Colour and Light
Compendium

Ulrich Bachmann / Marion Bernhardt

The Compendium provides descriptions and visual demonstrations of important concepts relating to colour and light. Its purpose is to explain relationships involving light and colour in scientific terms. The complete Compendium is found on the DVD-ROM of the multimedia publication COLOUR AND LIGHT. The book presents a small selection of terms.
Each concept is covered on one or two pages (A4, horizontal format) and can be printed out as a pdf document. Individual pages or sections can also be projected with a beamer for instructional purposes.
The Compendium is divided into three sections: Design, Physics/Engineering/Chemistry and Biology.
The concepts are organized by subject area. In some cases, concepts discussed in the Compendium encompass corresponding sub-concepts as well. All terms are listed in alphabetical order in the index.
The publication was created within the scope of the ColourLightLab research project (2005/2006) by the University of the Arts, Zurich and is aimed at teachers, students and other persons interested in colours.

Concept/Realisation: Marion Bernhardt
Illustration: Marion Bernhardt, Jecca Reichmuth
Layout: Florian Bachmann
Fotos: Mik Gruber
Editorial direction: Cecilia Hausheer
Copy editing: Kirstin Meditz
Translations: John Southard
Project direction: Ulrich Bachmann

CONTENTS

Information – Compendium
Contents
Alphabetic Contents

DESIGN
K01 Colour
K02 Colorimetry
K02 CIE colour system
K04 Additive colour mixture
K05 Subtractive colour mixture
K06 distinction characteristics I
K07 distinction characteristics II
K08 Colour appearance

PHYSICS, TECHNIQUE, CHEMISTRY
K09 Colour (physical)
K10 Luminescence
K11 Colour temperature
K12 Substantive colours
K13 Pigments
K14 Binders
K15 Dyes
K16 Light (physical)
K17 Wave model
K18 Particle model
K19 Refraction
K20 Interference colours
K21 Polarization
K22 Filters
K23 Dichroid filters
K24 Geometric optics
K25 Positive lens
K26 Dispersion
K27 Edge spectra
K28 Shadow
K29 Light scattering
K30 Colour printing: CMYK
K31 Screens: RGB
K32 Beamers
K33 LED
K34 White balance
K35 Physical values and units

BIOLOGY
K36 Colour vision
K37 Visual perception
K38 Optic tract
K39 Colour processing
K40 Colour constancy
K41 Light (biological)
K42 Sense of light
K43 Eye
K44 Types of eyes
K45 Human eye
K46 Absorption spectrum
K47 Light-sensing cells
K48 Human light-sensing cells
K49 Rods
K50 Cones
K51 Rods – cones
K52 Light reactions
K53 Light signals
K54 Purkinje phenomenon
K55 Three-colour theory
K56 Four-colour theory
K57 Retinal colour blindness
K58 Afterimage
K59 Adaptation
K60 Retina
K61 Retinal structure
K62 Fovea centralis
K63 Accommodation
K64 Eye movements
K65 Receptive fields
K66 Optical colour mixture
K67 Contrast enhancement
K68 Simultaneous contrast
K69 Assimilation
K70 Colour shadow

Index
References for illustrations

ALPHABETIC CONTENTS

A Absorption spectrum K46
Accommodation K63
Adaptation K59
Additive colours mixture K04
Afterimage K58
Assimilation K69
B Beamers K32
Binders K14
C CIE colour system K02
Colorimetry K02
Colour (physical) K09
Colour appearance K08
Colour constancy K40
Colour K01
Colour printing: CMYK K30
Colour processing K39
Colour shadow K70
Colour temperature K11
Colour vision K36
Cones K50
Contrast enhancement K67
D Dichroid filters K23
Dispersion K26
Distinction characteristics I K06
Distinction characteristics II K07
Dyes K15
E Edge spectra K27
Eye K43
Eye movements K64
F Filters K22
Four-colour theory K56
Fovea centralis K62
G Geometric optics K24
H Human eye K45
Human light-sensing cells K48
I Interference colours K20
L LED K33
Light (biological) K41
Light (physical) K16
Light reactions K52
Light scattering K29
Light signals K53
Light-sensing cells K47
Luminescence K10
O Optic tract K38
Optical colour mixture K66
P Particle model K18
Physical values and units K35
Pigments K13
Polarization K21
Positive lens K25
Purkinje phenomenon K54
R Receptive fields K65
Refraction K19
Retina K60
Retinal colour blindness K57
Retinal structure K61
Rods – cones K51
Rods K49
S Screens: RGB K31
Sense of light K42
Shadow K28
Simultaneous contrast K68
Substantive colours K12
Subtractive colour mixture K05
T Three-colour theory K55
Types of eyes K44
V Visual perception K37
W Wave model K17
White balance K34

K01 COLOUR

Artists and designers, physicists, chemists, biologists, psychologists, philosophers and people from many other fields have made significant contributions to the study of colour.[1] Newton was the first to investigate the physical properties of sunlight. His most famous experiment was the division of white light into the colours of the rainbow with the aid of a glass prism. Goethe was Newton's most vociferous critic. He took a phenomenological approach to colour. Today, we realize that both of these great scholars gained important insights that are actually quite compatible with one another.

Colour is a phenomenon that has physical, physiological and psychological components. One of the physical properties of surfaces is their capacity to absorb or reflect light. The nature of this light depends upon the spectral composition of the illuminating light source, which is the primary determinant of every colour effect. This physical aspect of "colour" is what is known as "colour stimulus", to which the light-sensing cells in the eye of the observer respond. The processes colour sets in motion within these sensory cells make up its physiological component, and this aspect of colour is known as "colour valence". "Colour sensations" are generated by signals transmitted by the light-sensing cells via the optic nerve to the brain. This is the psychological component of colour.

Every colour is also characterized by its specific hue and degrees of saturation and brightness.

1 Cf. John Gage, *Kulturgeschichte der Farbe. Von der Antike bis zur Gegenwart, London, 2003.*

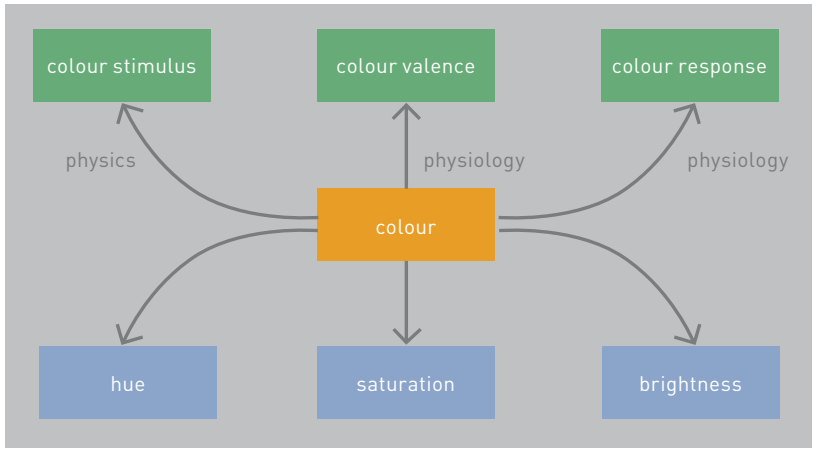


Fig. Overview of the characteristics of colour by component

K02 COLORIMETRY[1]

Precise measurement and classification of coloured light is an indispensable prerequisite for many technical applications. This is the function of colorimetry. Examples of such technical applications include computer screens, colour televisions and digital cameras. The addition of coloured light by means of additive colour mixture serves as the basis for precise colour communication.

Spectrophotometric instruments are used to determine which light waves are reflected by or allowed to pass through a sample. The composition of the illuminating light used in such tests can also be measured precisely. These two values characterize colour stimulus. They are identified for the entire visible spectrum, i.e. from 380 to 760 nanometres. Colour stimuli are objective phenomena and can therefore be readily expressed in numerical form.

Another phenomenon studied with the aid of colorimetry is colour valence, which describes the physiological effects of a colour stimulus in the eye of the observer. The terms colour and colour valence are often used synonymously and represent a mathematically definable value with three dimensions, which thus has a spatial character. These dimensions are the three base colours of red, green and blue involved in addititive colour mixture, as defined in three-colour theory. They represent the RGB colour spectrum. Individual colour valences always have red, green and blue components, which are referred to as colour values. These, too, can be calculated precisely.

Colour stimulus, colour valence and colour value can be defined precisely and are useful factors in the mathematical description of colour in colorimetry.

1 Cf. G. A. Agoston, *Color Theory and its Application*, in *Art and Design,* second completely revised and updated edition, Berlin, Heidelberg, 1987, pp. 47 – 65 and 66 – 104.
Cf. Günter Wyszecki, *Farbsysteme*, Göttingen, Berlin, Frankfurt, 1960, pp. 21 – 37.
Cf. Stephen E. Palmer, *Vision Science. Photons to Phenomenology,* Massachusetts Institute of Technology, 1999, pp. 689 – 700.

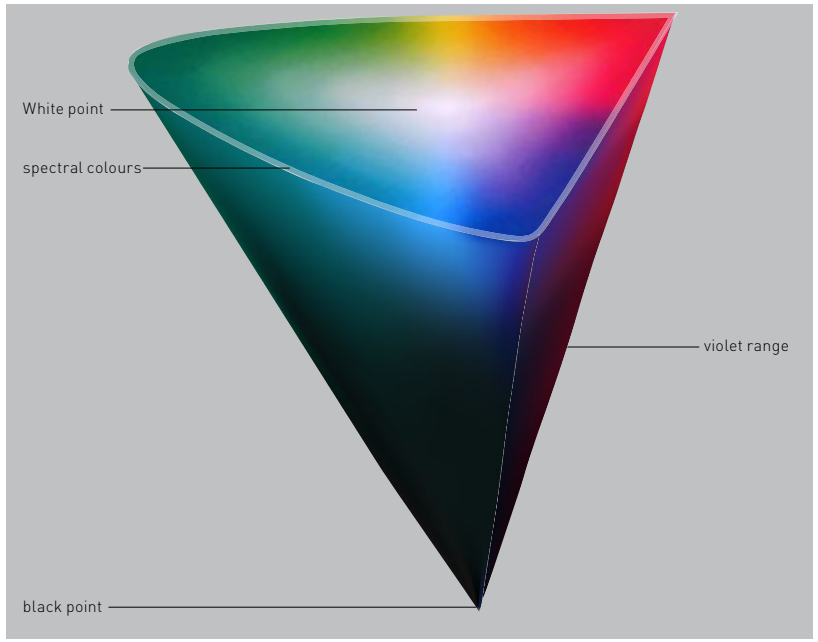
K02 CIE CHROMATICITY DIAGRAM

The CIE colour spectrum has been defined on the basis of the laws governing additive colour mixture, i.e. the mixture of light waves of differing lengths. It is named after the Commission Internationale de l'Éclairage (International Lighting Commission). This standardized colour spectrum represents a response to a practical problem, as it was determined that certain additive light mixtures representing pure spectral colours (which are therefore highly saturated) cannot be produced through the simple addition of the three base colour red, green and blue. Thus virtual base colours were defined through mathematical conversion and designated as X, Y and Z rather than red, green and blue.[1] X stands for virtual red, Y for virtual green and Z for virtual blue. All physically extant colours (colour valences)

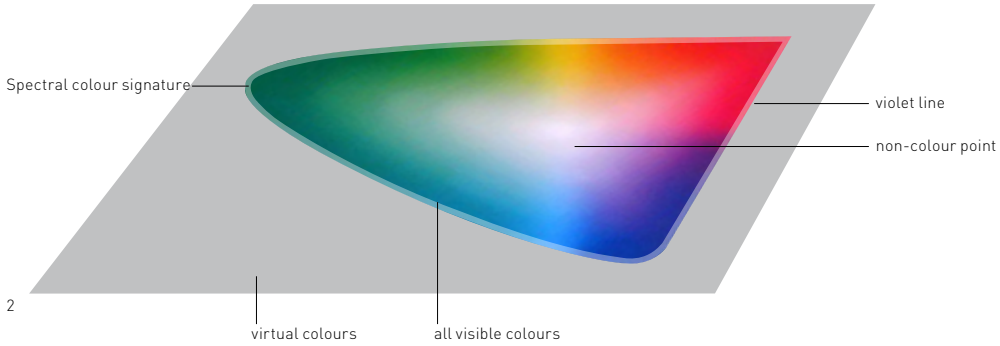
The CIE Commission went on to develop a profile of the so-called standard observer based on an average of measurements for a group of 17 people. The study was initially limited to sharp vision in bright daylight as registered by the fovea. The field of vision was subsequently extended to 10 degrees.

The colours in the CIE colour spectrum are arranged as parts of a colour body (Fig. 1), which has the shape of a cone flattened on one side. The cone is upside-down, i.e. points downward. The tip of the cone lies at the black point, the origin of the base colours and all other colours. The colour body has a curved outer surface, on which the spectral colours are arranged, and a flat side surface, on which the purple colours are located. This conceptual body stands as a model behind the horseshoe-shaped CIE chromaticity diagram (Fig. 2).

Fig. 1 Colour body in the CIE colour spectrum. All colours originate from black. Every possible type of colour is located inside the colour body. The purple colours lie on a flat side surface, the spectral colours on a curved surface.
Fig. 2 The bottom of the colour body lies at the level of white. All visible colours lies within the enclosed area. Only virtual colours lie outside it. The spectral colour curve and the purple line are indicated.



1



2

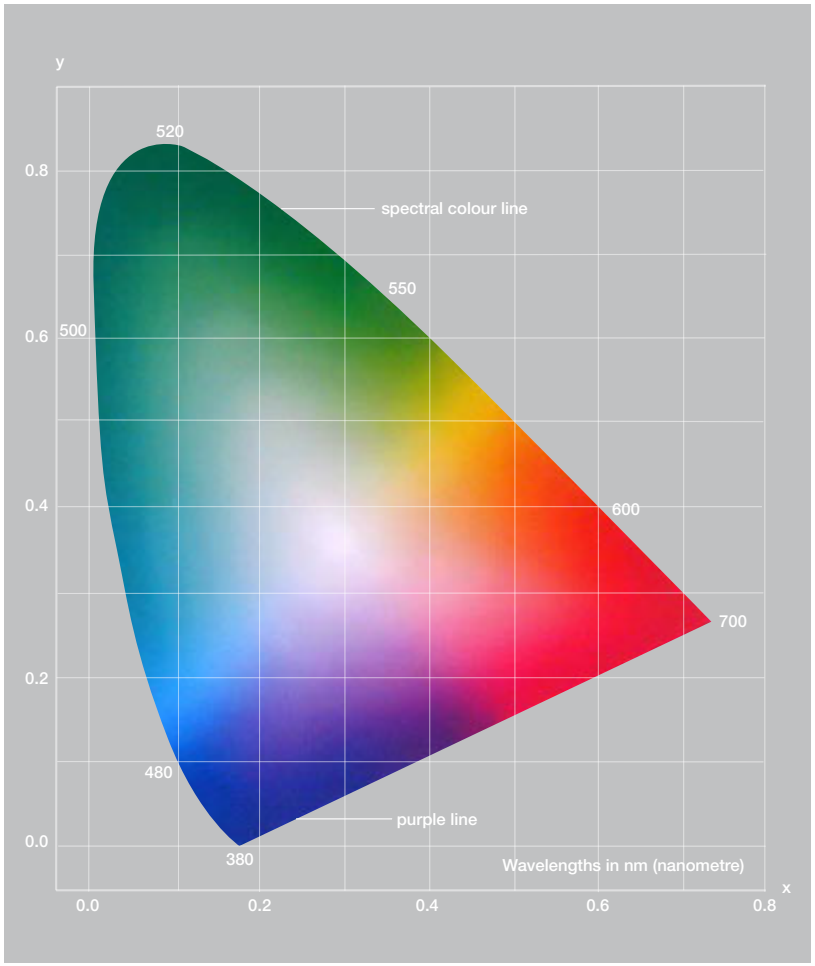
When the bottom of the colour body coincides with neutral white, i.e. the achromatic point, the sum of the values of red, green and blue is 1.[2] The achromatic point represents the midpoint of the horseshoe-shaped bottom surface of the colour body. It has a value of 0.333 for all variables. The surface is the actual CIE diagram (Fig. 3). It contains the standard variables x and y. The small z is missing is missing in the CIE diagram. It can be calculated by subtracting x and y from 1.

The horseshoe-shaped line along which the spectral colours lie is referred to as the spectral colour range. The straight line is called the purple line. All colours that are visible under a specific illumination are encompassed by the two.

Colours are defined mathematically with CIE terms, e.g. CIE (x,y,Y) $CIEILLD_{65}$. In this example, $CIEILLD_{65}$ represents a standard light source with a colour temperature of 6500 Kelvin. The x and y values represent the concentrations of red and green. The result of simple subtraction of these two values from 1 is z, i.e. the blue concentration of the specified colour. Because the chromaticity diagram lies at the level of 1, it provides no information about the brightness of a colour. The value Y represents the brightness sensitivity of the green light-sensing cells in daylight vision. Thus Y, the value for virtual green, is a reference for brightness.

If brightness diminishes, the CIE chromaticity diagram is shifted within the colour body toward the black point. The positions of the individual colours does not change relative to each other; all colour locations are retained. A type of colour is defined by its exact position within the CIE colour body. When it is multiplied by a brightness value, the result is a specific colour valence or colour. It is the type of colour that defines a colour regardless of illumination. The perceived colour hue is derived by multiplying the type of colour by the brightness value.

Fig. 3 CIE chromaticity diagram



Mixtures of coloured light can be reconstructed with the aid of the CIE chromaticity diagram. When two colour locations are connected by a straight line, all possible mixtures lie along that line. If, for example a straight line is drawn from a spectral colour through the achromatic point, the corresponding complementary colour will be found at the intersection of the line with the opposite line. In other words, complementary colours produce white light. As one moves closer to the achromatic point on the chromaticity diagram, colour saturation diminishes toward zero. Conversely, as one moves from the achromatic point to the spectral colour curve or the purple line, colour saturation increases toward 100%. Pure spectral monochrome light as a saturation value of 100%.

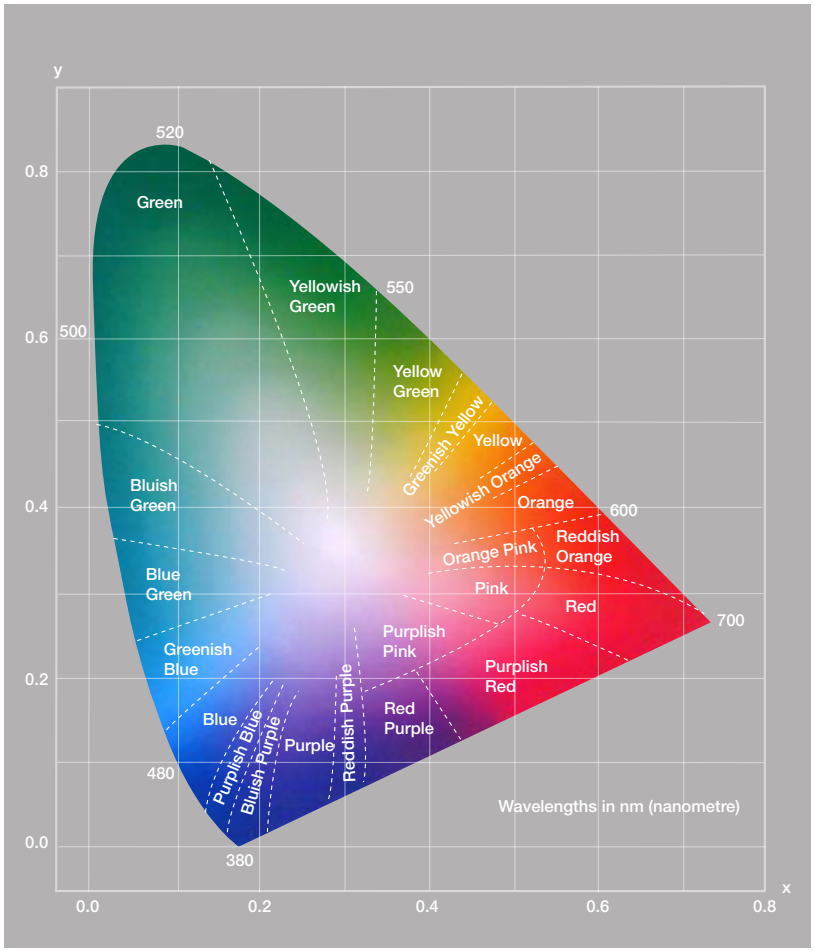
Computer screens also work with light mixtures composed of the three base colours red, green and blue. Their positions can be inscribed in the CIE chromaticity diagram, forming a triangle. Enclosed within the triangle are all of the colours that can be displayed on the screen.

The range of colours available to a four-colour printer can be represented as a polygon in the CIE chromaticity diagram. When the triangle of the screen is superimposed over the polygon of the printer, one recognizes that not all of the colours displayed by the screen can be printed and, conversely, that other colours can be printed but not displayed on the screen.

1 Cf. G. A. Agoston: *Color Theory and its Application*, in *Art and Design*, second completely revised and updated edition, Berlin, Heidelberg, 1987, pp. 47 – 65 and 66 – 104.
Cf. Günter Wyszecki, *Farbsysteme*, Göttingen, Berlin, Frankfurt, 1960, pp. 21 – 37.
Cf. Stephen E. Palmer, *Vision Science. Photons to Phenomenology,* Massachusetts Institute of Technology, 1999, pp. 689 – 700.

2 Cf. Wyszecki, *Farbsysteme*, op. cit., p. 30.

Fig. 4 CIE chromaticity diagram with colour names



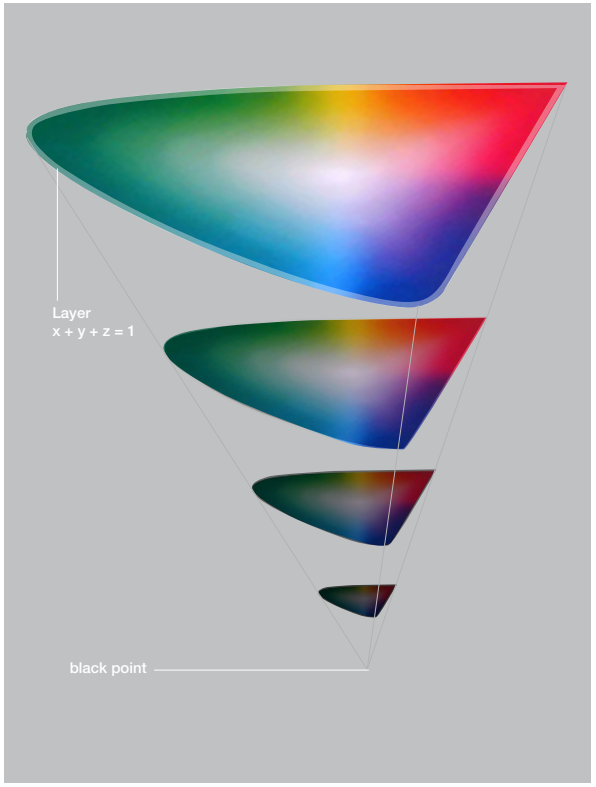


Fig. 5 Darkening as a shift of the chromaticity diagram toward the black point. The colour locations do not change. Only brightness changes.

