agreement with then current neurophysiological findings. The first stage is represented by absorption of light in the three cone types. The second stage is based on activities in the post-receptoral cells in the eye, with two possible alternative versions. The third stage is the basis of perceptual opponency. Figure 94.1 shows the spectral response curves of the third stage with the cross-overs of the response functions being in good agreement with average perceived unique hues. The fourth stage involves what the authors defined as color-selective complex cells, presumed cells that fire in response to activation of the system at

Fig. 94.1 Response functions of the De Valois third-stage cone-based model of color perception [4]



particular wavelength ranges. In addition, they proposed two achromatic systems: one active in the magnocellular and the other in the parvocellular pathways in the brain.

It is evident that the De Valois model of color perception is very complex and included much information available at the time about activity of the visual system. At the same time, it was somewhat controversial for a number of reasons. More than 20 years later, it appears that the activities in the brain related to color perception are even more complex than assumed by the De Valois and a broadly supported model is still in development.

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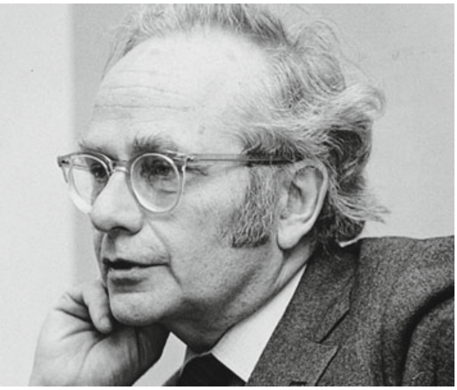
Chapter 95
Hubel, David Hunter 1926–2013



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David Hubel was born on February 27, 1926 in Windsor, Ontario, Canada to American parents. His father was a chemical engineer. The family moved to Montreal where Hubel attended public schools and privately experimented with chemistry and participated in his father's hobby of photography. He attended McGill College in Montreal where he studied medicine, graduating in 1951, followed by a residency at the Montreal Neurological Institute. In 1954, he was offered a neurology residency at Johns Hopkins University in the USA. As a dual citizen, Hubel was drafted for two years into the Armed Forces at the Walter Reed Institute in Washington. There he was able to do neurophysiological research work, beginning with the development of a microelectrode making possible measurement of electrical currents in single neurons of the brains of cats. After moving back to Baltimore in 1958, he resumed work at the Wilmer Institute of Johns Hopkins where he did cooperative work with another researcher, the Swedish neuroscientist

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Torsten Wiesel, who had been involved in making electrophysiological measurements in lateral geniculate cells in cats. This was the starting point of a nearly two-decade long joint effort, ultimately resulting in both of them receiving the Nobel Prize for Physiology or Medicine in 1981. In 1959, Hubel, Wiesel and their mentor Stephen Kuffler were recruited by the Harvard University Medical School where Hubel remained and maintained a lab until much past his official retirement. Hubel died on September 22, 2013 in Lincoln, MA [1].

95.1 Neurobiology of the Mammalian Visual System

Their first research concerned the determination of the receptive fields of neurons of cats in the striate cortex of their brain, finding neurons that respond to straight lines of varying angles and others that respond to movements. With this approach, they opened an entirely new path of research concerning the neurobiology of the mammalian visual system. They expanded the tests to higher mammals, spider and rhesus monkeys and macaques, where they found comparable results. These and further experiments indicated the presence of what they called simple, complex and hyper-complex kinds of cells in different locations of the animals' brains. In rhesus monkeys, they located cells with opponent-color responses as well as cells where color and spatial responses interacted. They determined the lateral geniculate nuclei in the brain to be major transition points of data between the eyes and the vision center at the back of the brain. They identified six layers in the lateral geniculate nuclei (LGN) in which different aspects of the information received in the retinas is processed before being passed on to the visual center in the back of the cortex (Figs. 95.1 and 95.2). They followed the information from the LGNs to the cortex. There they identified layers in so-called ocular dominance columns where the information is further processed depending on the dominant function of the column of cells: motion, brightness, color, etc.

Another field of their research was the effect of early visual deprivation on how the physiology of the visual system is expressed in the brain, indicating that deprivation results in damage from which the visual system does not completely recover.

Hubel and Wiesel co-authored a total of 28 articles describing their extensive and revolutionary research work into the neural complexity of the mammalian visual system, laying much of the foundation of an expanding field of knowledge that, however, continues to remain incomplete. Hubel and Wiesel ended their cooperation in the mid-1970s. Hubel began collaborations with other vision researchers: Margaret Livingstone, Stephen Macknik/Susana Martinez-Condé and others [1].