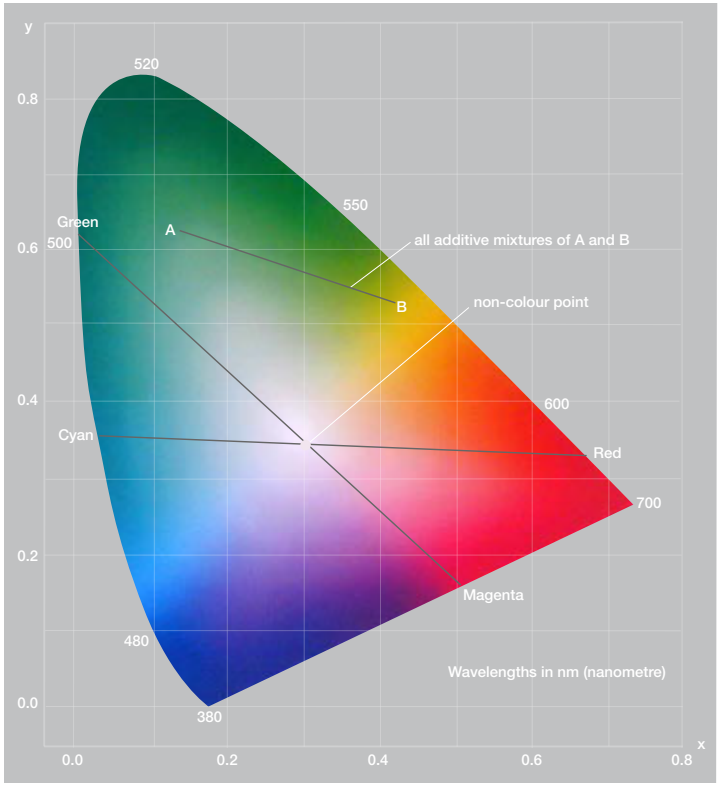


Fig. 6 Straight lines connecting colours A and B, the complementary colours green and magenta, cyan and red, as a description of additive colour mixture

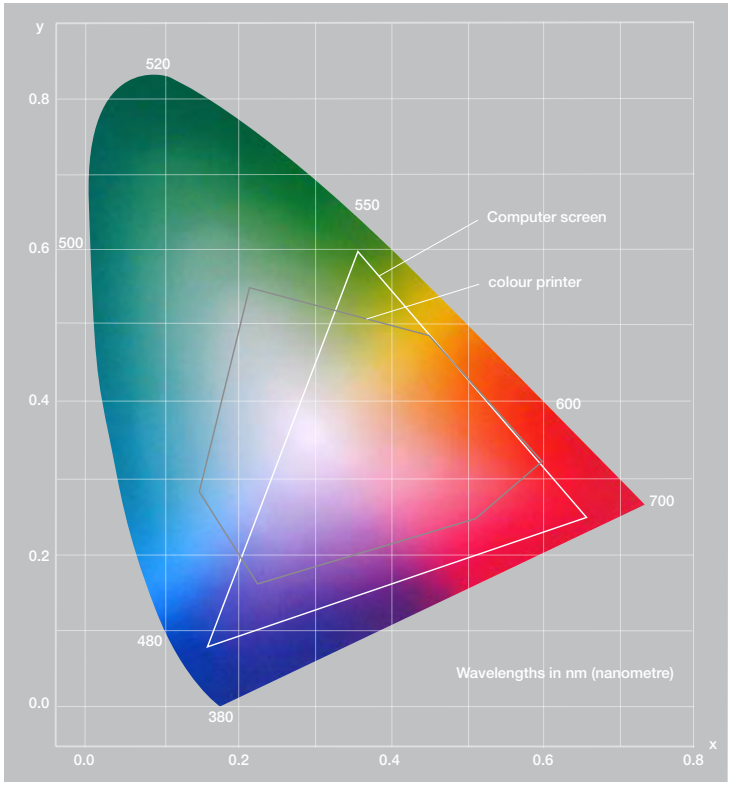


Fig. 7 The colour range of a screen as compared to a colour printer.

K04 ADDITIVE COLOUR MIXTURE

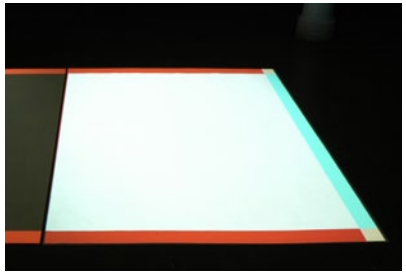
When light waves of different wavelengths overlap, the values of their spectra are added together. Thus we speak of additive colour mixture. It is easily described in mathematical terms, as opposed to subtractive colour mixture, which involves reciprocal effects of interaction with the colour substance. Additive colour mixture is based on pure light that is mixed without reciprocal influence.

The more a different colour light is added, the closer the mixture comes to white light. Conversely, white light can be broken down into its component spectral colours by a prism. Only three light waves are required to produce white, achromatic light. These are light waves that have not been produced through mixing. For technical purposes, it is specified that these must be a certain red, green or blue. These three base colours form the mathematical basis for colorimetry.[1] Mixtures of these colours encompass all of the colours that can be displayed on a screen. The following formula applies to these mixtures:

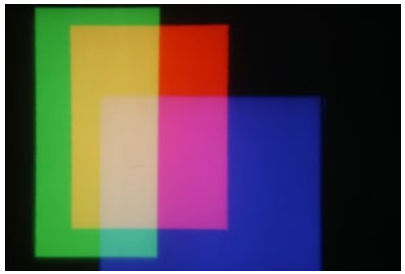
Colour = red component + green component + blue component.

This is known as the "internal" additive colour mixture. However, it is not sufficient for the computation of all possible hues. The "external" colour mixture is also required for this purpose. One of the three base colours is added to the colour which cannot be mixed using the "internal" mixture formula. The sum equates to the sum of the other two base colours.

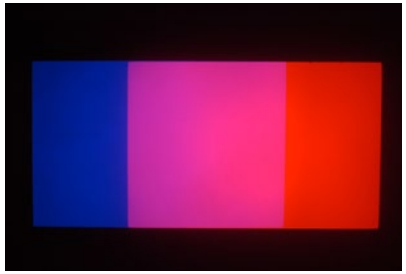
1 Cf. Günter Wyszecki, *Farbsysteme*, Göttingen, Berlin, Frankfurt 1960, pp. 21 – 37.



1

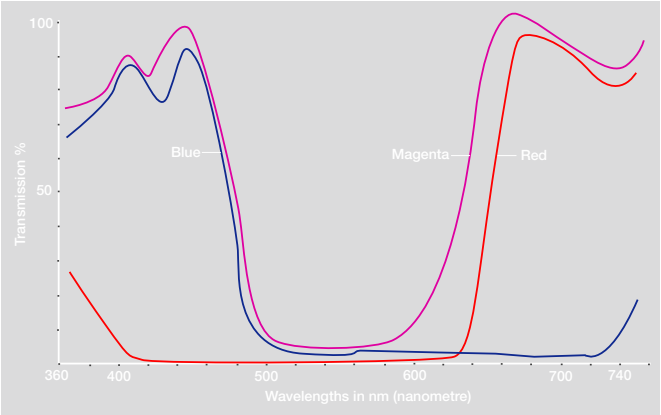


2



3

Fig. 1 The example in the "Pigment Carpet" installation shows the additive colour mixture white, which is composed of red and cyan-coloured light.
Fig. 2 When light colours are mixed, brightness increases. White light is the sum of all light colours.
Fig. 3, 4 When light that passes through a blue filter is mixed additively with light that passes through a red filter, the two spectra are added together. The resulting magenta contains both colours, i.e. red and blue.



4

K05 SUBTRACTIVE COLOUR MIXTURE

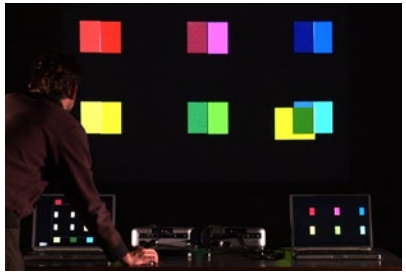
The world of subtractive colour mixtures is the world of material substances. Pigments, dyes, paints and even colour filters possess properties which, when mixed, always result in a reduction of reflected or filtered light, i.e. to a "subtractive" result. Mixing all of the colours in a paint box produces a dark-grey, dirty, dull mass. The pure individual colours eradicate each other through reciprocal absorption. No colour information reaches the eye. The mixed paint appears dark and colourless.

The greatest degree of subtraction produces black. Colour filters arranged in a series show a clear process of subtraction: the first colour filter allows only a little coloured light to pass, from which the second filter removes more light, and so on until no more light can pass through the sequence of filters.[1]

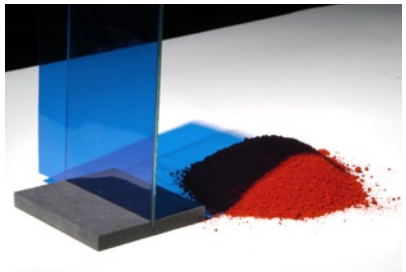
When white light falls on a coloured substance, the substance filters out all components of the spectrum except for the colour or hue that is finally transmitted to the eye. When coloured light fall on a coloured substance, the outcome is the same as that produced when light passes through two successive colour filters. When a coloured substance is illuminated with its complementary colour, it absorbs all of the incoming light particles, i.e. none of the incoming light is reflected. The spot illuminated in this way appears black. This extreme outcome is achieved only when true complementary colours are involved, as the one colour must absorb the other completely.

Because subtractive colour mixture always depends on the material characteristics of the substances involved, it is very difficult to calculate the result of mixture with a second colour in advance. Mixtures can be different in colour even when apparently similar substances are mixed with another substance. Cyan, magenta, yellow and black, as the "key colour", are the based colours from which all other colours can be mixed in colour printing.

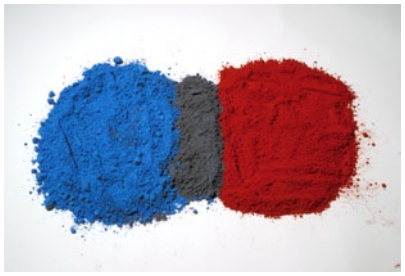
1 Cf. Stephen E. Palmer, *Vision Science, Photons to Phenomenology,* Massachusetts Institute of Technology, 1999, pp. 693f.
Cf. Günter Wyszecki, *Farbsysteme,* Göttingen, Berlin, Frankfurt 1960, pp. 37 – 42.



1



2



3

4

Fig. 1 The "Intermediate Colours" installation demonstrates that illumination of colour cards with coloured light produces subtraction. The mixtures produced through subtraction are the familiar mixed colours found in a paint box.
Fig. 2 The extreme case of subtraction is the illumination of a colour with its complementary colour. Though it seems paradoxical, the illuminated surface appears black.
Fig. 3 The mixture of two pure pigments produces a subtractive mixed colour.
Fig. 4 Colour filters and pigments behave in the same way. When white light passes though two successive colour filters, the visible outcome is the subtraktive mixed colour.

K06 COLOUR DISTINCTION CHARACTERISTICS I

Chromatic colours (Fig. 1): all colours (or hues) other than the neutral (achromatic colours)
Spectral colours (Fig. 2): highly saturated chromatic colours
Achromatic colours (Fig. 3): the neutral colours of black, white and grey
Complementary colours (Fig. 4-6): two colours that produce a grey-black when mixed. In most colour systems, including the "Colour Dimensions", these are positioned opposite one another.
Base colours (Fig. 7 and 8): cyan (C), magenta (M), lemon yellow/yellow (Y) are the primary colours used for substance mixtures. Red (R), green (G) and blue (B) are the primary colours for coloured light mixtures. Conversely, RGB are the secondary colours for substance mixtures and CMY the secondary colours for coloured light mixtures.
Warm and cold colours (Fig. 9): The terms "warm" and "cold" are not precisely defined colour distinction characteristics but rather descriptive terms for mood values or tendencies in a certain direction. Vermilion (red tending toward orange) is ordinarily referred to as the warm pole, cyan as the cold pole. The warm colours are associate with activity, cold colours with passivity. In the "Colour Dimensions" system, the colours are arranged in warm and cold groups, i.e. the warm yellow-red group on the left and the cold blue group on the right side. Within the warm and cold groups, further distinction is made between warmer and colder hues. In the yellow-red group, the hues become warmer as they move from yellow to vermilion. In the blue group, the hues grow progressively colder from ultramarine toward cyan.

Cf. Johannes Pawlik, *Theorie der Farbe*, Cologne 1990, pp. 11 – 15 and 63 – 64.
Cf. Moritz Zwimpfer, Farbe – *Licht, Sehen, Empfinden*, Bern, Stuttgart 1985, no. 420 – 423.

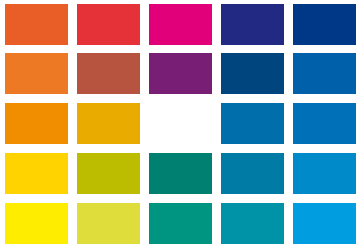
K07 COLOUR DISTINCTION CHARACTERISTICS II

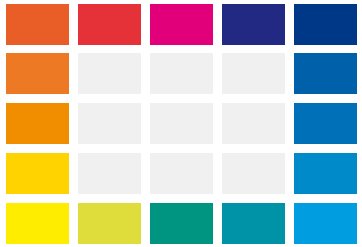
The term "hue" denotes the pure colour value, independent of saturation and brightness. (Fig. 1) The 16 hues in the "Colour Dimensions" system are positioned along the outside edge, comparable to the arrangement in the colour circle. (Fig. 2)

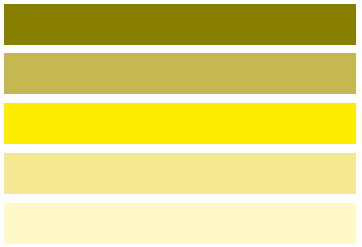
Saturation represents the degree of chromatic colour in a hue. The saturation of a spectral colour diminishes when it is mixed with an achromatic colour. The spectral colour is dimmed. In Fig 3 the saturation of the colour lemon yellow is reduced through the addition of the following achromatic colours: upward through the addition of dark-grey and black, downward through the addition of light-grey and white. The addition of the complementary colour can also diminish the saturation of a spectral colour. In this case, we speak of a broken colour. (Fig. 4)

Brightness designated the degree of brightness or darkness of a colour. Distinction is made between the intrinsic brightness of the spectral colours (Fig. 5) and the brightness or darkness of dimmed colours (tonal values). (Fig. 6)

Cf. Johannes Pawlik, *Theorie der Farbe*, Cologne 1990, pp. 11 – 15.
Cf. Norbert Welsch, *Farben, Natur, Technik*, 2nd edition, Munich 2004, p. 384, 388, 401.


1


2


3

4

5

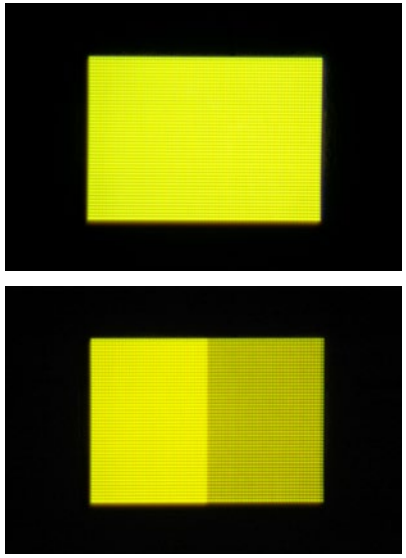
6

K08 MANIFEST COLOURS

A person who observes a grove of palm trees from above over a period of twenty-four hours would claim spontaneously to have seen green palms at all times of the day. Yet on second thought, he would have to admit that he had seen different hues in the morning light than at noon, in the afternoon, in the evening and in the moonlight. The spectral composition of illuminating light changes constantly as the Sun moves across the sky. In order to recognize the actual green hues of the palms at any given time, the habitual colour constancy response must be overridden. It is colour constancy alone that helps the observe avoid confusion in assigning colours to objects under changing light conditions.

If one looks at the manifest colour without regard to its context, one is astonished to realize that it represents the same substance. Thus, for example, an olive green can be a manifest colour of a light lemon-yellow.

Fig. 1 When a yellow field is darkened, the change of colour toward olive green is particularly noticeable.



K09 COLOUR (PHYSICAL)

Light is absorbed at the surface of non-light-permeable, non-reflective substances and objects, i.e. a part of the spectrum is subtracted, while remainder is diffusely reflected. Physicists speak of diffuse reflection or merely reflection.[1] A blue object, for example, absorbs yellow light from the spectrum of illuminating light and emits blue light. The designation for the colour of an object describes the emitted light that reaches the viewer's eye.

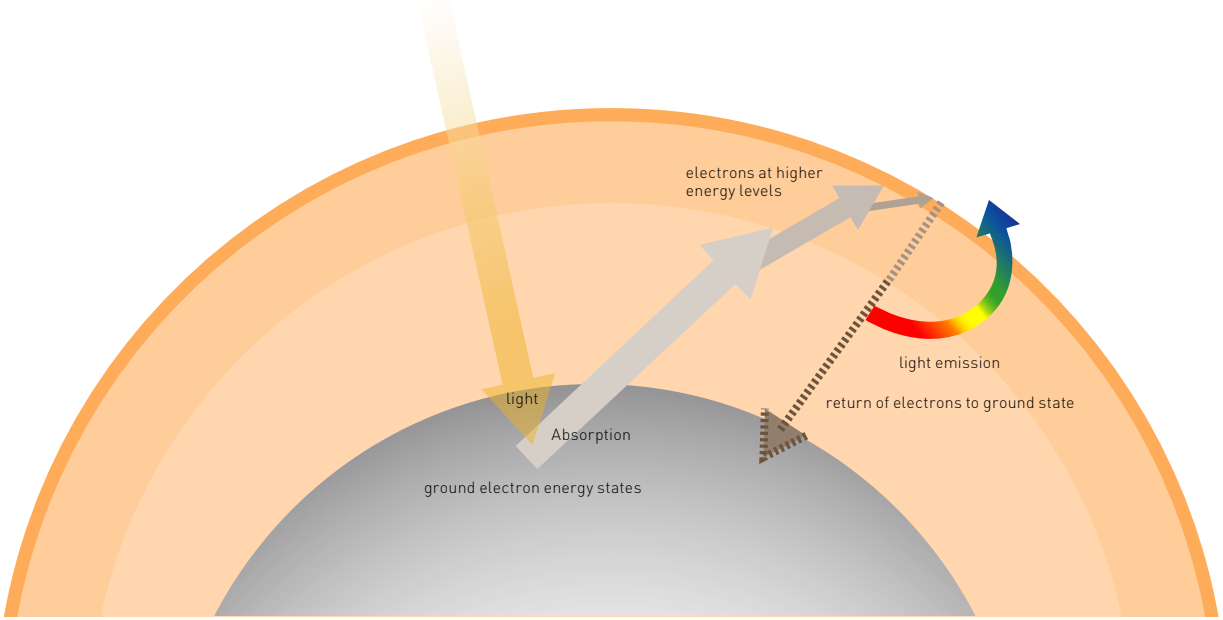
In the atomic model of quantum physics, the absorption of light particles is conceived as a process in which light particles transfer their energy to electrons bound to the nucleus of the atom. This places the electrons in a state of excitation. As they return to their original state, the electrons release light particles, which are registered as reflected light in the viewer's eye. This phenomenon is known as spontaneous emission or the release of light particles.[2] Emitted particles possess less energy than incoming light particles and thus have a longer wavelength.

1 Cf. Ekbert Hering, Rolf Martin, Martin Stohrer, *Physik für Ingenieure*, 6th edition, Berlin, Heidelberg 1997, pp. 404ff.
Cf. Jost J. Marchesi, *Handbuch der Fotografie*, Band 1: *Geschichte, Chemisch-physikalische und optische Grundlagen*, Schaffhausen 1993, p. 136.

2 Cf. Horst Hänsel, Werner Neumann, *Physik, Atome, Atomkerne, Elementarteilchen*, Heidelberg, Berlin, Oxford 1995, pp. 242ff.

Fig. 1 An intensely illuminated pigment appears in a lighter colouration.
Fig. 2 The molecular energy model demonstrates the excitation of electrons to a higher energy level.

1



2

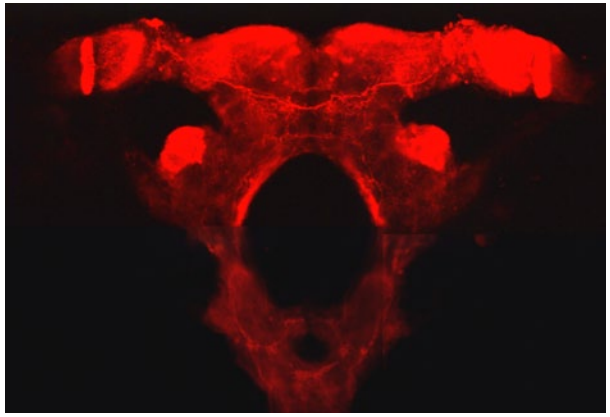
K10 LUMINESCENCE

Aside from thermal light emission, which occurs when a substance is heated, there is also a non-thermal form, known as luminescence. "Glow-worms" can be observed in flight in the evening hours. They exhibit bioluminescence, which is also characteristic of deep-sea fish and red algae.

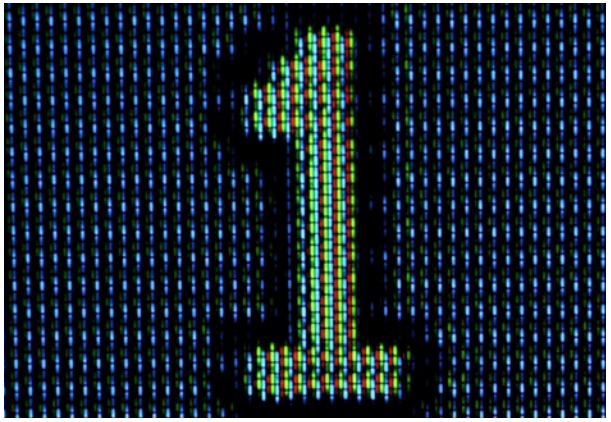
If the mineral fluorite is exposed to high-energy ultraviolet light, it begins to glow. This glow is not merely a reflection of incoming stimulation light. Incoming light is initially stored in the atoms of the mineral and then emitted as long-wave light. This phenomenon is referred to as fluorescence. Modern methods of microscopy include the marking of cell structures with fluorescent substances. If these structures are then exposed to ultraviolet light, the marked areas fluoresce. This method has largely replaced the riskier technique of marking with radioactive substances.

Phosphorus compounds can also be made to emit light through exposure to high-energy light. Because this light can be emitted in the base colours of the additive colour mixture, they are used in the production of colour television screens. This technology is based on the fluorescent properties of light phosphors.

Fig. 1 Marking of cell structures with fluorescent dyes in fluorescence microscopy.
Fig. 2 The individual light phosphors of a television picture tube are recognizable from close up.



1



2

K11 COLOUR TEMPERATURE

"Hot objects emit light radiation due to their temperature",[1] a phenomenon that can also be observed when an industrial furnace is heated. At first, the interior core is dark red, but the colour then shifts to light-red and yellow to "white-hot". Pyrometry involves techniques used to determine the temperature in a furnace on the basis of colour. Every colour of the illumination light can be assigned to a specific temperature, known as colour temperature. The corresponding unit of measurement is the Kelvin, which is based on a scale beginning at absolute zero (0 Kelvin equates to –273°C; 0°C equates to 273 Kelvin). As the temperature rises, the wavelength of the emitted light shifts from red to blue. The flame of a candle, for example, emits primarily yellow light and appears bluish only at its hottest point. Light bulbs emit light with a colour temperature of approximately 3400 Kelvin as their tungsten filaments are heated. Roughly 90% of their energy is lost as pure thermal radiation; the remainder is visible as reddish to yellowish light. Extremely bright sunlight may reach colour temperatures of up to 10000. Normal daylight is measured at about 5600 Kelvin. The types of daylight film commonly used in photography are designed for this colour temperature. Artificial light film is adapted for use with bulb lighting with a colour temperature of about 3200 Kelvin.[2]

1 Cf. Hermann Haken, Hans Christoph Wolf, *Atom- und Quantenphysik. Einführung in die experimentellen und theoretischen Grundlagen, Berlin, Heidelberg 2000, pp.55ff.*

2 Cf. Jost J. Marchesi, *Handbuch der Fotografie*. Band 1: Geschichte, Chemisch-physikalische und optische Grundlagen, Schaffhausen 1993, pp. 132ff.

1

2

3

Fig. 1 Depending on their temperature, candle flames exhibit colours ranging from yellowish to bluish white.
Fig. 2 Welders work with very high temperatures and bluish flames.
Abb. 3 In fireworks, metals are burned and produce a colourful array in all colour variations.

K12 SUBSTANTIVE COLOURS

As physical colours, substantive colours are the exact opposite of coloured light. Whereas precisely predictable additive colour mixtures can be made with coloured light, the outcome of a subtractive mixture of substantive colours can only be predicted approximately. The light-absorbent and reflective characteristics of the material surface are crucial factors in this process. They are highly complex and it is virtually impossible to describe them mathematically.
The substantive colours cyan, magenta and yellow are the base colours for subtractive colour mixtures. In theory, a mixture of these colours can only produce black. Practically speaking, however, the outcome is a dark grey. Thus in four-colour printing, pure black is always added to the three base colours. Thus the colour code CMYK signifies "Cyan", "Magenta", "Yellow" and K as the symbol for black (key colour).
If substantive colours are exposed to white light, they absorb their complementary colour and reflect the remainder of the spectrum. The reflected light is mixed additively to produce the perceived colour.

Fig. The substantive colours in the glass dishes are the colours of the "Colour Dimension" system.

K13 PIGMENTS[1]

Pigments are non-water-soluble, ordinarily crystalline colour particles with diameters ranging from one-thousandth to one-millionth of a millimetre which absorb light and reflect it diffusely. Each light wavelength corresponds to an optimum particle size. The smaller the particles, the greater the colour strength of a pigment. Colour strength is a measure of a pigment's ability to influence the colour of other substances.

Because a pigment is composed only of fine, coloured powder, a binder is required in order to produce a paint from a pigment. Oil paint, for example, consists of a pigment suspended in linseed oil. An acrylic paint consists of a pigment suspended in an acrylic binder.

We distinguish between natural and artificial pigments. Natural pigments include earth pigments and vegetable pigments. Earth pigments are metal oxides. They are the oldest form of paint or dye known to mankind, and were used by prehistoric cave painters. They processed reddish, and brownish earth pigments to produce ochre, sienna and umbra tones. Vegetable substances soluble in water or oil are also referred to as pigments. Chlorophyll is the most commonly occurring pigment; carotinoids give vegetables and fruits their yellow to purple colouration.

The group of artificial pigments comprises mineral and synthetic pigments. Mineral pigments are produced from metal oxides. Ninety-six percent of artificially produced pigments are mineral pigments. Berlin Blue, the first synthetic pigment, was produced in 1704. Other mineral pigments include titanium white, artificial ultramarine blue and highly toxic mercury oxide (cinnabar).

Fig. The mineral pigment cinnabar, the warmest colour in the system of paint colours.

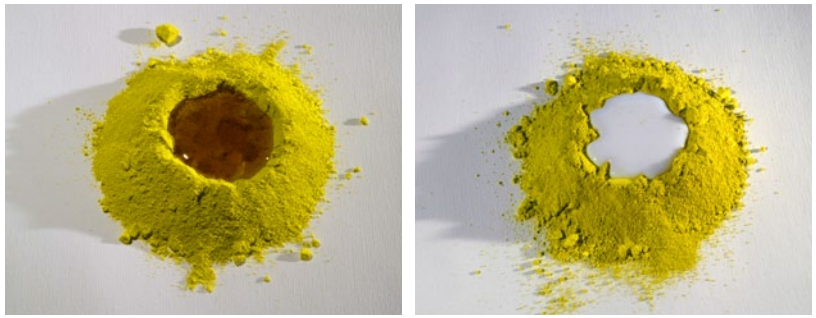
Synthetic pigments made of petroleum, anthracite coal and coal tar provide vividly coloured inks, dyes and paints for the printing and textile industries, painting and construction. They are highly light-resistant and durable, but their production is not without risk to the environment.

1 Cf. Norbert Welsch, Claus Chr. Liebmann, *Farbe, Natur, Technik, Kunst*, Munich 2004, pp. 151 – 153.

K14 BINDERS

In order to produce a paint from a powdered pigment, a binder must be added. Binders are transparent and colourless. They envelop the pigment particles and bond them to the substrate or ground coat of a painting. Depending on the type of binder added, distinction is made between oil paint, acrylic paint and casein paint. Binders influence the selection of painting techniques and the character of the finished painting. If a pigment is mixed with other ingredients, such as gum Arabic (from the acacia plant), the product is an aquarelle or transparent water-colour paint.

A pure pigment.



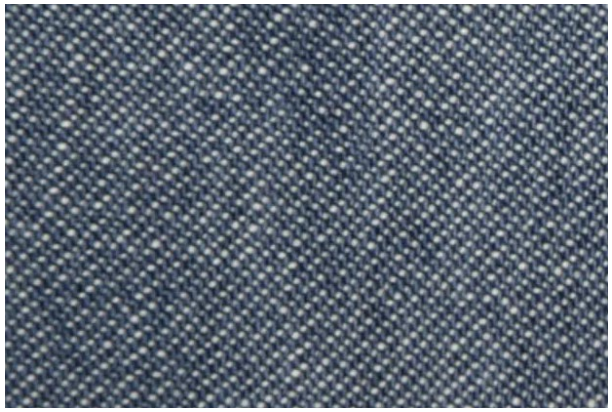
A pigment mixed with linseed oil to produce an oil paint. (left)
A pigment mixed with an acrylic binder to produce an acrylic paint. (right)

Oil paints and acrylic paints have very different appearances when applied to a ground coat.

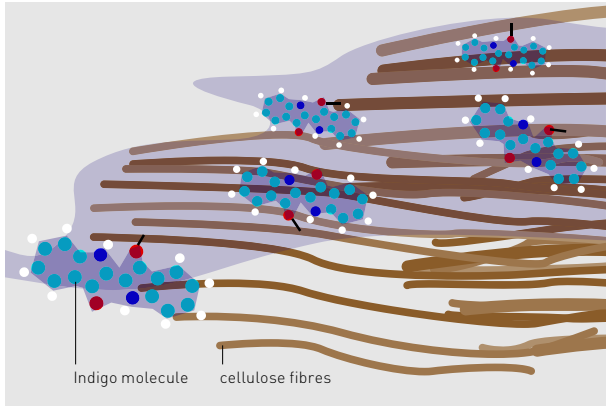
K15 DYES

In addition to non-water-soluble pigments, there are also soluble colour substances known as dyes. The can be dissolved in water or other liquids. During the dying process, they engage in chemical reactions with their carrier material. Examples include wool, silk and cotton dyes and wood stains. No binders are required for dyes, as they bond directly with their carrier material.
The discovery of artificial indigo in 1878 led to the industrial-scale dying of cotton. Such products as blue jeans dyed with indigo became major export goods.
Today, thousands of different dyes are used in a wide range of applications. The food industry, for example, uses certain dyes to heighten the appeal of its products. However, many of the by-products of dye production are extremely toxic.

Fig. 1 Cotton fibres in blue jeans are dyed with indigo.
Fig. 2 The dye forms a chemical bond with the textile fibres.



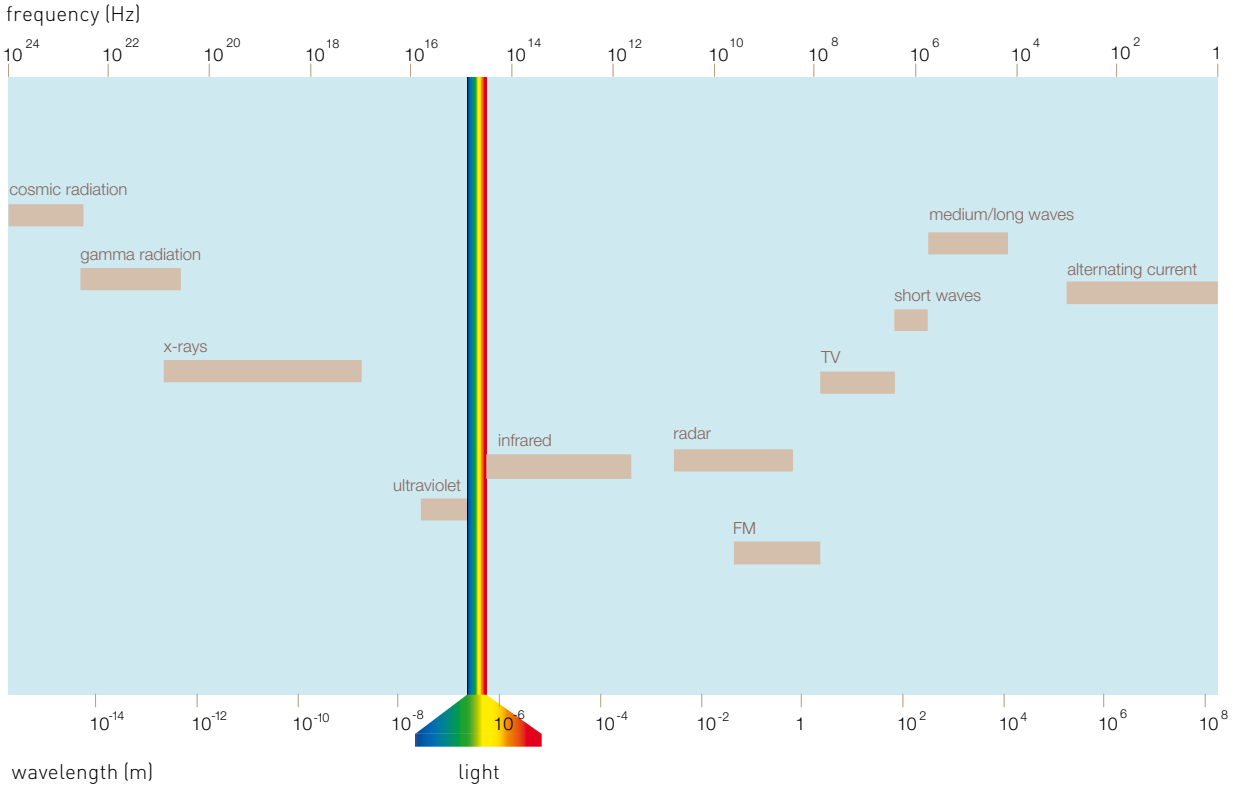
1



2

K16 LIGHT (PHYSICAL)

Light is a form of energy. At the experimental level, light is a great "neither-nor" or "this-and-that-too". Light has the properties of both electromagnetic waves and particles.
The wave model of traditional optics was long accepted as the definitive explanation of the phenomenon of light. Light is the visible range of the electromagnetic wave spectrum.
Yet it is not possible to define what light really is on the basis of the kind of linear thinking that is characteristic of classical physics.[1] Such observations as those published by Max Planck in 1900 left him no choice but to abandon these traditional modes of thought,[2] according to which a particle cannot be a particle and a wave at the same time. The time had come to abandon the macrocosm of classical physics and establish a new basis for the description of light.
Max Planck and Albert Einstein opened the door to the world of microphysics with their publications of 1900 and 1905. It is a world that resists observation and immediate experience. The hypothesis that light could appear in discreet packets, known as light quanta or photons, was truly revolutionary. Einstein introduced a new conceptual approach with his explanation of the "photoelectric effect" and it was for this – and not for the much more famous Theory of Relativity, that he was awarded the Nobel Prize.
According to Einstein, light could also have mass and momentum, like a tiny particle that moves at tremendous speed and never comes to rest. The speed at which light moves through a vacuum – the speed of light – is represented by the symbol c and equates to 300,000 kilometres per second.



1 Cf. Ekbert Hering, Rolf Martin, Martin Stohrer, *Physik für Ingenieure*, 6th edition, Berlin, Heidelberg 1997, pp. 2 – 5.
2 Cf. Joachim Grehn (ed.), *Metzler Physik*, 2nd edition, Stuttgart 1989, p. 365. Cf. Horst Hänsel, Werner Neumann, *Physik, Atome, Atomkerne, Elementarteilchen*, Heidelberg, Berlin, Oxford 1995, p. 15.

Fig. The electromagnetic wave spectrum clearly shows that the human environment is full of waves, but only a small portion consists of visible light (the range from 380 to 700 nanometres)..

K17 THE WAVE MODEL OF LIGHT

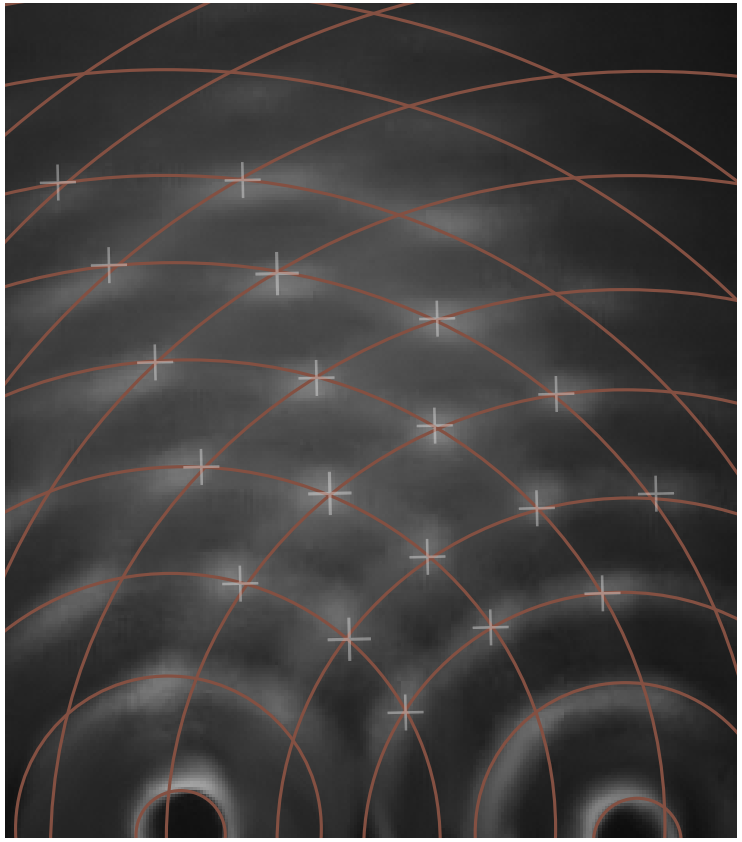
Physicists of the 18th and 19th centuries applied the two known wave phenomena of diffraction and interference, which they had learned to compute precisely for sound waves, to the study of light. Their efforts bore fruit, for light can exhibit the same behaviour in the form of electromagnetic waves.[1]

When two waves of similar shape, with peaks and troughs of the same height, are shifted by one-half of a wavelength and laid one over the other, each wave peak fills precisely one wave trough, and the two waves cancel each other out.[2] This is known as interference, a phenomenon that occurs the same way in water, sound and light waves.

When waves of water run toward an opening, new waves that expand in a circular pattern are formed behind the opening. Thus there is no point behind the opening which can be said to be in the "shadow of the waves". This phenomenon is referred to as diffraction.[3] Light is also diffracted at a slit.

Light is composed of electromagnetic waves in the visible range of the electromagnetic wave spectrum. Telephone, radio and television technologies are based on the movement of electromagnetic waves. Sunbathing exploits the effects of the wave phenomenon of long-wave infrared radiation on the skin. Ultraviolet radiation in the short-wave range of the spectrum can cause severe damage to organ and skin cells, and x-rays are equally hazardous.

Fig. Two overlapping water waves merge and intensify one another at points of intersection.



1 Cf. Horst Hänsel, Werner Neumann, *Physik, Atome, Atomkerne, Elementarteilchen,* Heidelberg, Berlin, Oxford 1995, pp. 2 – 5.

2 Cf. Joachim Grehn (ed.), *Metzler Physik,* 2nd edition, Stuttgart 1989, p. 128.
Cf. Ekbert Hering, Rolf Martin, Martin Stohrer, *Physik für Ingenieure,* 6th edition, Berlin, Heidelberg 1997, p. 392.

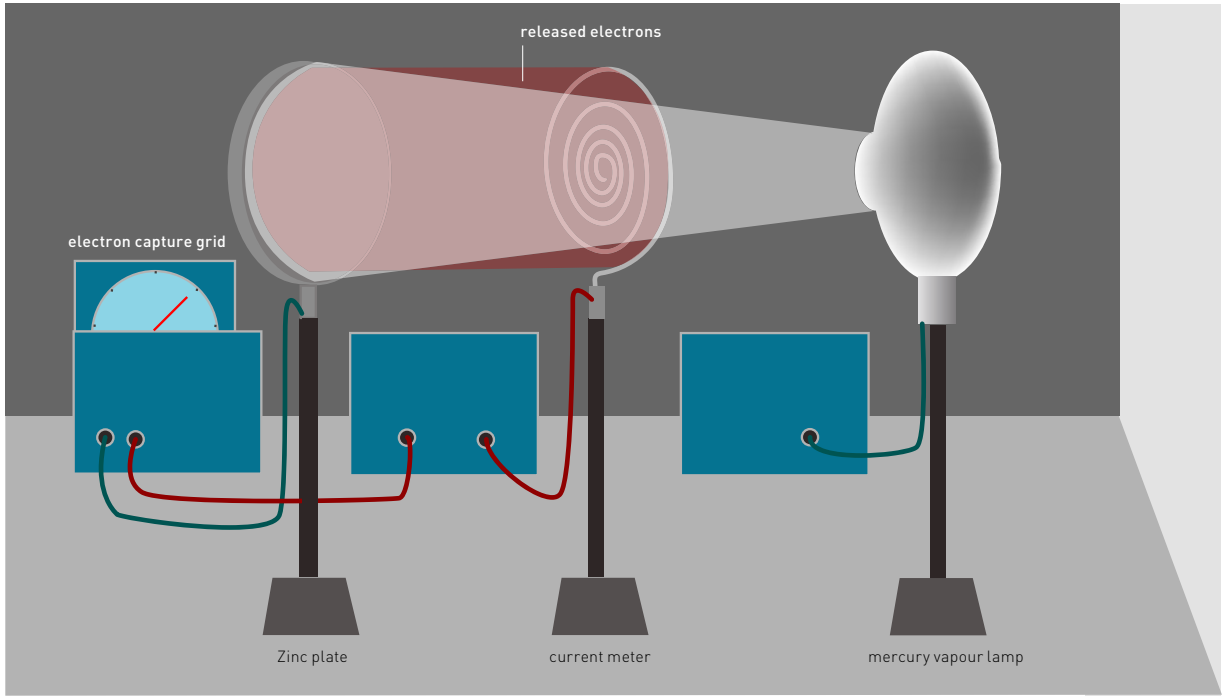
3 Cf. Joachim Grehn (ed.), *Metzler Physik,* 2nd edition, Stuttgart 1989, p. 135.
Cf. Hering, Martin, Stohrer, *Physik für Ingenieure,* op. cit., p. 397.
Cf. Jost J. Marchesi, *Handbuch der Fotografie. Band 1: Geschichte, Chemisch-physikalische und optische Grundlagen,* Schaffhausen 1993, p. 191.

K18 THE PARTICLE MODEL OF LIGHT

One of the most important experimental findings cited in support of the particle character of light was the photoelectric effect.[1] Although physicists were aware of the phenomenon as early as 1902, they found it difficult to understand on the basis of the wave model. It was Albert Einstein who explained the effect with his light-quantum hypothesis ("quant" meaning particle) in 1905. The concept of light composed of quanta provided him a means of explaining a number of different phenomena associated with light. It was not until later that the wave and particle models were integrated as equally important aspects of quantum theory.

To demonstrate the photoelectric effect, a zinc plate is illuminated with a bright mercury vapour lamp. Electrons are released from the metal and form a measurable electrical current, but not in every case. Scientists discovered that the light striking the plate had to have a sufficiently low wavelength. Current flowed only when the plate was exposed to high-energy, short-wave ultraviolet light. Only then did the higher intensity generate stronger current. Einstein's explanation was that electrons, the units of which electrical current is composed, are bound to atoms in the metal. They lie within the attractive electostatic field of the nuclei of the metal atoms. Energy is required to release them and generate electrical current. When such an electron is struck by a light particle with a certain energy level, it can split off from the metal atoms and enter the electrical field, producing measurable electrical current.

If the light particles have insufficient energy, nothing happens, even if intensity is increased significantly. This cannot be explained on the basis of the classical wave model, as an increase in intensity would trigger a greater reaction if light consisted only of waves.



1 Cf. Joachim Grehn (ed.), *Metzler Physik*, 2nd edition, Stuttgart 1989, pp. 359 – 366. Cf. Horst Hänsel, Werner Neumann, *Physik, Atome, Atomkerne, Elementarteilchen*, Heidelberg, Berlin, Oxford 1995, pp. 242ff.

Fig. Experimental configuration used to demonstrate the photoelectric effect. A zinc plate exposed to light from a mercury vapour lamp emits electrons which are measurable as electrical current.

K19 REFRACTION

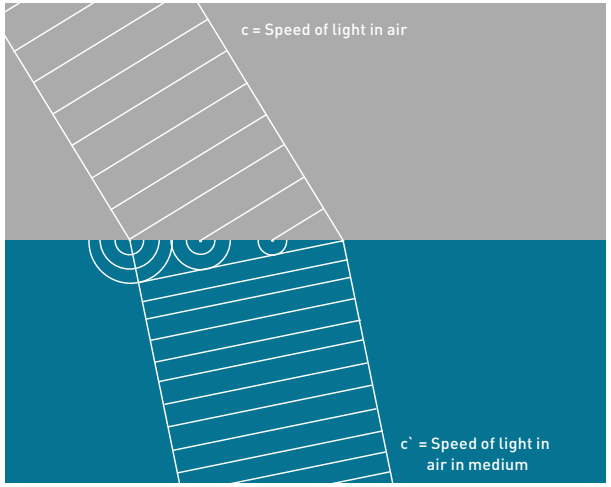
The wave model of light provides a suitable approach to the description of light refraction. Refraction occurs when light passes from one medium to another. Refraction phenomena can be observed, for example, at the boundary between air and water. Light moves at a different speed through air than through water or glass. Air is described as an optically thinner, water an optically thicker medium. When light passes from air into water or glass, it is refracted at a precisely determinable angle.

The relationship between the mathematically computed values for the impact and refraction angles corresponds to the relationship between the speeds of light in different media.[1] In optics, the relationship between the speed of light in a vacuum and its speed in the medium is known as the refraction index.

If the wave front of a ray of light travelling through the air strikes the surface of water, for example, part of the light is reflected, while the remainder enters the water and is refracted.[1] This happens because not all parts of the wave front strike the water's surface simultaneously. While a part of the ray begins to move through the water, the other is still on its way toward the surface. The new wave front that has begun to move through the water now proceeds at an angle and at a different speed. Refraction can be described mathematically with the aid of triangle geometry.

1 Cf. Ekbert Hering, Rolf Martin, Martin Stohrer, *Physik für Ingenieure,* 6th edition, Berlin, Heidelberg 1997, pp. 409ff.

1



2

Fig. 1 The brush in the glass is a classical demonstration of refraction.
Fig. 2 Refraction of a smooth wave at a boundary surface.

K20 INTERFERENCE COLOURS

Everyone is familiar with the shimmering colours of soap bubbles, butterfly wings and peacock feathers. And with the colours that appear on a film of oil on water or the surface of a CD.
All of these manifestations are the effects of one and the same physical phenomenon known as interference. The shimmering colours generated by interference in very thin layers of material are called interference colours. Interference is a manifestation of the mutual cancellation of identical light waves in which the peaks and troughs of the waves destroy one another when superimposed and shifted by one-half of a wavelength. This was first demonstrated by Thomas Young in 1801. However, this occurs with light waves only if a certain important condition is met. The movement of the peaks of the waves must be consistently equal for the duration of the observation. Practically speaking, light from two different sources cannot meet this requirement. Under natural conditions, it can only be fulfilled by light waves that originate from the same point.[1]
When the surface of a soap bubble, which is only 0.00012 millimetres (120 nanometres) thick, is illuminated by sunlight, light from the entire solar spectrum, i.e. of all colours, strikes the ultra-thin wall of the soap bubble, which is thinner than the wavelengths of visible light. Depending on the angle of impact and the refraction index of the soapy water on the surface of the bubble, some of the light waves will be reflected, others refracted. The refracted waves penetrate the surface and then strike the inside wall of the bubble, where some are reflected, while others are refracted again. The light waves that are reflected on the surface "interfere" with the light waves that are reflected in the same direction from the inside wall of the bubble. In the process, certain light waves cancel each other out, thereby removing a colour from the incoming spectrum. The remaining spectral

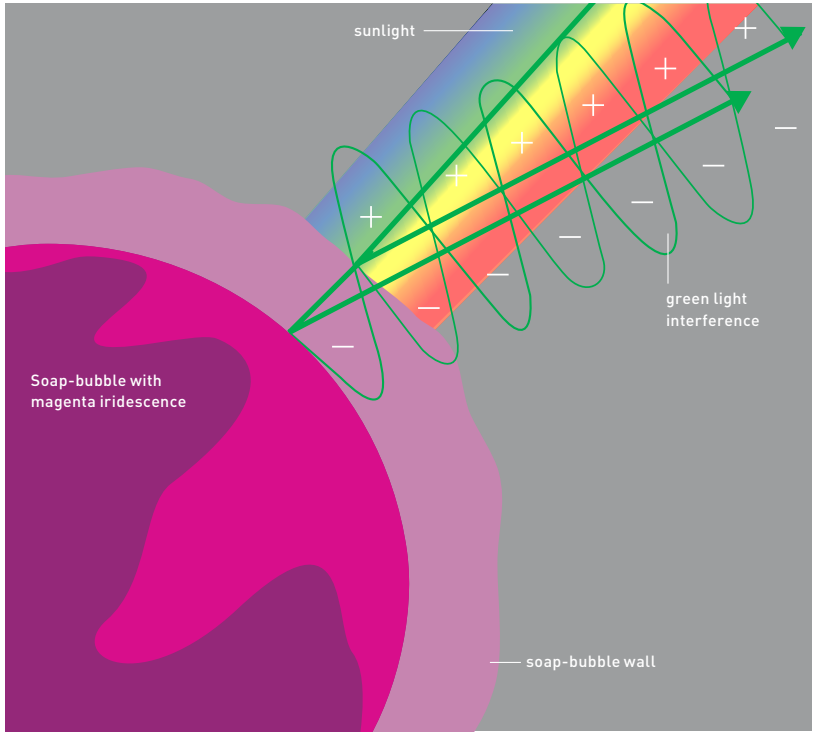


Fig. Schematic diagram of interference on the surface of a soap bubble.

colours are reflected back. With a layer measuring 120 nanometres, blue-green light is eliminated. The soap bubble appears in a reddish colour (white minus blue-green equals red). Depending on the thickness of the soap-bubble wall and the impact angle of the light striking the surface, a specific wavelength is cancelled out. The soap bubble shimmers in all colours.

Colour and layer thickness are mutually interdependent. This relationship is exploited in the filtering of light. One selected colour from the solar spectrum can be eliminated by applying a layer of a specifically calculated thickness to a plate of glass, while all other colours pass through the material and are visible as light of the complementary colour (see also dichroid filter).