Fig. 95.1 (Left) Sketch of the cross-section through a lateral geniculate nucleus (LGN) of a monkey showing the six layers of neurons that process data obtained from post-retinal neurons in both eyes. *i* indicates information from the eye on the same side as the LGN (ipsilateral), *c* indicates information from the opposite eye (contralateral). Each layer contains a representational map of the field of vision, with the maps precisely aligned [1]

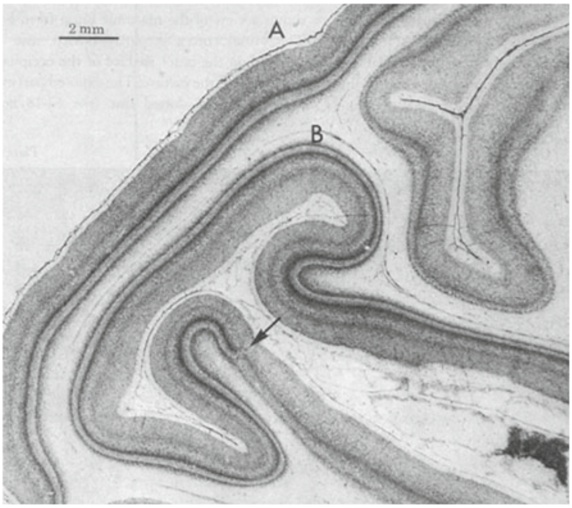

Fig. 95.2 (Right) View of layers of the visual area of the cortex of a cat, with A representing the outer and B an inner layer of the cortex. Different internal layers can be distinguished, being representative of the six layers identified by Wiesel and Hubel in LGN as well as the cortex [1]

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Chapter 96
Bartleson, C. James 1929–1987

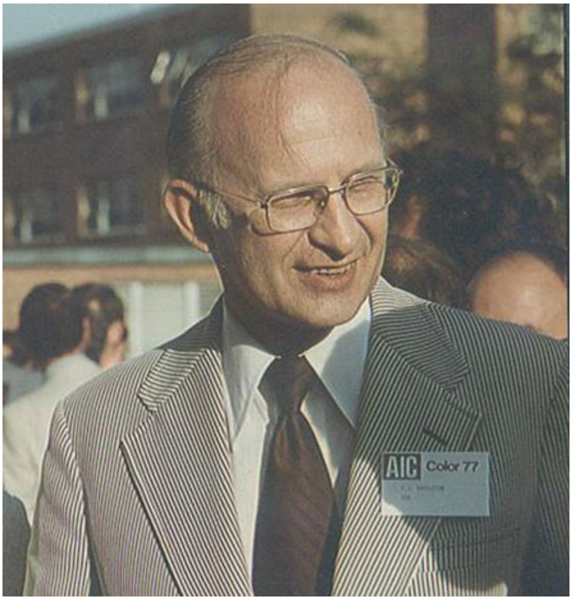

Image courtesy of R.W.G. Hunt

C. James Bartleson was an American color scientist who made very important contributions to colorimetry and visual science.

Bartleson graduated as an Associate of Photographic Science at the School of Photography at Rochester Institute of Technology (RIT), Rochester NY, USA, in 1951. He received a Ph.D. at the City University, London, England, in 1977.

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After high school, he enlisted in the marines and served as a frogman using photography. After his discharge in 1948, he spent a year doing freelance aerial photography and then enrolled in the School of Photography at RIT to obtain his degree of Associate of Photographic Science in 1951. There followed a three-year period working on the new Ansco Plenachrome system at the Pavelle Color Corporation in New York City.

96.1 Bartleson–Breneman Effect

In 1952, he moved to Rochester, NY, to start a career with the Eastman Kodak Company. His first assignment was in the Color Control Department under Ralph Evans, but his flair for research was noticed and in 1957 he moved to the Physics Division where he started his research on color and tone reproduction which led to the publication of a series of very significant papers, one of the most outstanding, in 1967, co-authored with Ed Breneman, being on the effect of light and dark surrounds on apparent contrast. His papers attracted various awards, and he was one of the first recipients of the C. E. K. Mees Award. He was also author, co-author, or editor of several books, including the five-volume series on "Optical Radiation Measurements." He was also much sought after as a lecturer, and his award of the British Colour Group's Newton Medal was accompanied by a masterly presentation [1].

In 1967, his outstanding reputation led him to be chosen to establish a research facility for the Macbeth Company, later the Macbeth Color and Photometry Division of the Kollmorgen Corporation, in Newburgh, NY.