1 Cf. Ekbert Hering, Rolf Martin, Martin Stohrer, *Physik für Ingenieure,* 6th edition, Berlin, Heidelberg 1997, pp. 444 – 450.
Cf. Jost J. Marchesi, *Handbuch der Fotografie. Band 1: Geschichte, Chemisch-physikalische und optische Grundlagen,* Schaffhausen 1993, pp. 186 – 189.

Fig. Examples of interference colours in everyday situations.

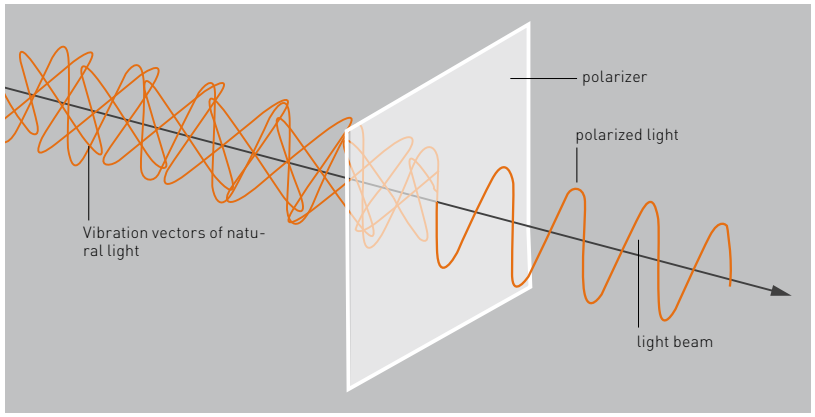
K21 POLARIZATION

Light moves as a light wave in a straight line through space. This property of light is exploited in optics for the purpose of making precise calculations. But light has another property as well. Perpendicular to the axis of movement, natural light waves vibrate in all directions. If we imagine the direction of movement as a vertical line, the vibration vectors of light are arranged around this centre like the spokes of a wheel.[1]

Polarization is a selective process. From all of these possible vibration directions, only a few or only one direction is filtered out. E. L. Malus observed a reflective window through a calcite-crystal prism in 1808. The light permeability of the prism was changed by rotating it. In a certain position, no light passed through the prism at all. Malus recognized that light, having passed through the window, had only one specific vibration level. It had been "polarized" by the glass in the window pane.[2] When light is partially reflected and partially refracted on glass, both parts of the light beam are polarized. The angle of impact plays an important role in this context.

Light is polarized not only when passing through glass but also in the atmosphere, through scattering and refraction on the molecules in the air. Many insects have special types of eyes which are capable of recognizing the direction of sunlight polarized in the atmosphere, providing additional information value. They make use of this capacity to orient themselves according to the position of the Sun. Sunlight is polarized in the atmosphere even when the Sun is obscured by clouds. The phenomenon enables bees and ants to find their way home without difficulty. The polarization of light on the surface of bodies of water helps beetles find water when their biotope dries out.[3]

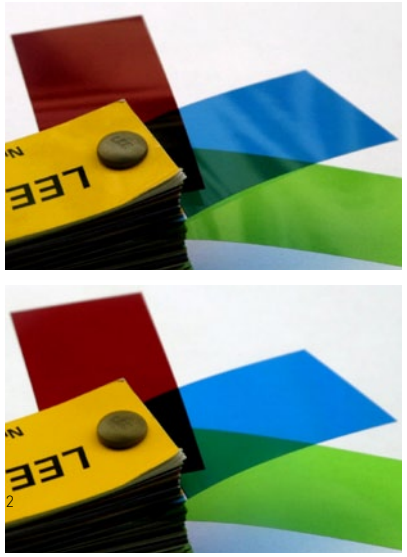
The polarizing properties of certain materials are exploited for the production of filters, including dichroid filters, for example.



1

Fig. 1 Light before and after passing through a polarizing medium.
Fig. 2 Light reflections are suppressed by polarizing filters.
The same motif, photographed with (right) and without (left) polarizing filter.

1 Cf. Jost J. Marchesi, *Handbuch der Fotografie. Band 1: Geschichte, Chemisch-physikalische und optische Grundlagen*, Schaffhausen 1993, pp. 194 – 201.
2 Cf. Ekbert Hering, Rolf Martin, Martin Stohrer, *Physik für Ingenieure*, 6th edition, Berlin, Heidelberg 1997, pp. 468 – 469.
3 Cf. M. F. Land & D-E. Nilsson, *Animal Eyes*, Oxford 2002, pp. 29 – 32.



2

K22 FILTERS[1]

Glass and certain plastics absorb and polarize light waves. A colour filter is used to eliminate all of the colours of the solar spectrum but one. With the aid of such a filter, light of the desired colour passes through the glass, while all other spectral colours are either absorbed or reflected. Colour filters function according to the principles of subtractive colour mixture. In this sense, they behave in the same way as pigments. The complementary colours appears in a shade between very dark and black. Light effects created with colour filters appear especially pure, as colours are selected directly from the spectrum and the remaining colours of light are mixed additively.

Filters are used frequently in analogue photography. The blue tint caused by strong ultraviolet radiation that often appears in photographs taken in the mountains can be eliminated with the aid of a "Skylight" filter, for example.

Colour filters are used in black-and-white photography to enhance contrast. The intrinsic colour of the filter appears lighter, the complementary colour darker. This explains why a cloudy sky photographed with a yellow filter appears richer in contrast. Green filters darken the complementary red and make green shades appear lighter and more intense. They are used most frequently in landscape photography. Polarizing filters are commonly used by landscape and architectural photographers to eliminate undesirable reflections and mirroring effects on water surfaces. These filters are made of highly compact plastics whose molecules are arranged in long parallel chains, ensuring that only one direction of vibration can pass through the filter.

1

2

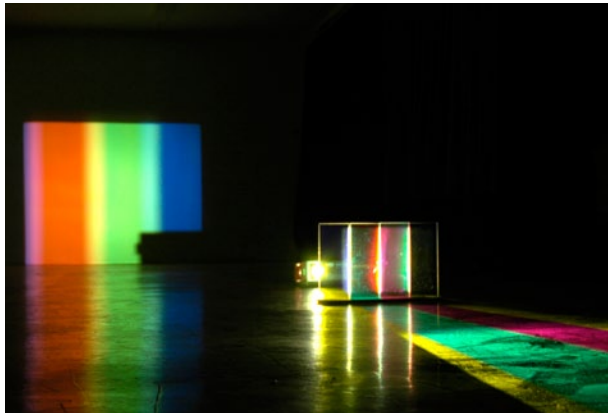
Fig. 1 Colour filters can be used to make quite precise subtractive colour mixtures.
Fig. 2 Complementary-coloured filters allow no light to pass.

1 Cf. http://www.foto-net.de/objektive/filter.html

K23 DICHROID FILTERS

The word "dichroos" comes from the Greek and means "two-coloured". Dichroid filters have a remarkable dual character. They are mirrors which reflect the light of a certain colour but also allow the complementary colour of the reflected light to pass through.
Dichroitic substances, including primarily crystalline quartz, calcite and tourmaline and especially plastics, divide incoming beams of light as determined by their polarization. The one part retains its constant material-dependent speed of light, while the other is refracted and has its own direction-dependent refraction index. The two light beams are then polarized in directions perpendicular to one another.[1]
As many as fifty layers of plastic of different thickness are vapour-coated onto a glass plate to produce a green dichroid filter. When white light falls onto the green dichroid filter, magenta-coloured light is reflected, as polarized green light is cancelled out during reflection by interference on the thin layers. However, green light, which is polarized perpendicular to the eliminated light, passes through the filter unhindered.[2] The colour effect depends primarily on the angle of impact of the incoming light.

1 Cf. Ekbert Hering, Rolf Martin, Martin Stohrer, *Physik für Ingenieure*, 6th edition, Berlin, Heidelberg 1997, pp. 470 – 473.
Cf. Jost J. Marchesi, *Handbuch der Fotographie. Band 1: Geschichte, Chemisch-physikalische und optische Grundlagen,* Schaffhausen 1993, pp. 196 – 197.
2 Cf. Homepage of the Rosco company, www.rosco.com



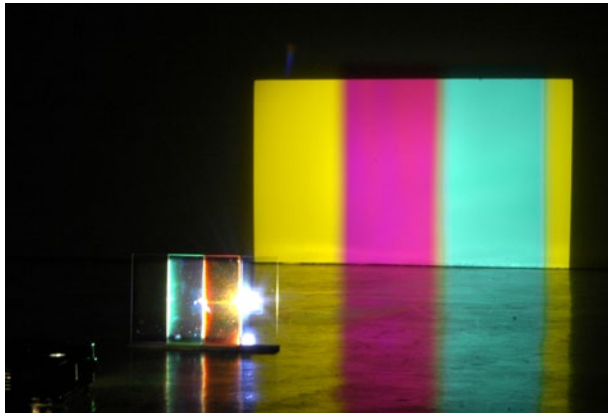
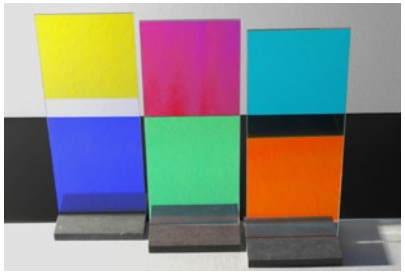


Fig. Four dichroid filters are positioned in front of a slide projector. The filtered colours appear on one wall (Yellow, Magenta, Cyan), the reflected complementary colours on the opposite wall (Blue, Green, Red). Additionally, additive colour mixtures appear as small stripes.

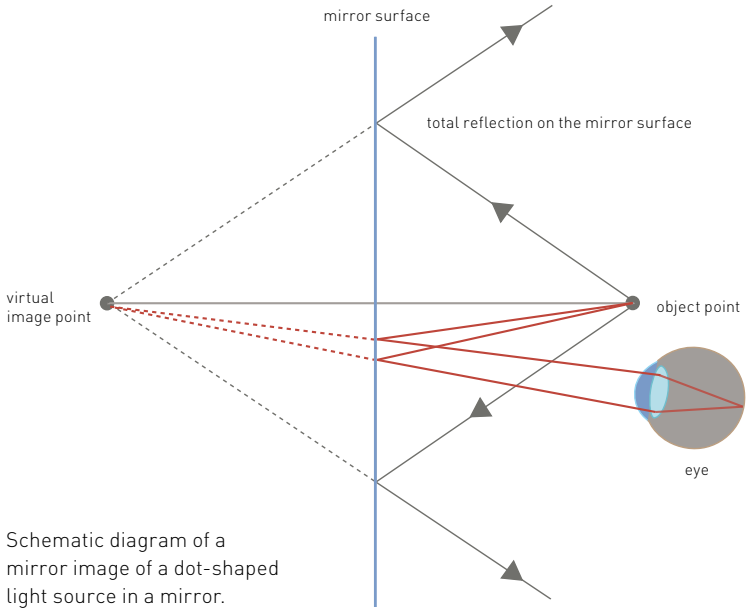


K24 GEOMETRIC OPTICS

The basic precondition for a geometric physics of light, or geometric optics, is the linear movement of light rays through a vacuum and through such homogeneous media as air and glass. The path of a light particle through these media can be depicted as a linear ray or beam. The vertical line of a light wave front also describes a straight ray or beam. This is what is actually meant by the term "light ray". Geometry is useful means of calculating this macroscopic behaviour of light.
The reflection of light rays on reflective surfaces, for example, is governed by the law of reflection established by Euclid in 300 BC. This laws states that the angles of impact and reflection are equal and that the incoming and reflected light rays lie on the same plane. In the eyes of the observer, a mirror image appears to lie as a virtual image behind the reflective surface. Within this virtual image space, the reflection points have the same distance from the surface as the points of the reflected image.[1]
The path of a light ray through a positive lens can also be illustrated with the aid of geometric optics. A virtual image is also created of all objects that lie within the focal length of the lens. Light refraction in all types of prisms can also be computed geometrically. The visualization of the path of light in optical instruments such as telescopes and microscopes is also an application of geometric optics.

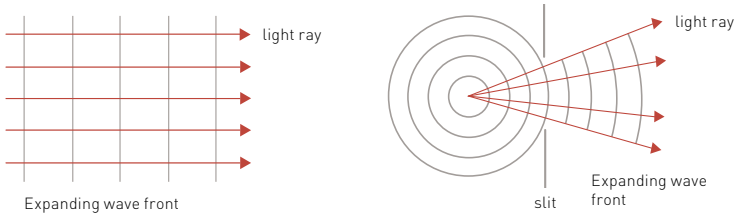
1 Cf. Ekbert Hering, Rolf Martin, Martin Stohrer, *Physik für Ingenieure,* 6th edition, Berlin, Heidelberg 1997, pp. 404 – 405.

Reflection



Schematic diagram of a mirror image of a dot-shaped light source in a mirror.

Schematic diagrams of light rays.



K25 POSITIVE LENSES

Positive or convex lenses are circular, outwardly rounded objects, ordinarily made of glass. Mathematically speaking, they are the sum of an infinite number of interconnected prisms. Light impacting in parallel lines on the lens is refracted to a specific point, which is known as the focal point. When strong sunlight is bundled at the focal point, paper can be set afire.

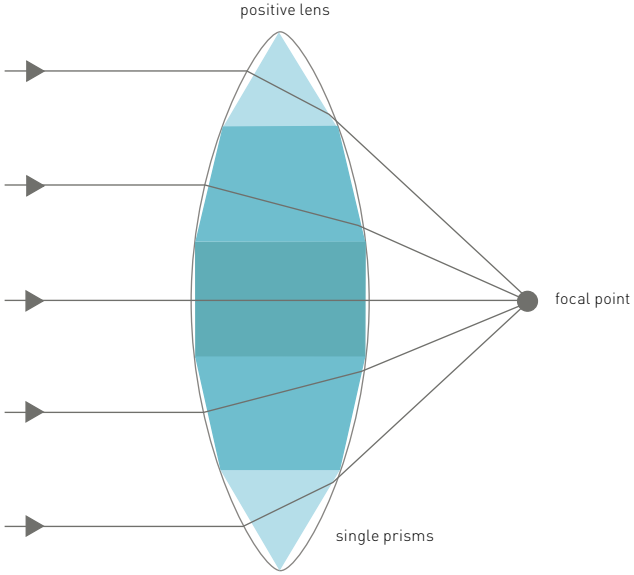
In front of the lens is the object space with its object points, behind it the image space with its image points. Due to the symmetry of the lens, there is one focal point in each of these spaces. The two focal points lie on a vertical axis through the centre of the lens. Ideally, an object point is converted into its corresponding image point through a parallelogram. A reverse virtual image appears behind the lens. The relationship between the size of the image and the size of the object is referred to as the image scale.[1]

In essence, the image that is cast on the plane of the film inside the camera is only one single plane within the object space which can be depicted in sharp focus. However, the eye cannot possibly detect this degree of sharpness when focusing the camera, and thus there is an area in front of and behind this plane that is also interpreted as sharply focused. This is referred to as depth of field.[2]

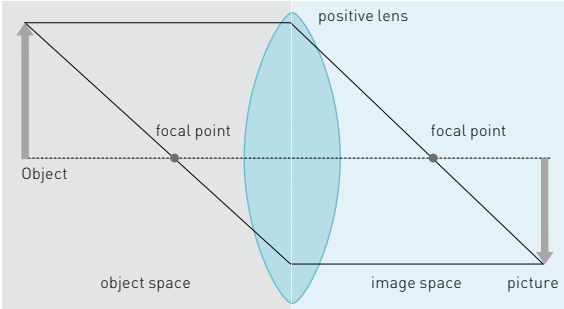
In actual practice, glass lenses produce faulty images, since red, green and blue light have three different focal points (longitudinal chromatic aberration).

The lens also refracts more strongly around its edges than in the centre. Here again, the refracted rays do not meet at a single point. This is known as spherical aberration.[3]

Fig. 1 Structure of the positive lens as the sum of multiple prisms.
Fig. 2 Idealized schematic diagram of the lens.



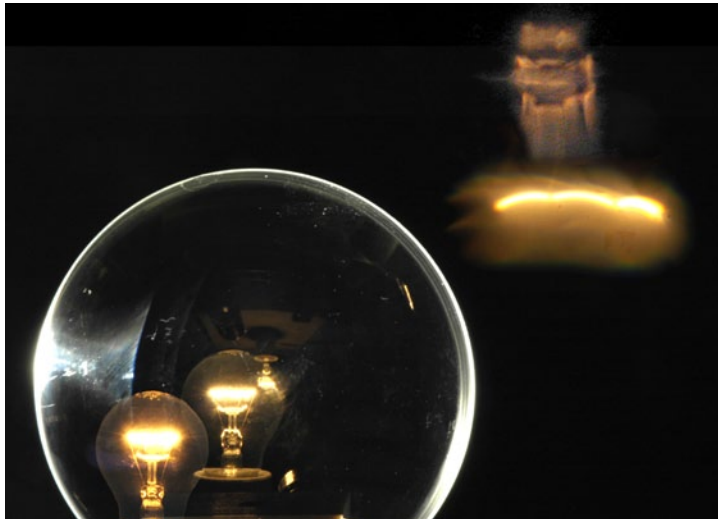
1



2

In nature, lens eyes have natural elastic positive lenses that exhibit the same kinds of image defects. Because the lens eye and the mechanisms in the brain responsible for processing optical stimuli have adapted perfectly to this situation, these "defects" are not apparent.

1 Cf. Jost J. Marchesi, *Handbuch der Fotografie. Band 1: Geschichte, Chemisch-physikalische und optische Grundlagen,* Schaffhausen 1993, pp. 156ff.
2 Cf. Marchesi, *Handbuch der Fotografie. Band 1, ibid.*, pp.169 – 173.
3 Cf. Marchesi, *Handbuch der Fotografie. Band 1, ibid.*, pp. 225 – 229.



3

Fig. 3 Glass lens, isolated and with focal point and projection.

K26 DISPERSION

Newton was the first to recognize that white light is a mixture of many different colours. The instrument he used in making this discovery was a ground glass with a triangular cross-section – a prism. With the aid of a prism, he was able to break an incoming ray of white light into its component parts. This process is known as dispersion.[1]

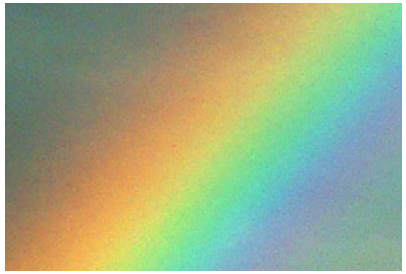
Rainbows are the product of the dispersion of sunlight on raindrops, which refract and separate sunlight in exactly the same way as a prism. The band of the rainbow is called the spectrum, the resulting colours, which cannot be broken down further, are known as spectral colours or prismatic colours.

All spectral colours, bundled in a lens, produce white light. This is the basis for additive colour mixture. Refracted sunlight generates a continuous spectrum. Luminous gases, such as neon, exhibit only very few lines when their light is refracted in a prism. They have discontinuous spectra. Every light source has its own specific spectral composition.

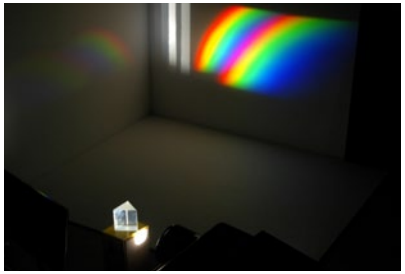
The spectrum of visible light encompasses wavelengths from 380 to 700 nanometres (nm). It is bordered by invisible short-wave ultraviolet and long-wave infrared and by visible blue and red.

When blue and red light are mixed, the products are non-spectral, 100 %-saturated magenta and all hues of purple.

1 Cf. Ekbert Hering, Rolf Martin, Martin Stohrer, *Physik für Ingenieure,* 6th edition, Berlin, Heidelberg 1997, pp. 413ff.
Cf. Jost J. Marchesi, *Handbuch der Fotografie. Band 1: Geschichte, Chemisch-physikalische und optische Grundlagen,* Schaffhausen 1993, pp.182 – 183.



1



2

3

the light spectrum

wavelengths in nm (nanometres)

4

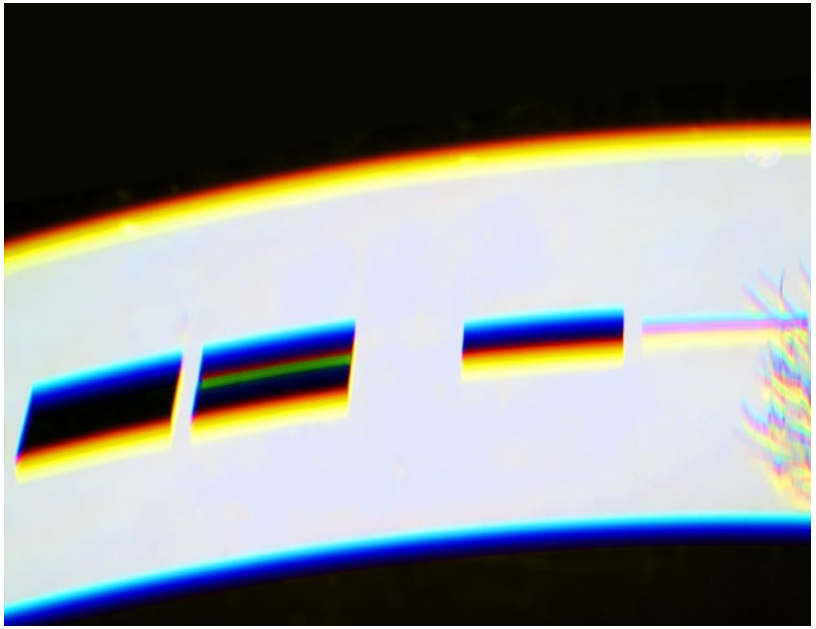
Fig. 1 The rainbow is an example of dispersion on raindrops.
Fig. 2 The glass prism separates white light into spectral colours.
Fig. 3 When two spectra overlap in such a way that the blue range of the one mixes with the red range of the other, magenta becomes visible.
Fig. 4 The scale of light wavelengths and their corresponding colours.

K27 EDGE SPECTRA

When one examines rectangular black fields on a white background through a prism, one sees a part of the spectrum of white light along the boundaries between white and black. These are known as edge spectra and are visible as colour progressions. One edge of the rectangle exhibits a progression from red to yellow; the opposite edge shows the progression from ultramarine to cyan. If there is a narrow white slit in the rectangle, the yellow and cyan components of the edge-spectrum are superimposed to form green. If one examines a thin black line, the blue component blends with the red component to form magenta. The same effect is achieved by examining the black rectangle through a prism at a 45° angle.

Fig. 1 Installation at the Zurich-Stadelhofen Canton School.
Fig. 2 Edge spectra become visible through a prism.
Fig. 3 The black fields in the illustration make it possible to see edge spectra through a prism.

1



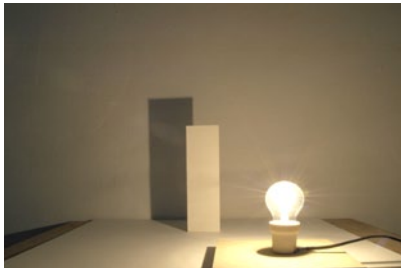
2

3

K28 SHADOW

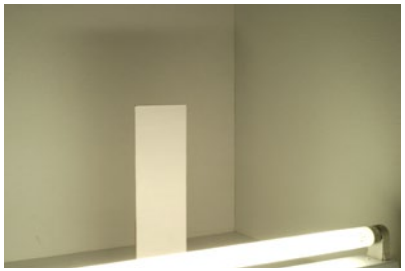
Light and shadow are bound inseparably together. The source of light plays an important role in this relationship. Essential factors are the distance[1], form and position of the light source.
The distant Sun casts virtually parallel rays of light on the Earth. Clearly outlined shadows appear on the ground. Artificial light sources such as light bulbs are much closer to the objects they illuminate, which means that they produce larger shadows. The three-dimensional shape of a source of light also influences shadow formation. Thus, for example, light from a small light bulb with clear glass casts a sharply outlined shadow, whereas fluorescent tubes or very large light bulbs produce shadows with diffuse outlines from the same distance. The darkest part of a shadow is the umbra, the lighter area is called the penumbra. When multiple shadows overlap, the overlapping area lies within the umbra.[2] The position of the light source determines how the shadow is cast and influences its size. The shape of a shadow is determined by the relationships between the light source, the illuminated object and the surface on which the shadow is cast. These observations relate to all shadows cast by objects. The object's own shadow is referred to as the object or intrinsic shadow.

1



2

3



4

5

Fig. 1 - 2 Shadow variations resulting from different distances.
Fig. 3 Intrinsic shadows of three-dimensional objects.
Fig. 4 Fluorescent tubes have diffuse shadow boundaries; point light sources have sharp shadow outlines. (see Fig. 2)
Fig. 5 Umbras and penumbras of two different light sources.

The perception of shadow differs in quality depending on whether one is viewing an entire scene or focuses on a detail located within the shadow. A shift of gaze alone changes the perception of brightness. A dark object in a shadow appears lighter when it is focused upon. This relates to brightness constancy, which is analogous to colour constancy.[3]

1 Cf. Ralph M. Evans, *An Introduction to Color,* New York, London 1948, pp. 50 – 52.
Cf. Friedrich Dorn, Franz Bader, *Physik Mittelstufe,* Hanover 1980, pp.194 – 195.
2 Cf. Joachim Grehn (ed.), *Metzler Physik*, 2nd edition, Stuttgart 1989, pp. 304 – 305.
3 Cf. Evans, *Introduction to Color*, op. cit., p. 16

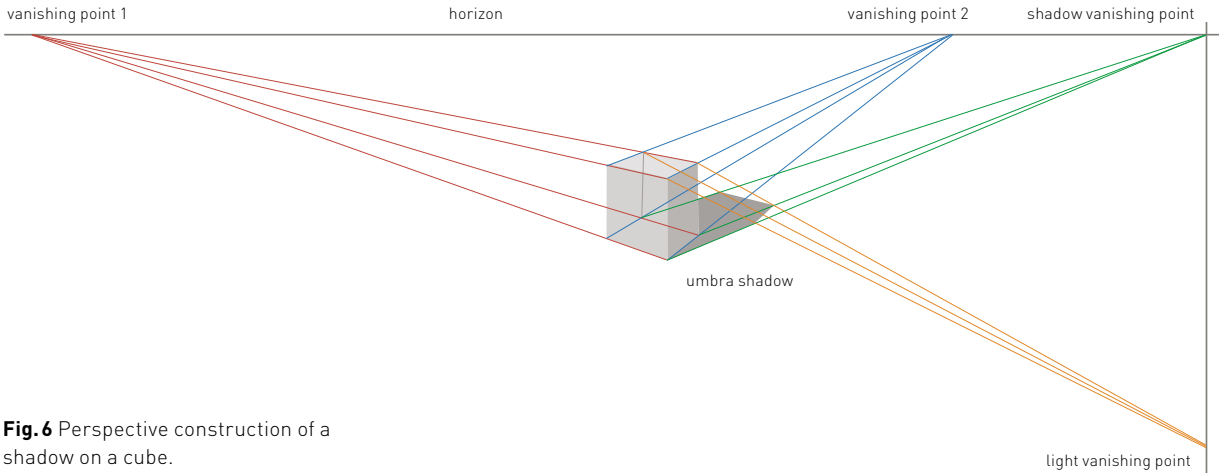
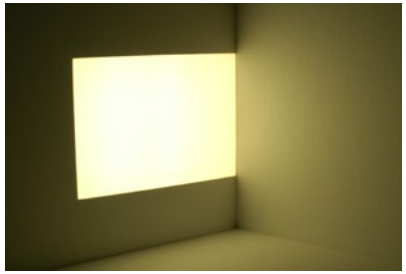


Fig. 6 Perspective construction of a shadow on a cube.

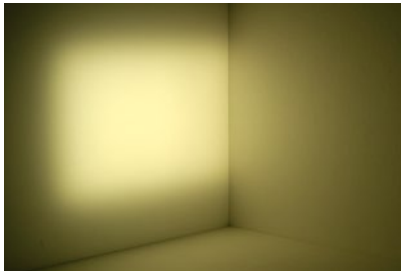
K29 LIGHT SCATTERING

Light that strikes non-transparent obstacles is diverted and divided into bundles of rays that move in different directions. The size of the object plays a crucial role in loss-free diversion.
Diffuse light conditions of the kind experienced in foggy weather are manifestations of light scattering. The blue sky is also the product of the scattering of sunlight by molecules in the upper layers of the atmosphere. Here, blue light is scattered more intensely, and intense blue light is perceived. Even the "light rays "described by Prof. Gernot Böhme, which become visible when sunlight breaks through clouds, are manifestations of light scattering on small, spherical drops of water.[1]
When an image is projected onto a focusing screen, the appearance of the image is influenced by the scattering of light on the surface of the screen. Lamp shades made of paper or white glass scatter light in the same way.[2] The beams of light emitted by projectors are also produced through scattering on small, opaque suspended particles.

1 Cf. Ulrich Bachmann (ed.), *Farben zwischen Licht und Dunkelheit*, Sulgen/ Zurich 2006, p. 117 – 119
2 Cf. Jost J. Marchesi, *Handbuch der Fotografie. Band 1: Geschichte, Chemisch-physikalische und optische Grundlagen*, Schaffhausen 1993, p. 193.
Cf. Ralph M. Evans, *An Introduction to Color*, New York, London 1948, p.162.

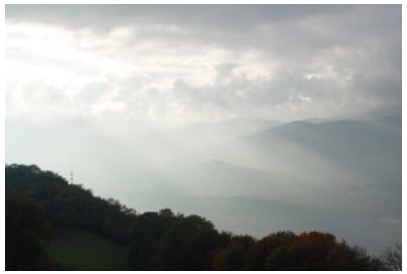


1



2

3



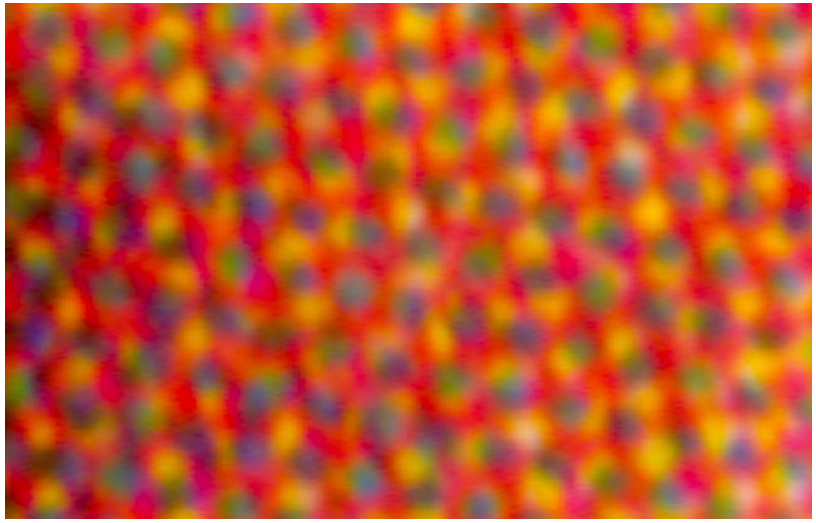
4

Fig. 1 Indirect lighting
Fig. 2 Transparent lamp shades give off light in scattered form.
Fig. 3 The blue of the sky is a product of light scattering.
Fig. 4 Sunlight breaking through clouds is a manifestation of light scattering.

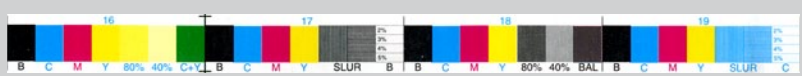
K30 COLOUR PRINTING: CMYK

The four-colour printing process was first used by Jakob Christoph Le Blon circa 1710.[1] The most common flat-printing process is offset printing. Working with the four base colours of the subtractive mixture of cyan, magenta, yellow and pure black, four separate images are printed one over the other. In order to ensure that as much pure colour is applied to the substrate, the individual images are matrixed, i.e. broken down into a large number of adjacent matrix dots. These dots are ordinarily round but may also be elliptical or square. Undesirable Moiré patterns emerge when matrix dots are not positioned at specific angles. Thus each colour is assigned a certain angle in colour printing. The dominant colour in an image is always positioned at a 45° angle. In most cases, black lies near yellow at a 90° angle, cyan at a 105° degree angle and magenta at a 165° angle. The degree of fineness in the matrix determines the quality of the reproduced colour scale. The limit is reached when individual colour dots merge and contrast is lost in the darker portions of the image. In addition to the fineness of the matrix, the type of paper used also plays an important role in image quality. A fine matrix can be used for a light-coloured image on coated paper in sheetfed offset printing. Conversely, much larger matrix dot gaps are required for dark images printed on coarse newsprint using the webfed offset process.[2]

1 Cf. Norbert Welsch, Claus Chr. Liebmann, *Farbe, Natur, Technik, Kunst,* Munich 2004, p. 131, pp. 324 – 331.
2 Cf. Mattias Nyman, *4 Farben – ein Bild. Grundwissen für die Farbbildbearbeitung mit DTP,* Berlin, Heidelberg 1994, pp. 2 – 5.



1



2

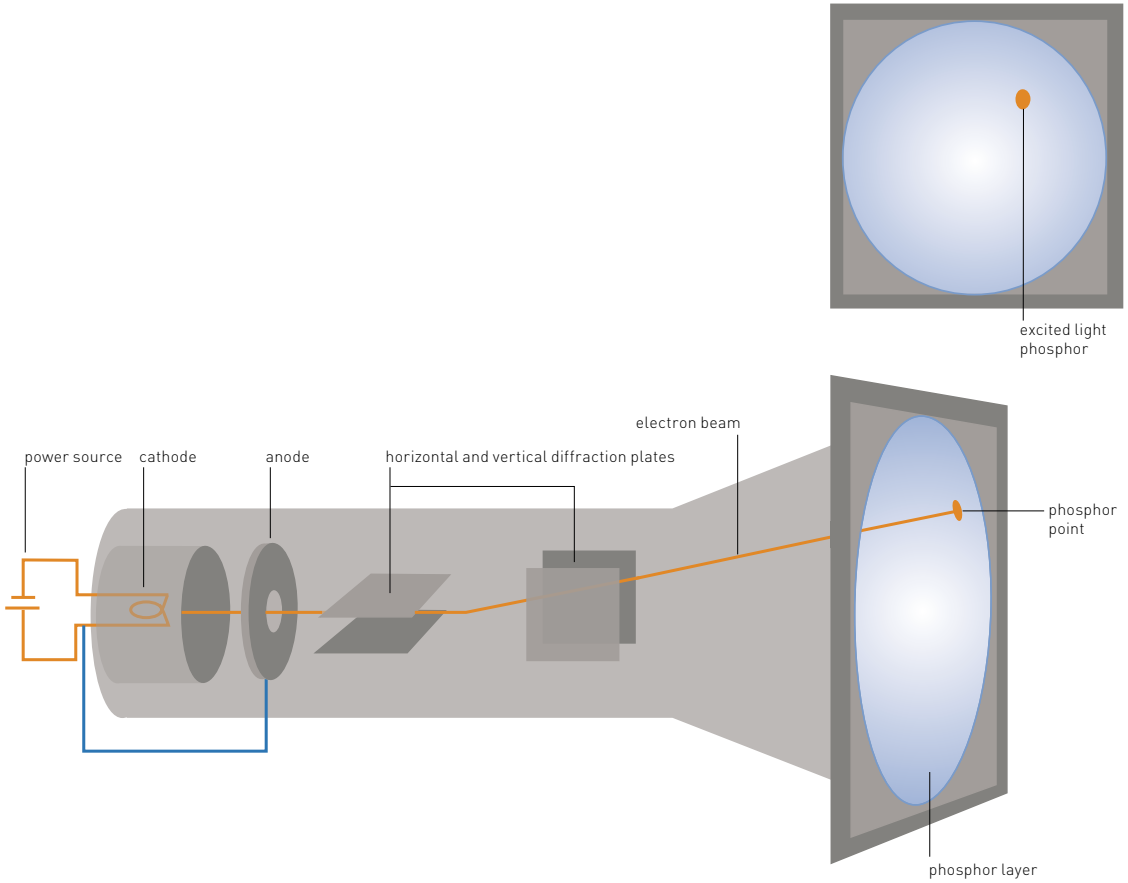
3

Fig. 1 Different angular positions of the individual colours in four-colour printing.
Fig. 2 CMYK print strip samples are also found on printed paper packaging.
Fig. 3 Each colour channel has its own image. Together, the four colour channels produce a final four-colour product.

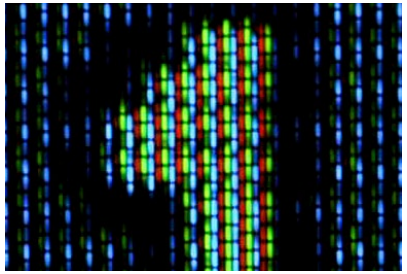
K31 SCREEN: RGB

The classical television/monitor screen is a Braun's tube. A stream of electrons passes line by line over a plate of glass coated with fluorescent substances. When accelerated electrons strike a fluorescent dye, a light signal is generated at that point. The picture on a black-and-white television appears each time the stream scans 625 lines. At a frequency of 50 to 85 images per second, the human eye can no longer distinguish the individual images.
The picture tubes in colour televisions set work in much the same way, with three streams of electrons which excite red, green and blue light phosphors, respectively. Additive colour mixture produces the colour image. In television signal transmission, brightness data is referred to as luminance, coded colour data as chrominance.
A major disadvantage of tube-type screens is their weight and bulky shape. This has led to the development of the liquid-crystal display or LCD screen. The first liquid-crystal displays were introduced in digital clocks, and the technology was later applied in screen production. Liquid crystals are capable of changing back and forth between different states and polarizing light in an electrical field. Liquid crystals work like light valves. For every image dot or pixel in a colour image, light passes through red, green or blue colour fields. When current is applied, the liquid crystals are aligned and no more light is allowed to pass through. In this way, image generation is controlled by additive colour mixture at each pixel. Today, this image generation process is an indispensable part of digital photography and computer technology.[1]

1 Cf. Norbert Welsch, Claus Chr. Liebmann, *Farbe, Natur, Technik, Kunst*, Munich 2004, p. 131, p. 337.



1



2

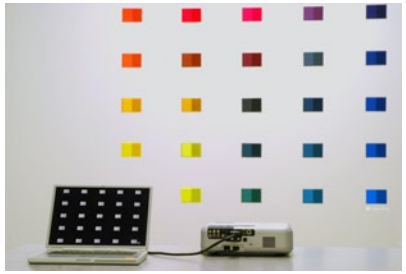
Fig. 1 Schematic diagram of a Braun's tube.
Fig. 2 Tube screen: image generation through additive mixture of luminous red, green and blue light phosphors.

K32 BEAMER

The beamer is named for the English word "beam". It is a projector that receives an image signal from the monitor output of a computer or laptop and converts it back into a projectable image. There are two types of beamers: LCD and DLP beamers. Both types are based on the same principles of optics. They enlarge a small image with the aid of a lens and project it in sharp focus onto a remote surface.

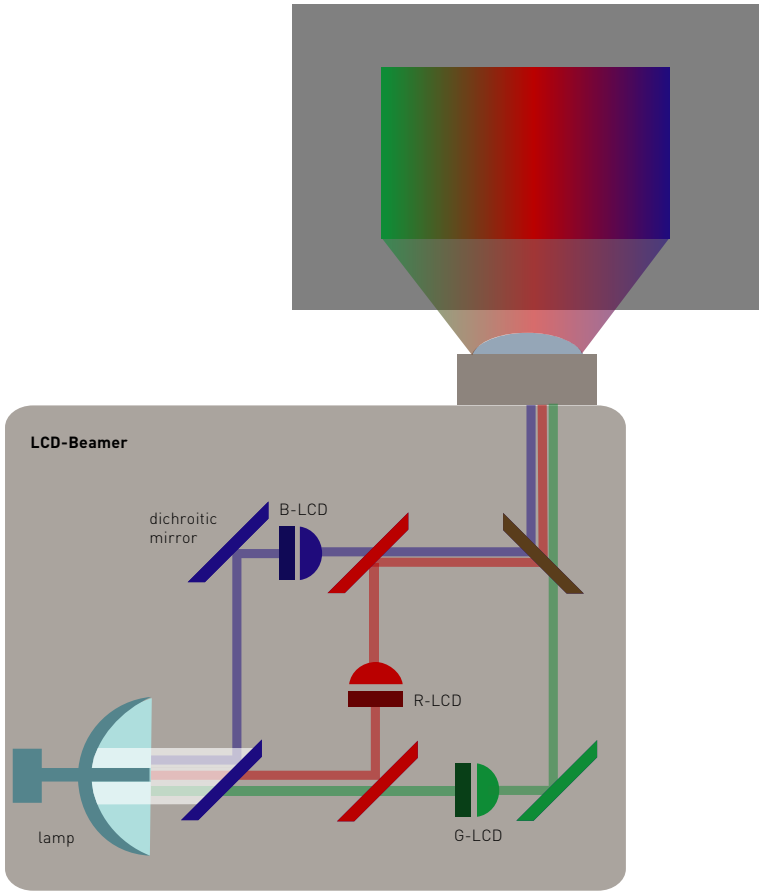
In liquid-crystal display or LCD beamers, light is initially broken down by three dichroid mirrors into the primary colours of red, green and blue and simultaneously cast onto numerous small liquid-crystal fields, each with its own transistor. Electrical signals transmitted by a computer or laptop control the flow of light at this point. Three prisms blend the light from the three partial liquid-crystal images into a single image that is then projected. LCD beamers produce sharp, bright images with consistent colours and are therefore ideal for presentations. In some cases, however, individual pixels are visible in the projection.

The second beamer technology is based upon the principle of digital light processing. Light from a built-in lamp passes through a rapidly rotating colour wheel. The wheel allows red, green and blue light pass to pass through a lens in succession to a kind of "light valve". The light valve is a semiconductor chip containing a large number of tiny, rotatable mirrors. Each pixel is projected separately by one of these small mirrors. Image data is encoded on the basis of the position of the individual mirrors. Depending on a mirror's position, a pixel can be lightened or darkened on the projection surface. Red, green and blue images appear in succession. Since the eye cannot respond rapidly enough to distinguish these separate images, what it perceives is a



1

Fig. 1 The projection is a reproduction of the image displayed on the screen.
Fig. 2 Configuration of an LCD beamer



2

four-colour image. These beamers tend to be quite compact, since they require only a chip for image generation. They are very light-intensive and generate more homogeneous images than LCD beamers.

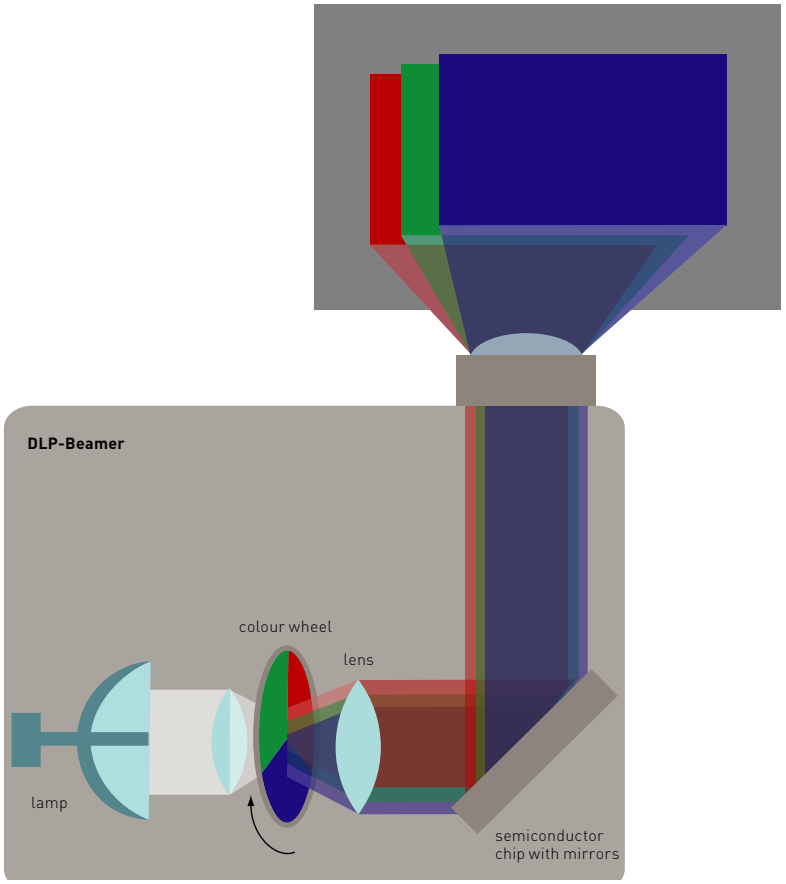


Fig. 3 Configuration of a DLP beamer

3

K33 LED (LIGHT EMITTING DIODE)

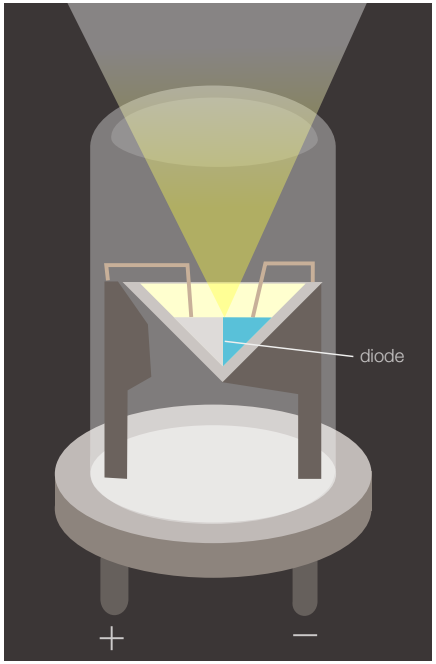
When electrical equipment or appliances are switched on, a red, green or white lamp ordinarily begins to glow. Because no heat is radiated in the direction of the light, as with other lamps, it is named as "cold" light. LEDs are produced in all colours. Last blue LEDs were developed. Red, green and blue LEDs are for example the components of large screens.

LEDs are manufactured from chemically altered semiconductor materials. Pure silicon or germanium does not conduct electricity at room temperature. When these materials are heated or exposed to light, however, the electrons in the crystal are released. They increase the conductivity of the semiconductor abruptly and substantially. This semi-insulating, semi-conductive property is the foundation of modern electronics. Semiconductor effects have now been achieved at room temperature using combinations with other substances which either supply or absorb additional electrons.

A diode is a component of electronic systems. It comprises an electron-rich n-semiconductor and an electron-poor p-semiconductor. Current can pass through the diode in one direction only, i.e. from the electron-rich to the electron-poor semiconductor. This makes it possible to control current flows within extremely small spaces.[1]

1

2

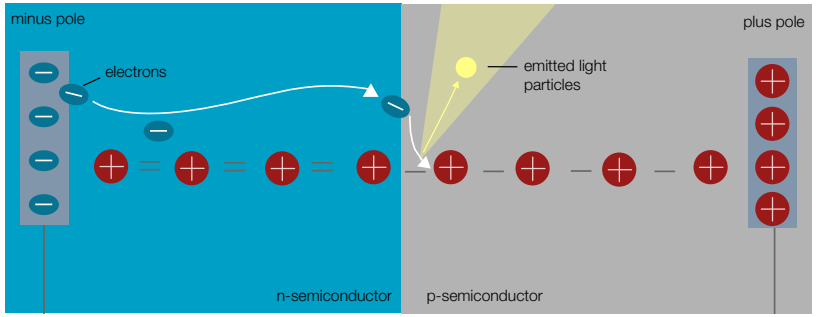


3

Fig. 1 All colour mixtures can be produced on large LED screens. It is now possible to show colour films on LED screens.
Fig. 2 Close-up view of an LED
Fig. 3 Schematic diagram of an LED

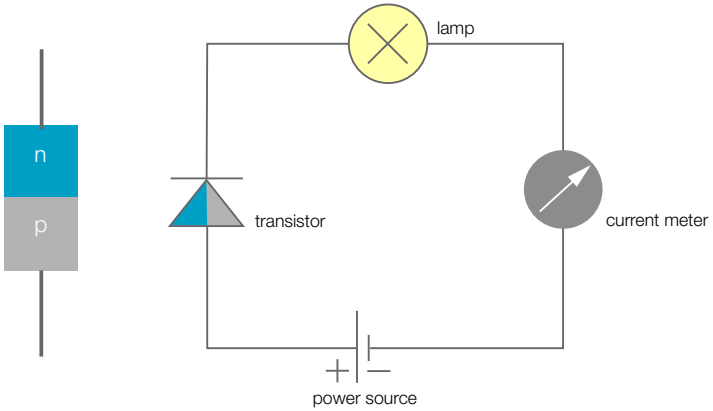
When electrons jump from the n-semiconductor to the p-semiconductor, light particles are released during the transition. This effect was only weakly detectable in the first materials used for this purpose. In recent years, semiconductors have been improved through chemical means to achieve progressively increasing yields of released light particles. This type of light harvesting is not thermal, as in light bulbs, but rather purely electronic.[2]

1 Cf. Friedrich Dorn, Franz Bader, *Physik Mittelstufe*, Hanover 1980, pp. 358 – 360.
2 Cf. Norbert Welsch, Claus Chr. Liebmann, *Farbe: Natur, Technik, Kunst*, Munich 2004, pp. 338 – 339.
Cf. Ekbert Hering, Rolf Martin, Martin Stohrer, *Physik für Ingenieure*, 6th edition, Berlin, Heidelberg 1997, pp. 690 – 691.