When his time at Kollmorgen came to an end in 1974, the following year, at the then age of 45, he enrolled in the School of Ophthalmic Optics and Visual Science at The City University, London, England, and obtained his Ph.D. in 1977. With typical enthusiasm, he constructed an ingenious apparatus for studying the effects of adaptation on perception, and the resulting thesis was of outstanding quality.

He then returned to Rochester, NY, to resume his career at Kodak, where he soon established a reputation as a most valuable consultant for other members of the staff.

He was President of the Association Internationale de la Couleur (AIC) from 1978 to 1981, reviving it from a moribund state, and he took part in several committees of the CIE (Commission Internationale de l'Éclairage).

His main interests included optics, vision, photometry, colorimetry, color perception, color applications, and color photography. His leisure interests also included photography and travel.

Bartelson was a co-author of R. W. Breneman, R. M. Hanes and C. J. Bartelson, *Color: a Guide to Basic Facts and Concepts*, New York: Wiley 1963. He was the co-editor with Franc Grum of Vol. 2 in the five-volume series Optical Radiation Measurement, titled *Color Measurement*, New York: Academic Press 1980.

He also authored some 50 original papers, mainly dealing with color photography and vision.

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Chapter 97
Nayatani, Yoshinobu 1927–2009

Courtesy of the color science association of Japan

Yoshinobu Nayatani was a Japanese color scientist who made significant contributions to the development of color appearance models and contributed diligently to the color research community. He was born in 1927 and passed away on May 29, 2009, in Hyogo prefecture in Japan [1].

He obtained a bachelor of electrical engineering from Osaka University in 1951. After graduation, he accepted a position at the Electro-Technical Laboratory of

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Japan (ETL) and in 1952 worked as technical officer in the Ministry of International Trade and Industry (MITI). His activities included photometry, colorimetry, and fundamental theory of illumination engineering. Over this period, he continued his higher education and obtained a Ph.D. from Osaka University in 1961. From 1962 to 1963, Nayatani studied at the National Research Council of Canada as a post-doctoral fellow under the advisement of Gunter Wyszecki to examine visual colorimetry. In 1974, he became the Director of the Osaka Branch of ETL where he continued to work until his retirement in 1980 [2].

He joined the Faculty of Engineering at Osaka Electro-Communication University as a junior college professor in 1980 and in 1982 accepted the position of professor from the Faculty of Engineering of the same university. From 1995 to 1997, he served as the Dean of Faculty of Engineering, and in 1998, he became an Emeritus Professor and then served on the Board of Trustees from 1999 to 2002.

97.1 Color Appearance

Nayatani served on the Editorial Board of the journal *Color Research and Application* from 1977 until 2008. He served as President of the Color Science Association of Japan from 1984 to 1986. He was an active member of the CIE and served as Chairman of Division 1 technical committee TC 1.3 on Standard Sources for 8 years, and of TC 1.32 on Prediction of Corresponding Colors. He was an honorary member of the Japanese National Committee of CIE, the Color Science Association of Japan, Illuminating Engineering Institute of Japan (IEIJ), and Japanese Society for Quality Control. He was the chair of the organizing committee for the International Colour Association (AIC) quadrennial conference in Kyoto in 1997 and facilitated the development of the first CIE approved color appearance model that became known as CIECAM97s. He also served as the Chairman of the organizing committee of the International Color Science Association of Kyoto Games from 1995 to 1999.

He received several awards for his contributions to the field of color science. His most notable awards include the Illuminating Engineering Institute of Japan Prize (1966), the Deming Prize for individual contribution to quality management (1985), and in 1990 the Illuminating Engineering Institute of Japan award for the paper "Optical Density Functions of Lens and Macular Pigment Estimated from the Color Matching Functions." His contributions to the field of color science were also recognized by the AIC in 1993 when he was selected as the recipient of the prestigious Deane B. Judd Award. In 1997, he received the Isao 4 award in Japan. He also received an award from The Color Science Society of Japan in 1998. A special testimonial for color technology was organized in his honor in 2003 by "Suga Foundation for Promoting Weathering Technology."

His professional interests pertaining to color covered information processing at the interface between psychology and physics as well as color engineering (color appearance and metamerism). He published several papers on the relationship between color order systems, color appearance [3], and color difference.

Among his publications were some manuscripts concerned with the special role of gray and adding gray as a central color in the opponent color order system. In this approach, the two opponent axes would be changed from red–green to red–gray and gray–green and from yellow–blue to yellow–gray and gray–blue. He continued contributing to color science right up to his death. Although some studies seemed to support the special role of gray, this proposal has not been further investigated.