2

Fig. 4 When electrons switch from the n-semiconductor to the p-semiconductor, light particles are released.



K34 WHITE BALANCE

Photographers have battled since the earliest years of colour photography with the problem of achieving an authentic reproduction of colour impressions under constantly changing light conditions. Every light source, be it natural or artificial, has its own specific colour temperature, which is characterized by its own unique brightness scale.
The human eye is capable of adapting perfectly to these constant changes. Even mixed light consisting of incoming sunlight and artificial lighting in indoor rooms does not appear tinted to the viewer. The eye selects the brightest field of vision as a reference or white point, adjusting all colour sensations with reference to this point of greatest light intensity, i.e. it effects a "white balance".
In analogue photography, this problem has been addressed by introducing special kinds of film materials, such as artificial light or daylight film. A wide range of different filters is also used. Flash light also produces a colour temperature for a fraction of a second that comes very close to that of daylight.
The problem of "white balance" is solved in a much more elegant fashion in digital photography. Electronic light sensors convert incoming light signals into electrical voltage signals.[1] These signals are then converted into a binary numerical code and recalculated with reference to the illumination light prevailing at a given time using a specific computation method. It is also possible to switch from automatic to manual white balancing in response to special light conditions. Mixed light situations have a particularly irritating effect on the automatic white balance function. The camera may adjust to the wrong light source, producing an undesirable tint in the image. The solution in such cases is to perform white balancing manually with reference to the desired illumination light.

1

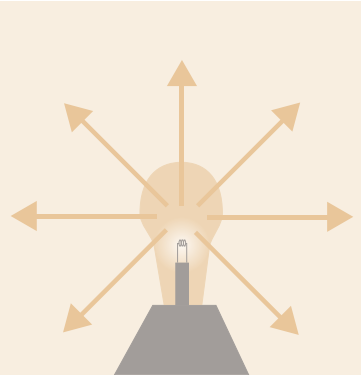
2

Fig. 1 The room shown in the photograph appears in natural daylight. In this case, a daylight film can help to solve the problem of tinting in analogue photography.
Fig. 2 Without white balancing, the photograph of the same room under neon light exhibits a blue tint.

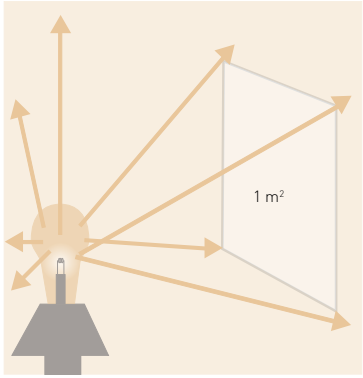
1 Cf. Jost J. Marchesi, *Handbuch der Fotografie. Band 3: Farbtheorie und Farbmetrik, Farbumkehrtechnik, Negativ-Positiv- und Direkt-Positivtechnik, Digitale Fotografie*, Gilching 1998, pp. 247 – 260.

K35 PHYSICAL VALUES AND UNITS [1]

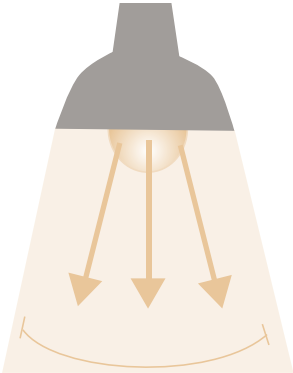
Luminous flux Ð (unit: lumen [lm]): The entire visible radiation emitted by a light source is known as luminous flux. (Fig. 1)
Light amount Q (unit: lumens times second or hour [lms], [lmh]): The total light output from a light source over a specified period of time is referred to as light amount.
Illuminance E (unit: lux, which represents lumen per square meter [lx]): The luminous flux striking a specified workplane is defined as illuminance. (Fig. 2)
Luminous intensity I (unit: candela [cd]): The intensity of luminous flux in a certain direction (steradiant) is referred to as luminous intensity. One candela is equivalent to the luminous flux originating from 1/60 cm2 of a black object at the melting temperature of platinum. (Fig. 3)
Luminance L (unit: candelas per square meter [cd/m2]): Luminance is the luminous intensity reflected vertically from a surface. It characterizes the perceived brightness of a substantive colour or light source. (Fig. 4)
Light efficiency Ð (unit: lumens per watt [lm/W]): This value describes the strength of the luminous flux generated by an electrical current.
Colour reproduction (unit: Ra value): This value represents the extent to which colours produced by illumination with a light source deviate from standard colours of a DIN light source. At Ra = 100 all colours appear as if illuminated by the optimum reference light source.
Exposure H (unit lux times second [lxs]): This is an important unit of measurement in photography. It indicates the period of time film material is exposed to light.



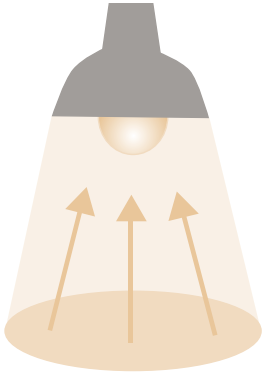
1 luminous flux



2 luminosity



3 light intensity



4 light density

1 Cf. Jost J. Marchesi, *Handbuch der Fotografie. Band 1: Geschichte, Chemisch-physikalische und optische Grundlagen*. Schaffhausen 1993, p. 137 – 140.

K36 COLOUR VISION

Colour vision requires at least two types of light-sensing cells (photoreceptors) which exhibit different maximum light-absorption capacities for their photopigments, thus providing different, independent sets of data for processing into a colour impression. A single type of photoreceptor cannot distinguish between a large quantity of light emitted with long-wave, low-energy radiation or a small quantity of light emitted with shortwave, high-energy radiation. Night vision, which relies on only one type of photoreceptor and thus does not recognize colour, is characterized by this limitation.

Daylight vision in humans relies on three different types of light-absorbing sensory cells known as cones. These photoreceptors are stimulated differently when exposed to light of a given wavelength. Three separate values are assigned to this incoming light. The specific ratio of these values creates the impression of a specific colour. If these individual values were generated by exposure to three different light wavelengths, the same colour impression would result.1

The excitation values of the three types of photoreceptors corresponding to the RGB colour spectrum, which is based upon additive colour mixtures. The three primary colours, red, green and blue, are mixed and produce a colour impression that conforms to reality.

Human colour perception is actually much more complex, however, and does not depend solely on the three cone absorption values. They are an absolute prerequisite for colour vision, however.

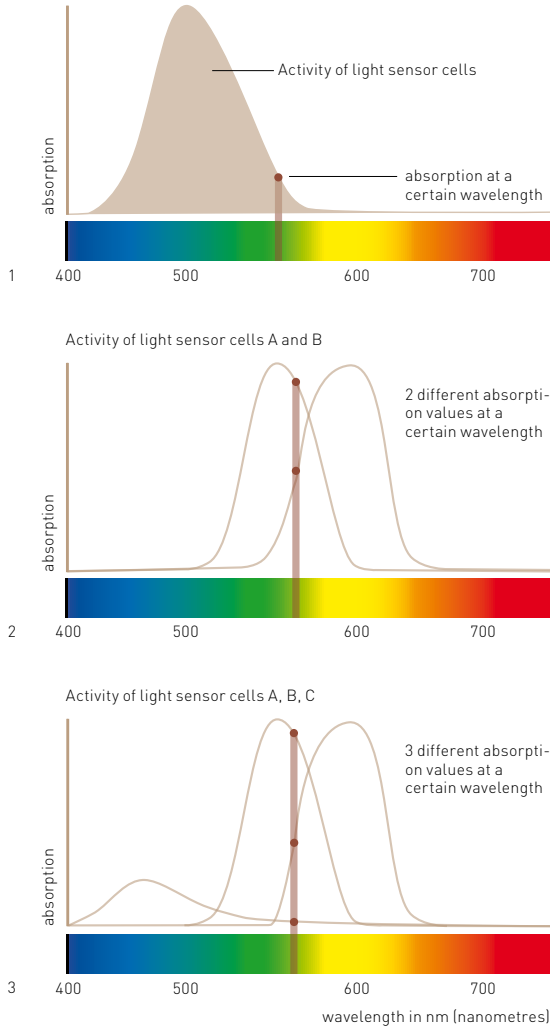
Animals with retinas containing more different types of photoreceptors exhibit more highly differentiated colour vision. However, an absolute requirement for colour vision is the presence of at least two different types of photoreceptors.

1 Cf. Werner Schmidt, *Biophysik des Farbensehens,* Constance, 1999, pp. 52 – 56.

Fig. 1 Vision with only one type of photoreceptor is illustrated with the aid of the wave spectrum of visible light. This type of photoreceptor provides for light-and-dark vision only. Colours cannot be distinguished.

Fig. 2 If two types of photoreceptors are present, two absorption values, a and b, are assigned to a given wavelength. Colour information is derived from the ratio a:b.

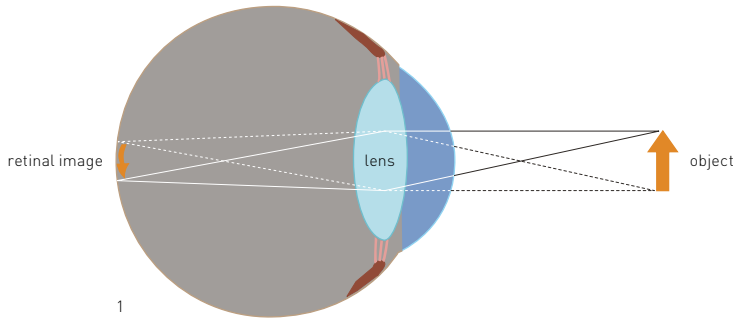
Fig. 3 If three different types of photoreceptors are present, exposure to light of a given wavelength produces three values, a, b and c. A three-colour sensory impression is derived from the ratio a:b:c.



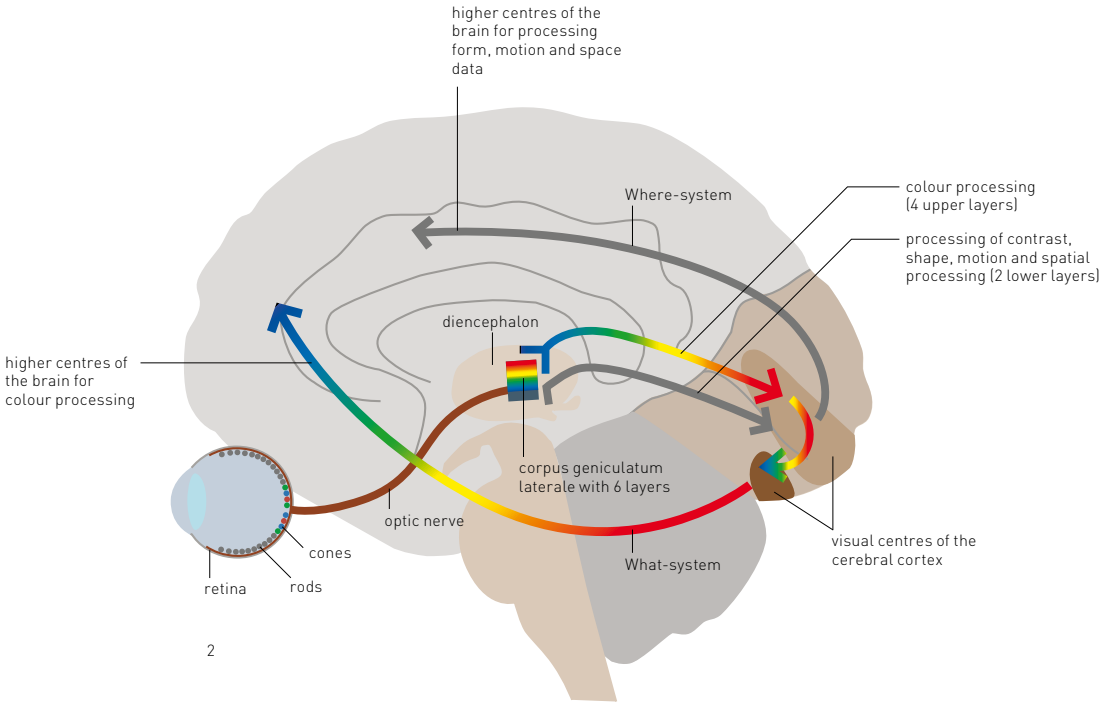
K37 VISUAL PERCEPTION

A great deal of though has been given in research to the question of how an upside-down retinal image that is truly sharp only in the centre of the field of vision produces an impression of reality.
On the basis of cell reactions to specific stimuli at all levels of the optic tract, initial conclusions were drawn with respect to how the human visual system works. Important insights have been gained from studies of injuries to the region of the brain responsible for vision and from research on colour-blindness.
Initial studies were performed on the optic nerve, i.e. on the ganglia cells. These investigations showed that the retina is divided into receptive fields. This helped explain the phenomenon of the separation of figure and background.[1]
In-depth research on the corpus geniculatum laterale, the target zone of the optic nerve, revealed two different information processing systems.[2] The one is incapable of colour differentiation, is extremely sensitive to the smallest differences in contrast and exhibits a very high processing speed, to the detriment of sharp focus. It is responsible for the perception of motion and three-dimensionality and supports spatial orientation. Thus Margaret Livingstone refers to it as the Where System. The second system provides for high-resolution colour perception. Accordingly, it is less contrast-sensitive and processes information more slowly but provides for more precise recognition of surface structures and complex details. Livingstone refers to this perceptual system as the What System. Thus impressions are assigned during the process of perception to certain categories and then processed separately. All processing functions proceed simultaneously and are networked with one another. Each of the two systems makes a contribution to the overall visual impression of the outside world.

Fig. 1 Idealized schematic diagram of the path of light in the eye. The convex lens gathers incoming light. An upside-down image is produced on the retina.
Fig. 2 The subdivision of the different aspects of perception into two separate systems: the "What System" and the "Where System".



1



2

Another important characteristic of visual perception is the striving for constancy. Constancy of perception is indispensable to organisms in a constantly changing physical world and provides the true basis for biologically meaningful use of visual capacities.[3]

1 Cf. David Hubel, Torsten Wiesel, *Brain and Visual Perception. The story of a 25-Year Collaboration,* Oxford 2005, pp. 93–103.
2 Cf. Margaret Livingstone, *Vision and Art. The Biology of Seeing,* New YorK2002, pp. 46 – 68.
3 Cf. Vincent Walsh, Janusz Kulikowski, *Perceptual Constancy. Why things look as they do*, Cambridge 1998, pp. 262–282 and 323 – 351.

Fig. In a visual montage of people in a park, the viewer readily recognizes that colour constancy has not been taken into account.

K38 OPTIC TRACT

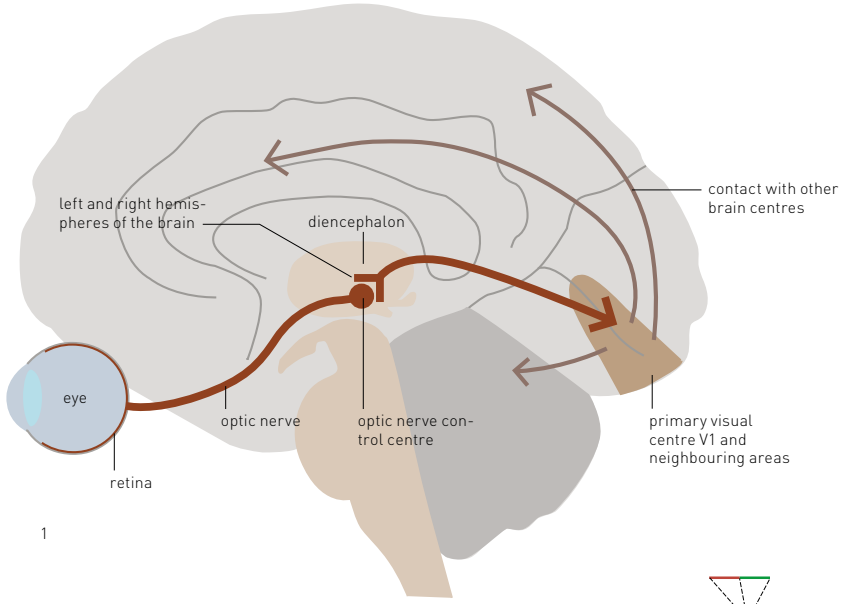
Light stimuli are processed by a chain of successive nerve cells referred to as the optic tract. It begins with the retina. The light-sensing cells in the retina transmit electrical impulses via the optic nerve to the diencephalon and from there to the visual processing centres in the cerebral cortex in the back of the head, which are in turn linked to many other centres of the brain.[1]

Some 126 million light-sensing cells are connected to one million optic nerve cells. The inside of the optic nerve is linked to the central region of the retina, the fovea centralis. Its exterior receives input from the retinal periphery. This refers to the topography of the retina, which is preserved as a map in the optic tract. Relationships between neighbouring light-sensing cells are reflected in the structure of the processing centres farther along the optic tract.[2]

Because signals are also processed from two eyes, the processing paths must be closely coordinated. The optic nerve junction (chiasma opticum) is positioned at the level of the base of the diencephalon. It is here that optic inputs are actually sorted. What is registered on the right side of the retina is processed in the right hemisphere of the brain; input from the left side of the retina is processed in the left hemisphere.

The fibres of the optic nerves converge with the cells in the right and left corpus geniculatum laterale in the diencephalon. The topographic map of the retina is clearly recognizable here. The region of the fovea is represented to a disproportionate degree, which accounts for the high resolution of central vision. Image processing tasks are separated and distributed in the corpus geniculatum laterale, with its six layers.[3]

The two lower layers composed of large cells process contrast, movement and spatial- depth information very quickly, but they are colour-



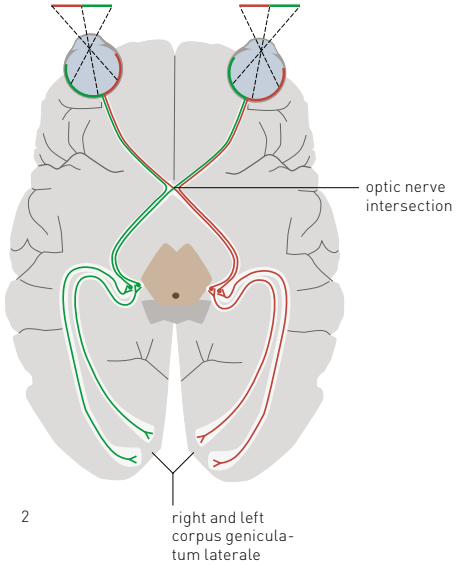


Fig. 1 Schematic diagram of the optic tract viewed from the side.
Fig. 2 Schematic diagram of the optic nerve junction, which ensures that data from the right and left regions of the retina are processed in the right and left hemispheres of the brain, respectively. The lens reverses the retinal image, but this phenomenon is not perceived.

blind. The four upper layers consisting of small cells react hardly at all to contrasts; they work more slowly but are sensitive to coloured light. They are part of the colour-processing optic tract.[4]
The distributed processing of image information is transmitted to the cerebrum. The first station in the cerebrum is the primary vision centre. If this centre is damaged, the patient becomes blind, even with intact eyes and optic nerve. Impairments in the contact regions of the primary vision centre limit the recognition of visual images. From there, signals are transmitted to more specialized regions of the cerebrum. If these connections are impaired, lines and parts of a face, for example, may be clearly recognizable but not the person to whom they belong.

1 Cf. Margaret Livingstone, *Vision and Art. The Biology of Seeing,* New York, 2002, p. 48.
Cf. N. Welsch, C. Liebmann, *Farbe,* Heidelberg, 2003, p. 255.
Cf. Stephen E. Palmer, *Vision Science. Photons to Phenomenology,* Cambridge, 1999, p. 25.
2 Cf. Robert F. Schmidt, Gerhard Thews, *Physiologie des Menschen,* Berlin, Heidelberg, New York, 1995, pp. 295 – 296.
Cf. Roger Eckert, *Tierphysiologie,* Stuttgart, New York, 1993. p. 263.
3 Cf. Margaret S. Livingstone, David H. Hubel, *"Psychological Evidence for Separate Channels for the Perception of Form, Color, Movement and Depth",* in *The Journal of Neuroscience,* 7 (11), November 1987, pp. 3416 – 3468.
4 Cf. Livingstone, *Vision and Art, op. cit.,* pp. 46 – 52.

K39 COLOUR PROCESSING IN THE BRAIN

From the retina to the higher brain centres, colour stimuli are processed along a chain of nerve cells known as the colour pathway. Such image characteristics as depth, movement, contrast and form are analyzed separately from colour data. [1]

The colour encoding cone signals from the retina are collected in ganglia cells in the optic nerve. These cells lead to the brain and transmit their electrical impulses to the four upper cell layers of the corpus geniculatum laterale, which comprises four upper layers of very small cells (P-cells) and two lower layers with much larger cells (M-cells). Studies of P-cells have shown that they are capable of responding to coloured light stimuli. They work more slowly and are not sensitive to differences in contrast. Their receptive fields are composed of a monochrome centre and a complementary-coloured surround. The centre and the surround work in opposite ways. The complexity of the receptive fields increases farther along the optic tract. Anatomically speaking, the cells of the colour tract belong to the part of the perceptual system that is linked with object recognition. Colour and object recognition form a system referred to by Livingstone as the "What System".[2]

The colour pathway ultimately leads to the primary vision centre in the cerebral cortex, which also has clearly defined cell layers which receive incoming colour signals and pass them on to drop-shaped cell complexes (blobs). Large numbers of colour-sensitive cells are found in the blob regions.

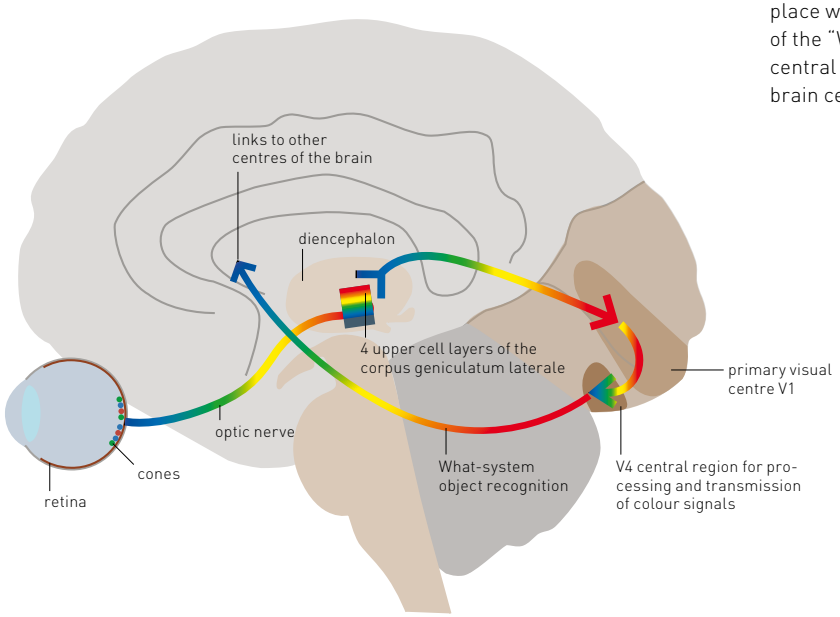


Fig. The colour pathway has its own place within the optic tract. It is part of the "What System". Region V4 is the central hub for all further links to other brain centres.

Further colour processing takes place in Region V4 of the cerebral cortex in the back of the head. This region is located quite close to the primary visual centre of the cerebral cortex (V1), which initially receives all signals for visual perception. People with damaged V4 regions can neither see nor conceive of colours. Their world is much like a black-and-white film, and they cannot even imagine different colours.

1 Cf. John G. Nicholls, A. Robert Martin, Bruce G. Wallace, *Vom Neuron zum Gehirn. Zum Verständnis der zellulären und molekularen Funktion des Nervensystem,* Stuttgart, Jena, New York, 1995, p. 427.
Cf. Margaret Livingstone, David Hubel, *"Psychological Evidence for Separate Channels for the Perception of Form, Color, Movement, and Depth"*, in *The Journal of Neuroscience*, November 1987, pp. 3416 – 3468.
Cf. Margaret Livingstone, David Hubel, "Segregation of Form, Color, Movement and Depth: Anatomy, Physiology and Perception", in *Science*, May 6, 1988, pp. 740 – 749.

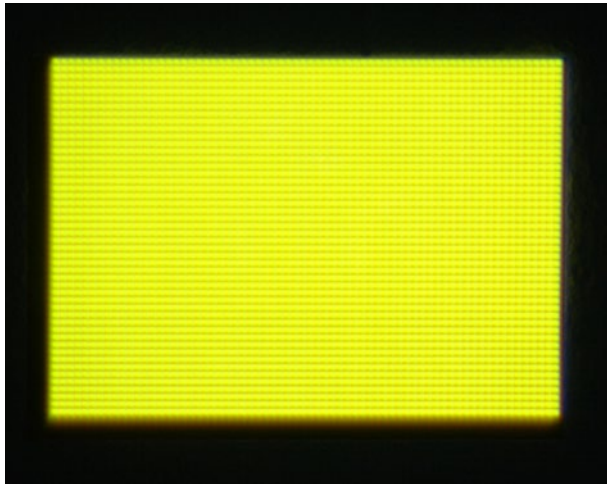
2 Cf. Margaret Livingstone, *Vision and Art. The Biology of Seeing,* New York, 2002, pp. 46 – 67.

K40 COLOUR CONSTANCY

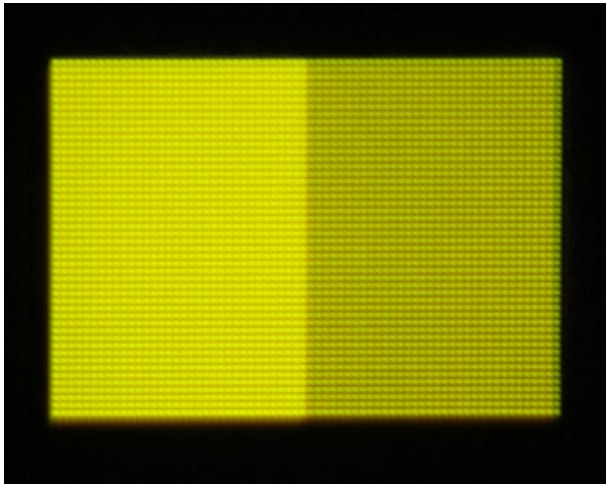
Photographs taken spontaneously indoors or outdoors under artificial light may exhibit a yellowish tint. When an individual enters an indoor space, the perceptual system adjust immediately to the artificial light, although the viewer is not aware of the different characteristics of the artificial light source. This consistency of perceived colouration is known as colour constancy. This process suppresses the perception of manifest colours, which are subject to constant change. With practice and concentration on individual colour hues, manifest colours can also be perceived consciously.

Light-sensing cells react to different colour values within a complete context. They do not register individual areas in isolation. The reflected light of the whole environment also plays a role in the further processing of light information. The lightest point serves as a reference value to which the visual system adjusts: the white point. Analogous to this process, digital photography effects a white balance as a means of computing pixels in adaptation to the colour temperature of the light source.

The first astonishing studies of colour constancy were conducted by Edwin Land, the inventor of the Polaroid camera in 1986. He observed that the colouration of a single illuminated area against a black background changes markedly in response to differences in illuminating light. If such an area were placed within a context of equivalent colour areas, however, and the overall impression were retained, the physical changes in the colour of the individual area would no longer be perceived. Land demonstrated that equivalent colour impressions are possible under changing light due to the influence of colour constancy.[1]



1



2

An explanation of colour constancy requires an understanding of the entire visual system at all levels and remains the focus of intensive research today.[2]

1 Cf. John G. Nicholls, A. Robert Martin, Bruce G. Wallace, *Vom Neuron zum Gehirn. Zum Verständnis der zellulären und molekularen Funktion des Nervensystems, Stuttgart, Jena, New York, 1995, p. 431.*

2 Vincent Walsh, Janusz Kulikovsky, *Perceptual Constancy. Why things look as they do,* Cambridge, 1998, pp. 323ff.

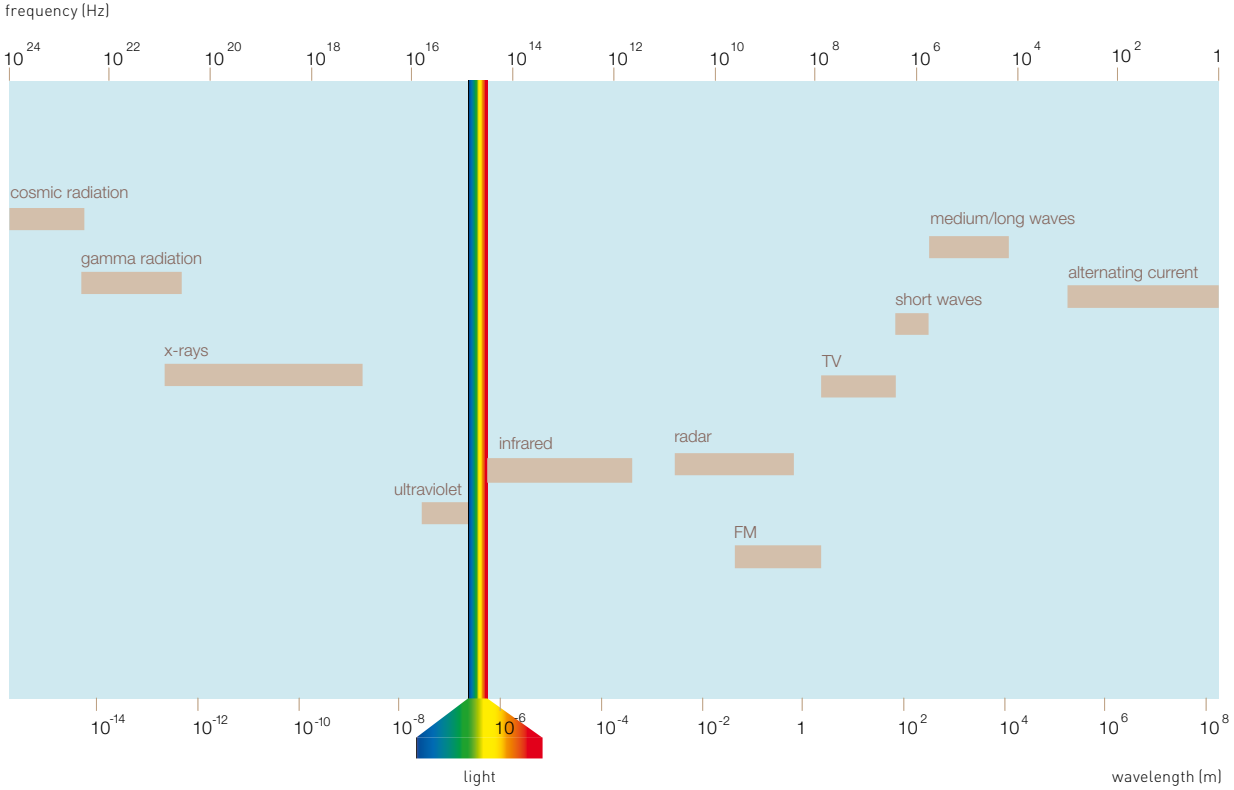
Fig. 1 Under white beamer light surface colours appear to be uniform in colour.
Fig. 2 When the intensity of the pro*jected light is reduced, in order that* dark and light colours lie directly opposite each other, noticeable changes in perceived colours may result. Thus, for example Lemon yellow appears to be olive green. Without comparison this colour change would hardly be noticed because of colour constancy.

K41 LIGHT (BIOLOGICAL)

Human beings are surrounded by a broad spectrum of electromagnetic waves.[1] Their environment is flooded with extremely short-wave cosmic radiation and the artificially generated waves (ranging from long to ultra-short) emitted by radio, television and mobile phone stations. However, the entire wave spectrum is not visible to the human eye, which is capable of seeing only light with wavelengths of between 380 and 760 nanometres (billionths of a metre). The waves in this very small segment of the spectrum represent visible light. Ultraviolet light is invisible to human beings, as is infrared radiation, which people sense only as warmth.
The corresponding light particles are known as photons. When they strike the light-sensitive retina of the eye, a signal is emitted and registered by the nervous system.

1 Cf. Jost J. Marchesi, *Handbuch der Fotografie*, vol 1, Schaffhausen, 1993, pp. 125 – 126.

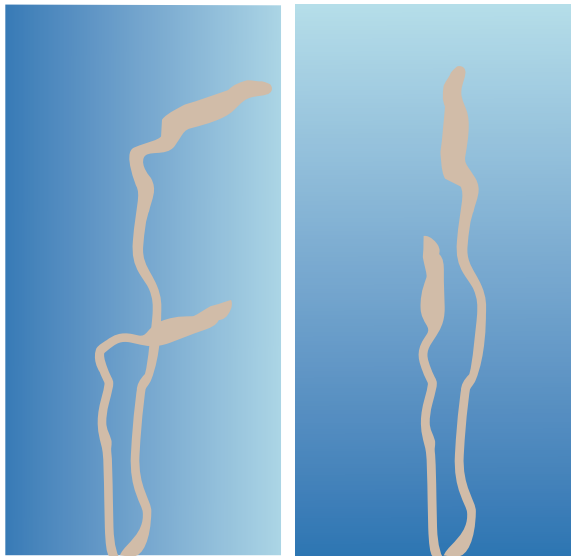
Fig. Only a small part of the electromagnetic wave spectrum is visible and referred to as light.



K42 SENSE OF LIGHT

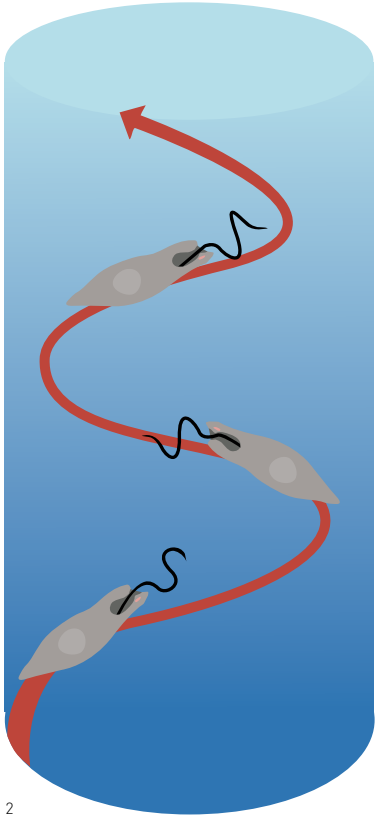
In the process of photosynthesis, light is the basis for the harvesting of energy and a factor that exerts an important influence on habitats. Living things, from single-and multi-cell organisms to plants, animals and humans are capable of responding to light and orienting themselves to incoming light.
In the quest for optimum living conditions, even single-cell organisms rely on light-sensitive structures to determine the intensity and wavelength range of ambient light.[1] Thus they move in response to changes in the direction of incoming light (phototaxis).
In plants, photosynthesis is more effective when they turn their leaves toward the light (phototropism).[2] The oxygen produced in the process is the foundation of life for breathing organisms.

1 Cf. Jerome J. Wolken, *Light Detectors. Photoreceptors and Imaging Systems in Nature*, Oxford, 1995, pp.17ff.
2 Cf. ibid., pp.64ff.



1

Fig. 1 The bulb of the Dictyostelium giganteum aligns itself toward incoming light.
Fig. 2 Euglena grazilis, a single-cell organism, measures the direction of incoming light and swims toward the light with the aid of its flagella.



2

K43 EYE

The eye is a highly sophisticated organ comprising three essential components: a light-gathering apparatus, a complex of light-sensitive cells, and a link to the nervous system. Eyes may have very different structures, but the underlying principle is always the same.
The unique characteristic of light-sensing cells is their capacity to absorb light particles and translate this process into the language of the nerve cells. The signals generated by these cells is passed on and processed farther along the optic tract. The language of the light-sensing cells encodes the quality of incoming light with great precision and conveys an exact impression of the outside world.

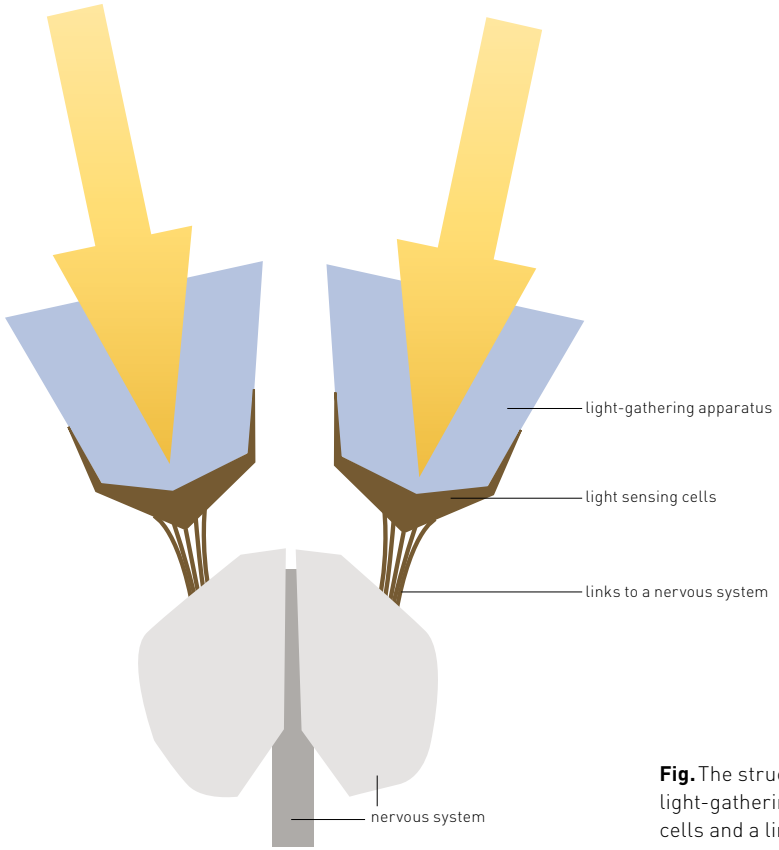
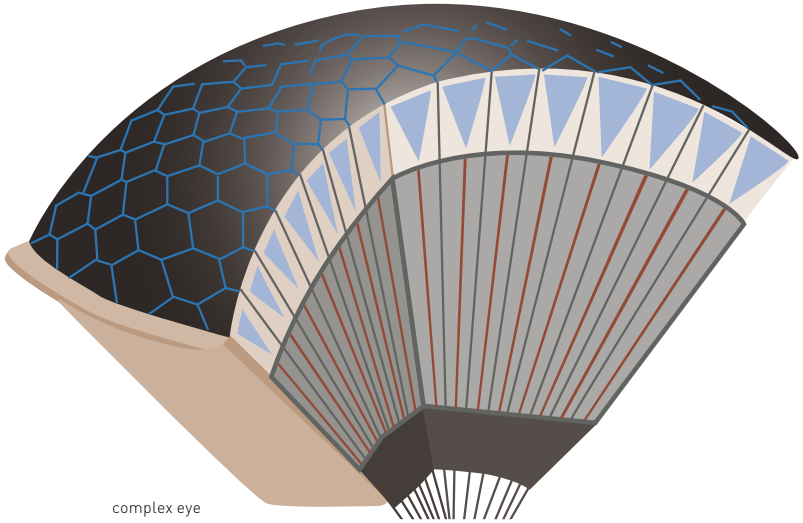


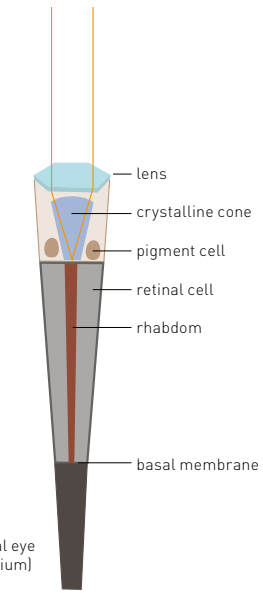
Fig. The structural principle of the eye: light-gathering complex, light-sensing cells and a link to the nervous system and the brain.

K44 TYPES OF EYES

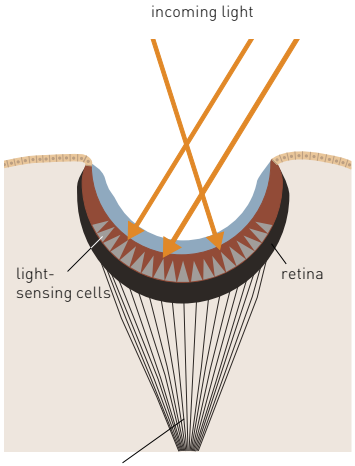
Complex, highly sophisticated eyes have evolved from simple, light-sensitive sensory cells in different families of animals. In life under differing light conditions, light-sensitivity and resolution capacity define the standards for the quality of a given type of eye.[1]
There are limits to the size and structure of the various types of eyes. Physically and physiologically speaking, however, large eyes are advantageous.[2] Thus, for example, the complex eye of a dragonfly consists of as many as 30,000 individual eyes.[3] Adapted to life in waters in which little light is available, the optics of the lobster's eye are capable of capturing 256 times more light than the human eye during the day.



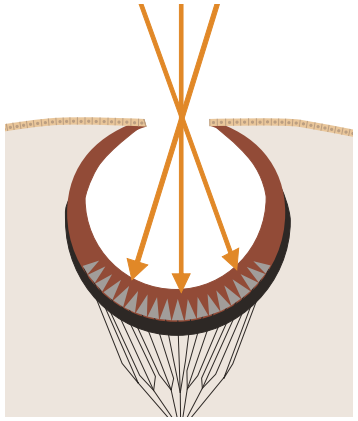
complex eye
4



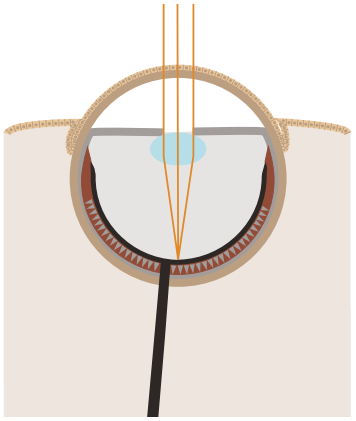
5individual eye
(Ommatidium)



1



2



3

Fig. 1 The concave-mirror eye gathers non-specific light. Only the general direction of light is recognized.
Fig. 2 The pinhole eye is open toward the outside, which does not pose a problem in water. Light is bundled more tightly and generates a qualitatively finer image.
Fig. 3 The lens eye bundles the light rays and generates a sharp image on the retina.

Fig. 4 The complex eyes of insects are composed of numerous individual eyes. The manner in which they work together determines the quality and resolution of the image.
Fig. 5 The ommatidium is a single eye within the group of eyes in a complex eye. Its specific structure makes even the polarization of light perceptible.

The following table provides basic information about the different types of eyes and their sensory capacities:

Type	**Sensory capacity (perception)**	**Example**
Light-sensing cells in the skin	light/dark	Worm
Concave-mirror eye	light/dark; directional vision	Limpet, medusa
Bubble eye	sharp image with low light intensity (pinhole-camera principle)	Nautilus
Lens eye	sharp, light-intense image (camera principle)	snails, vertebrates, humans
Complex eye	UV vision, polarization vision, Image production from a mosaic of individual eyes	Insects, crabs

1 Cf. Rüdiger Wehner, Walter Gehring, *Zoologie*, Stuttgart, New York, 1990, pp. 406 – 417.
2 Cf. M. F. Land, D. E. Nielsson, *Animal Eyes,* Oxford 2002, p. 51.
3 Cf. ibid., p. 125.

K45 HUMAN EYE

All components of the human lens eye are precisely coordinated to produce a sharp image on the retina. Light rays are initially refracted on the transparent cornea, which . has a marked convex form. This shape permits only one visual axis and one point at which vision is sharpest on the retina. There, at the focal point of the lens, is the fovea centralis. As a very thin part of the retina, the fovea centralis allows light to fall more intensely on the light-sensing cells responsible for daylight vision, the cones. This is the point at which the most dense concentration of cones is found. The eye continually refreshes the perceived image through rapid eye movements.

The eye is well protected against scattered light. It responds to imaging errors in the lens[1] by making specific adjustments. It has a mosaic of cones which is precisely adapted to the differing refraction of short-wave and long-wave light and corrects for chromatic aberration.

When the human pupil narrows to 2 mm under exposure to sunlight and expands to 8 mm in the dark, it increases the intensity of incoming light by a factor of ten. This may seem relatively insignificant, as the eye is capable of processing 1010-fold changes in the quantity of light, which is comparable to a ratio of one millimetre to ten thousand kilometres. The pupillary reflex ensures precise adjustment of light quantities in the eye and determines the light-sensitivity of the retina.[2] This guarantees optimum resolution regardless of the quantity of light. In bright light, for example, an average pupil opening of 2-3 mm is ideal in the sense that it ensures optimum resolution, which is supported by the optics of the eye.[3]

The lens produces an upside-down retinal image with a resolution that is exceeded only by that of predatory birds.[4] The retina is a highly complex fabric of nerve cells and an outer extension of the brain.

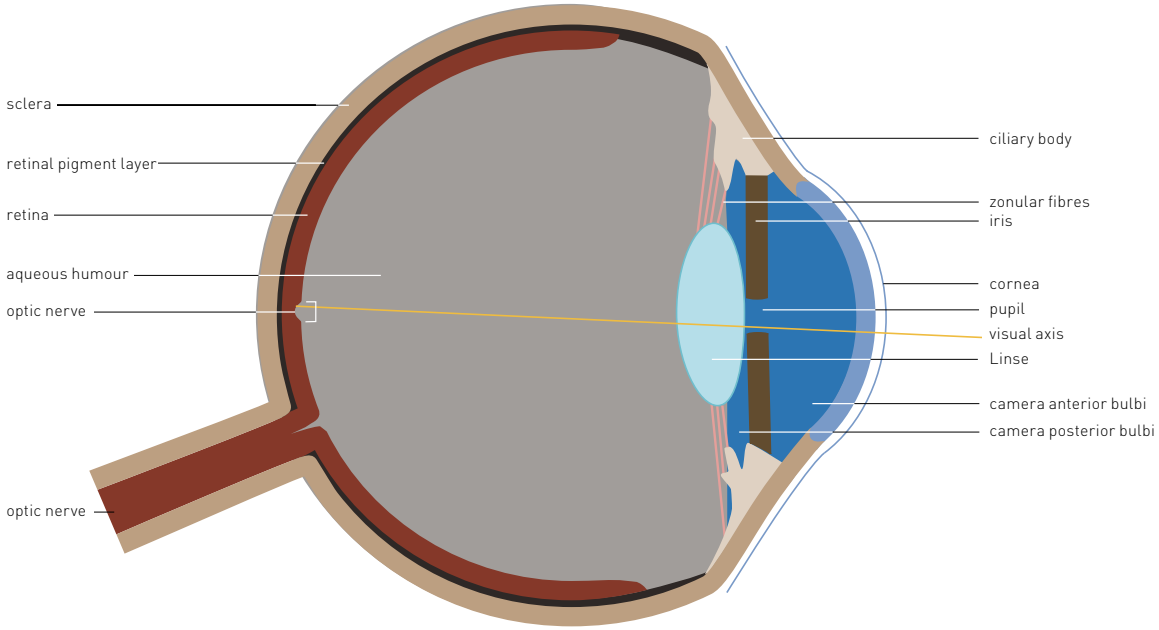


Fig. A schematic diagram showing the structure of the human eye. The visual axis is positioned at a slight angle to the optic axis and leads to the centre of the fovea centralis. The pigment layer or choroidea absorbs light and supplies the retina with nutrients. The sclera encloses and protects the eye.

Cornea, lens and the aqueous humour which fills the eyeball serve as filters for extremely short-wave ultraviolet light. In other words, if these filters were removed, human beings – like bees – could presumably see ultraviolet light.[5]
Vision through two eyes enables an organism to perceive spatial depth. However, this requires specialization in the processing of visual data.

1 Cf. Jost J. Marchesi, *Handbuch der Fotografie*, vol. 1, Schaffhausen, 1993, pp. 224–230.
Cf. David S. Falk, Dieter R. Brill, David G. Stork, *"Ein Blick ins Licht. Einblicke in die Natur des Lichts und des Sehens", in Farbe und Fotografie*, Basel, Boston, Berlin, 1990, p. 155.
2 Cf. M. F. Land, D. E. Nielsson, *Animal Eyes,* Oxford, 2002, p. 88.
3 Cf. ibid., pp. 72 – 81.
4 Cf. Margaret Livingstone, *Vision and Art. The Biology of Seeing,* New York, 2002, p. 70.
5 Cf. David S. Falk, Dieter R. Brill, David G. Stork, *"Ein Blick ins Licht. Einblicke in die Natur des Lichts und des Sehens", in Farbe und Fotografie,* Basel, Boston, Berlin, 1990, p. 156.

K46 ABSORPTION SPECTRUM

In the study of coloured biological substances, one frequently encounters diagrams in which absorption is shown as a function curve plotted above light wavelengths. This form of representation originated in spectral photometry, a precise method used to analyze coloured liquid solutions.

Following the prismatic division of white light into the individual spectral colours, a sample wavelength is illuminated for wavelength analysis.[1] Absorption describes the relationship between the light absorbed by the sample and the intensity of illuminating light. These values are entered above the respective wavelength, producing an absorption spectrum. When the light emitted by the sample is measured, the result is referred to as the transmission spectrum.