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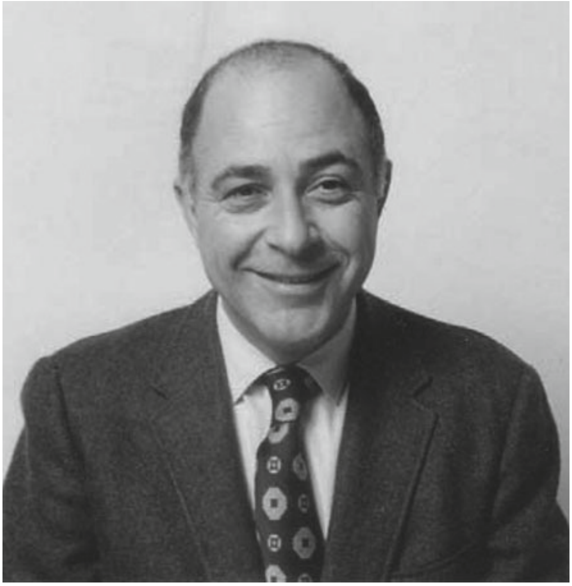
Chapter 98
Stanziola, Ralph A. 1931–2007



Donated by Ralph A. Stanziola

Ralph A. Stanziola, a consultant and teacher of color technology, was born in Philadelphia in 1931, received his B.S. degree in Chemistry from the Philadelphia College of Textiles and Science (now Philadelphia University), and resided most of his life in New Jersey. In his early years, at the Research and Technical Service for the Dyes Department of the American Cyanamid Company, Ralph learned color technology from such pioneers as Orrin W. Pineo and Edward I. Stearns. He next served for nine years as Technical Representative and General Sales Manager for the Davidson and Hemmendinger Company, and later became a Sales Manager for

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the Kollmorgen Corporation Color Systems division, which had acquired Davidson and Hemmendinger. He died on August 25, 2007, in Bridgewater, NJ, at the age of 75. He was married to Elsie Perantoni Stanziola.

In 1970, Ralph co-founded Applied Color Systems, Inc., where he eventually became the Executive Vice President and Technical Director. In May 1985, Ralph founded Industrial Color Technology, a consulting company under whose auspices he solved many industrial problems involving color control. For the rest of his life, Ralph remained a consultant for ACS (later named Datacolor), instructed their color technology seminars, and helped to create the first video training series on color technology.

98.1 Color Rule

Ralph held five US patents [1–5] and authored a large number of technical papers and presentations. He developed the Color Curve System for color communication and helped The Glad Products Company to develop the now-famous "Glad Difference," *Yellow and Blue Make Green*® seal. Less familiar will be his development (with Bob Swain of Chroma Corp.) of a method of using a colored sample to test the wear of a metal piece. The test consists of extruding a molded plastic piece made of component materials of two different colors and monitoring the color of the mixture. Earlier, Ralph developed the first colorant-dispenser system driven by computer color matching (1979) and patented a Maxwell-disk-based color simulator (1980). He also co-developed an asymmetrical color-tolerancing system using artificial intelligence algorithms (1991), a photonic visual color simulator using LEDs (late 1990s), and a new version of the Color Rule for testing observers and light booths for metamerism (2006).

Ralph joined the ISCC in 1962 and was an active member for the rest of his life. He co-chaired several ISCC meetings: the annual meeting in Princeton in 1992 that celebrated the 25th anniversary of the AIC; the 1994 joint meeting with the DCC; and the 2003 Williamsburg Conference on Industrial Color Problems held at Philadelphia University. He was instrumental in setting up the Education Interest Group and was the first to chair the Industrial & Applied Color Interest Group. In recognition of these contributions, Ralph received the 2004 Nickerson Service Award, and in 2005 became an Honorary Member of the ISCC. He also served as *Color Research and Application*'s Special Editor for Industrial Applications for 10 years.

In 1995, the Technical Association of the Pulp and Paper Industry presented Ralph with their Finest Faculty Award. As a member of the Federation of Societies for Coatings Technology, he received the Armin J. Bruning Award for his outstanding contribution to the science of color in the field of coatings technology. He was also a member of the American Association of Textile Chemists and Colorists, and the Detroit Colour Council.

Ralph’s numerous lectures included computer color-matching seminars at the Rensselaer Color Measurement Laboratory (Rensselaer Polytechnic Institute) and at the Munsell Color Science Laboratory (Rochester Institute of Technology). The many personal anecdotes he told in his color courses showed a wealth of experience not available in any book. Some urged him to write a book, but he preferred the humbler route of interacting directly with the world and with other people.

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