1 Cf. Werner Schmid, *Biophysik des Farbensehens,* Constance, 1999, p. 37.

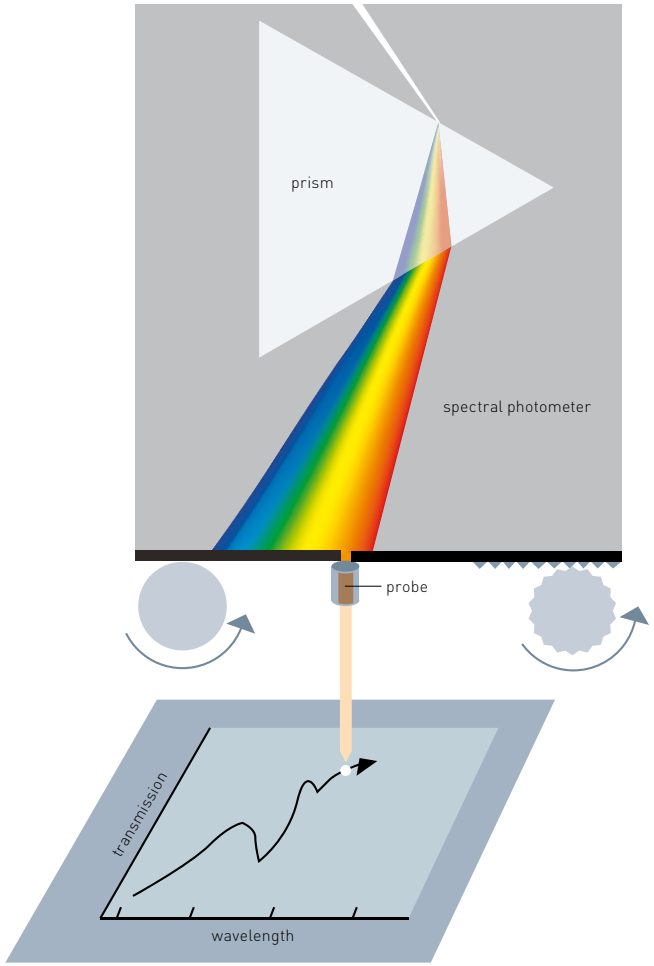


Fig. Schematic diagram of the functional principle of a spectral photometer.

K47 LIGHT-SENSING CELLS

The core of every retina is a complex of so-called light-sensing cells or photoreceptors. Light-sensing cells convert physical light stimuli generated by light particles that collide with them into electrical impulses, i.e. into the language of the central nervous system. Accordingly, light-sensing cells always contain a light-gathering component with a large surface area and pigments, a second component which generates an electrical signal and a third which transmits the signal via a contact point to a nervous system. A light-sensing cell or a group of sensory cells of the same type conveys an impression of light or dark, depending upon the intensity of incoming light.

Every light-sensing cell has its own specific absorption spectrum. Each type of cell is characterized by maximum absorption at a given light wavelength. Colour vision is possible if at least two types of light-sensing cells with different maximum absorption capacities are present. The greater the number of different types of photoreceptors on the retina, the more differentiated the colour impression perceived by the eye will be.

Chickens, for example, have five different types of light-sensing cells, the mantis crab up to twelve, humans four, dolphins and dogs only two.[1]

1 *Cf. Almut Kelber, Misha Vorobyev, Daniel Osorario, "Animal colour vision – behavioral tests and physiological concepts"* in *Biological Reviews* 78, 2003, pp. 81 – 118, here: p. 84.

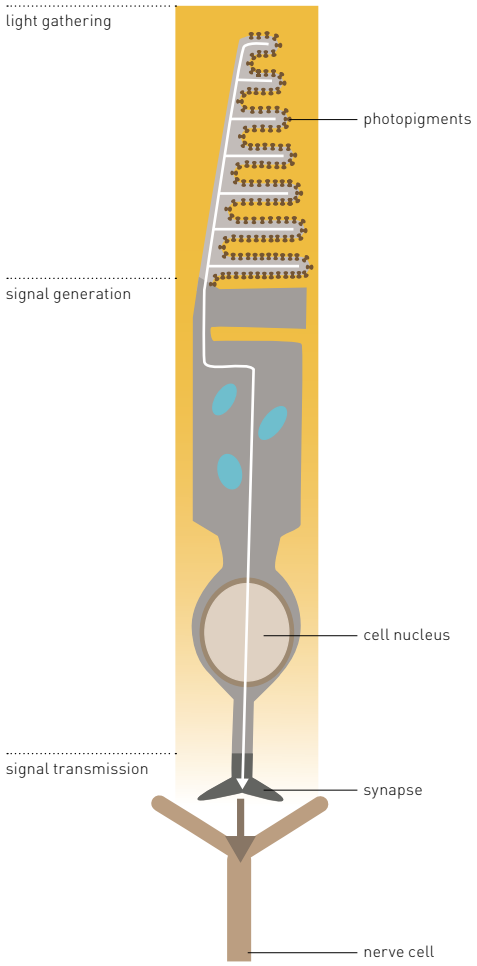


Fig. Schematic diagram of a light-sensing cell with its three different light-processing regions. The exact forms of these three regions are adapted to the specific functional principles of the eye, i.e. to the specific type of eye.

K48 HUMAN LIGHT-SENSING CELLS

The retina lies at the bottom of the eye and is embedded in the pigment layer of the sclera. Numerous layers of nerve cells are located on the upper surface of the retina. The light-sensing cells or photoreceptors, are positioned on the lower surface, which is not exposed to light, and are thus protected against light. All light-sensing cells in a healthy eye are directly linked via the optic nerve to the brain, which processes the signals they send.

The human eye has adapted to life under both diurnal and nocturnal conditions by developing two types of light-sensitive cells: rods for night vision and cones for daylight vision. The difference between the large amount of light processed during the day and the small quantities processed at night equates to a factor of 1010 – which is comparable to the ratio of one millimetre to ten thousand kilometres.[1] The specialized structure of the light-gathering components of the cells makes this tremendous accomplishment possible.

During the night, human beings rely on a single type of rod, which is why we may often have the impression of seeing only colourless light-dark contrasts. Bright daylight blocks the rods because a surplus of light inhibits their function. At this point, the less light-sensitive cones begin to do their work. Because there are three types of cones for red, green and blue light, human beings see in colour during the day.

Rods and cones have an abundant supply of light-gathering pigments. They absorb light best at very specific wavelength ranges: rod pigments at 498 nanometres in the blue-green spectral range, cone pigments and 437 nanometres in the blue or short-wave spectral range, at 533 nm in the green, medium-wave range and at 564 nm in the yellow-green range.[2] Scientists were astonished at the discovery that the cones that process red, long-wave light has its maximum absorption capacity in the yellow-green range. They are very similar to the green cones.

Only certain sets of light-sensing cells function at any given time, depending upon the quality of incoming light. At dawn or dusk, when colours are still recognizable and cones also begin to function, all light-sensing cells are active at once.

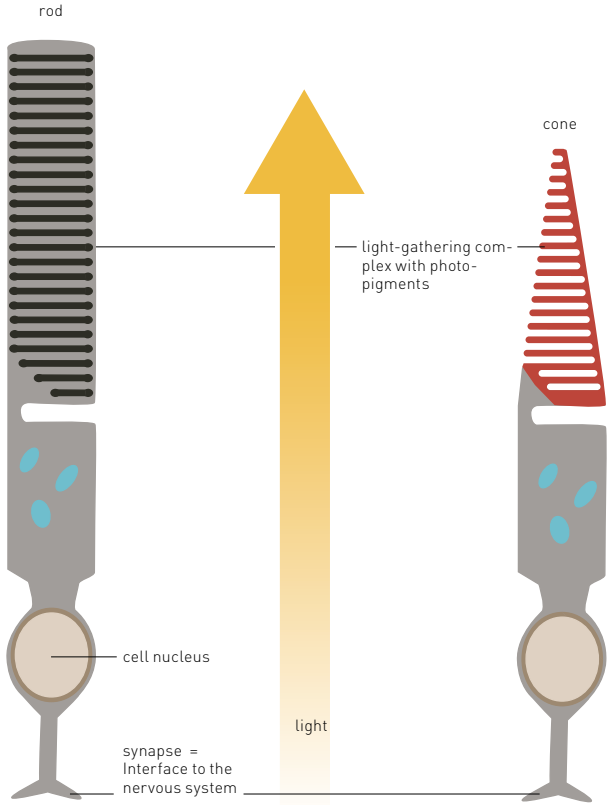


Fig. The image formed by rods and cones is not upside-down. Light-sensing cells in the human eye are exposed to light from the rear. Rods expand their surface area by storing discs with dense deposits of pigments. This enables them to capture and register even individual light particles. A light signal is electrically encoded and converted to a chemical signal at the point of transition to the nervous system. The nervous system converts them back to electrical impulses.

1 *Cf. M. F. Land, D. E. Nielsson, Animal Eyes,* Oxford 2002, pp. 19 – 20.
2 Cf. A. Kelber, M. Vorobyev, D. Osorio, *"Animal colour vision – behavioral tests and physiological concepts"*, in *Biological Reviews*, 78, 2003, pp. 81 – 118.

K49 RODS

The basis for human night vision is the activity of rods. They are found on all parts of the retina except for the fovea centralis.[1]
Rods consists of an outer and an inner segment. The outer segment is responsible for gathering light, the inner segment for generating and transmitting nerve impulses.[2]
The outer segment of rod cells is extremely well adapted to small quantities of light. The light-gathering surface area is enlarged immensely by the presence of stacked discs covered with dense deposits of the visual pigment rhodopsin. Thanks to this structural principle, even individual light particles can generate a light signal in these cells. Rods are only capable of transmitting light-dark signals, however. Thus night vision is colourless. Our inability to see objects in sharp focus at the dark is attributable to two facts: the first being that the fovea centralis is not needed at all at night, the second that rod activities are always the expression of many cells working at the same time. The visual pigment in rods is particularly effective in the blue-green spectral range (498 nanometres).[3] Blue-green surfaces look lighter in the dark, while red surfaces appear much darker or even black. Red does not generate a light signal in rods, as no absorption takes place. The result is the impression of blackness (Purkinje phenomenon).

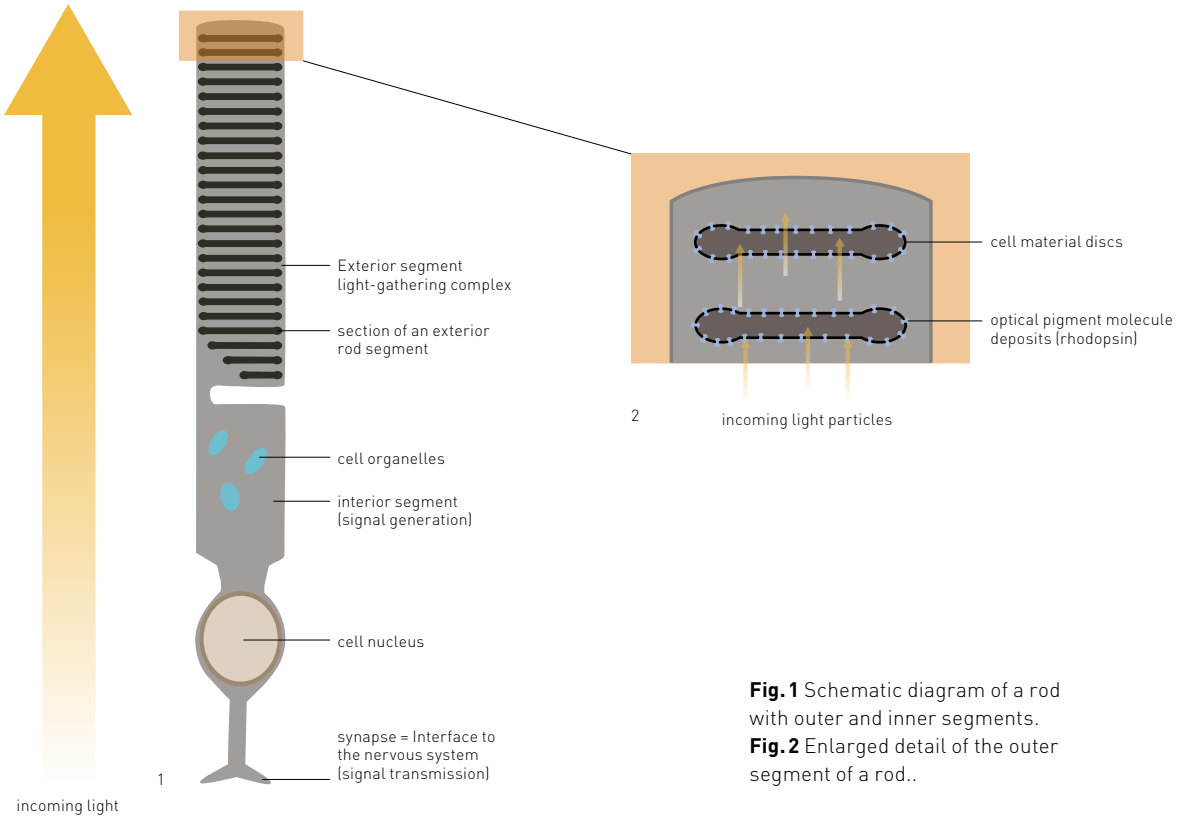


Fig. 1 Schematic diagram of a rod with outer and inner segments.
Fig. 2 Enlarged detail of the outer segment of a rod..

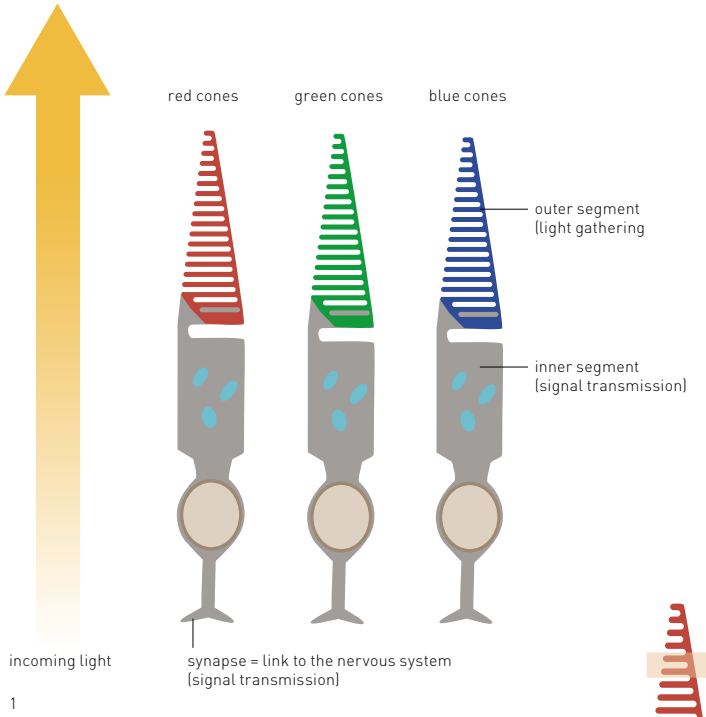
1 Cf. N. Welsch, C. Liebmann, *Farbe,* Heidelberg, 2003, p. 240.
2 Cf. Erik R. Kandel, James H. Schwartz, Thomas M. Jessell, *Principles of Neural Science,* East Norwalk, 1991, pp. 402 – 403.
Cf. John G. Nicholls, A. Robert Martin, Bruce G. Wallace, *Vom Neuron zum Gehirn. Zum Verständnis der zellulären und molekularen Funktion des Nervensyste*ms, Stuttgart, Jena, New York, 1995, pp. 376 – 378.
3 Cf. Frederike Woog, *"Farben der Natur. Sehen und gesehen werden",* in *Stuttgarter Beiträge zur Naturkunde*, 56, 2004, p. 38.

K50 CONES

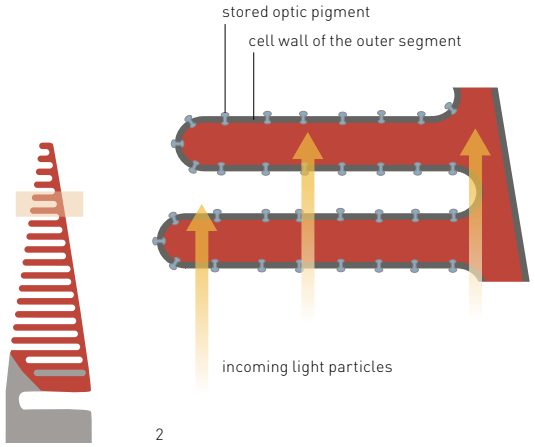
As light-sensing cells, cones are key components of the retina and responsible for colour vision during the day. Located at the intersection of the visual axis is the fovea centralis, which is occupied by light-sensitive cones. The processing of the light-signals received there promotes maximum resolution, as every single cone has a direct link to the brain.[1] The fovea centralis is solely responsible for the capacity to see images sharply.

Like rods, cones consist of an outer segment, which collects light, and an inner segment, which generates and transmits electrical signals. Light is captured by photopigments stored in the cell walls in the outer segment. Three different photopigments have been found in cones. They absorb light in the blue spectral range at 437 nanometres, in the green range at 533 nanometres and in the yellow-green range at 564 nanometres, respectively.[2] Thus we speak of red, green and blue cones, analogous to the three primary colours. Accordingly, the red cone has a pigment that exhibits optimum light absorption in the yellow-green range. However, because it is the only cone the covers the red range of the spectrum, it is referred to as the "red" cone. Whenever daylight enters the eye, there are always three different excitation values, as all three types of cones respond simultaneously. This enables the human organism to process colour information in addition to light-dark values.

Cones require daylight, i.e. large quantities of light. The have a much higher excitation threshold than rods, which means that they become active only when exposed to high light intensities. Thus because it is adapted to high light intensities, the structure of the light-gather outer segment is comparatively simple.



1



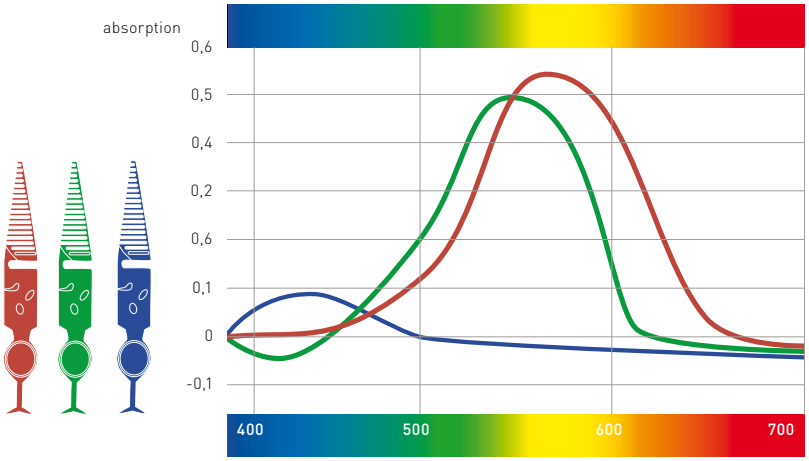
2

Fig. 1 Three schematic diagrams of cones showing the directions of incoming light.
Fig. 2 A detail of the outer segment of a red cone shows the distribution of photopigments. They absorb light in the yellow-green and red ranges of the spectrum.

Only red and green cones are found in the centre of the fovea centralis. Blue cones appear, in a somewhat dispersed patter, at its edge. Red excites the eye much more readily than blue. In order to achieve the same degree of excitation, a blue signal must be much more intense. Cones are distributed in a mosaic pattern in the fovea centralis, corresponding to the refraction of red, green and blue light by the lens.

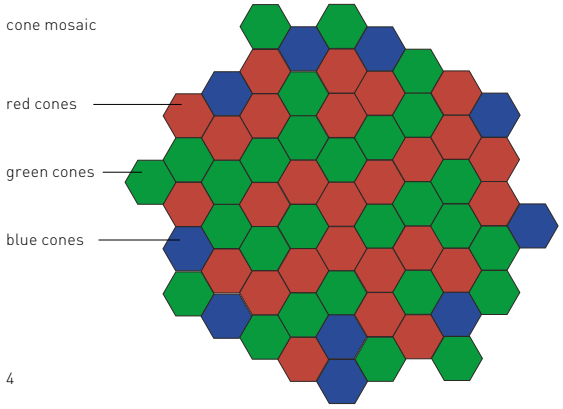
1 Cf. John G. Nicholls, A. Robert Martin, Bruce G. Wallace, *Vom Neuron zum Gehirn. Zum Verständnis der zellulären und molekularen Funktion des Nervensystems, Stuttgart, Jena, New York, 1995, p. 401.*

2 Cf. A. Kelber, M. Vorobyev, D. Osorio, *"Animal colour vision – behavioral tests and physiological concepts"*, in *Biological Reviews*, 78, 2003, p. 85.



3

Fig. 3 The absorption spectra of red, green and blue cones. High-energy blue light is absorbed less effectively than low-energy yellow light.
Fig. 4 The mosaic of cones in the fovea centralis exhibits fewer blue cones, which appear isolated near the edge. Blue, green and red light is seen in sharp focus, producing a clear colour image.



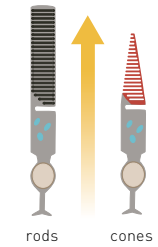
4

K51 RODS AND CONES IN COMPARISON

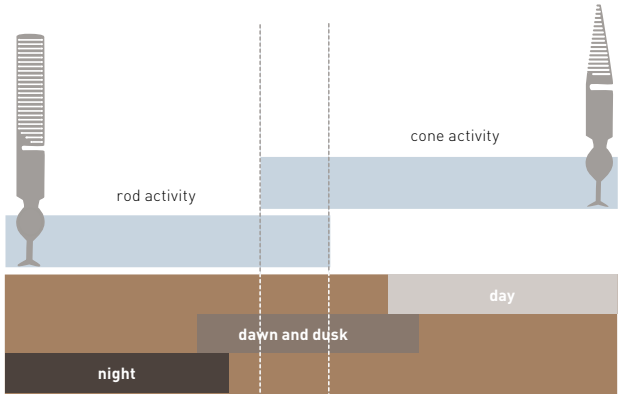
Differences between rods and cones and their systems[1]:

Rods	Cones
Specialized in night vision:	Specialized in daylight vision:
High light-sensitivity	Low light-sensitivity
More photopigments	Fewer photopigments
High signal amplification	Low signal amplification
Recognition of individual photons	Specialized in large quantities of light
Light saturation under exposure to daylight	Light saturation under exposure to highly intense light only
Low-speed resolution	High-speed resolution
Slow response to light	Rapid response to light
Long processing times	Short processing times
More sensitive to scattered light	Most sensitive to light falling along the optic axis

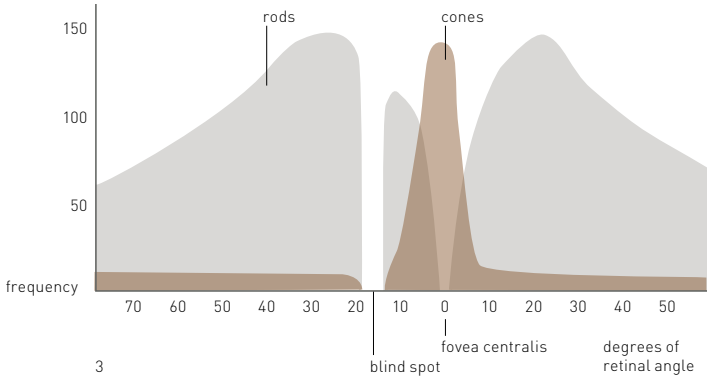
Rod system	Cone system
Blurred: Composite signals from many cells	High resolution and sharp focus: virtually no bundling of signal transmission
Do no appear in the fovea centralis.	Appear in concentration in the fovea centralis
No colour perception, as only one type of rod is present	Supports colour perception, as signals from three types of cones are processed



1



2



3

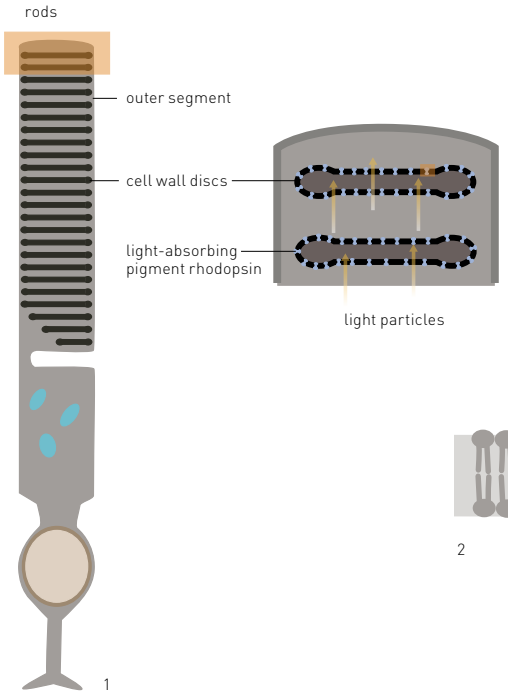
Fig. 1 Schematic diagrams: a cone on the left, a rod on the right. Light enters from the rear.
Fig. 2 The activity ranges of rods and cones overlap at dawn and dusk.
Fig. 3 The orb of the retina is subdivided into degrees. The fovea centralis lies at 0 degrees. The blind spot is located between 10 and 20 degrees, where the optic nerve exits the eye.
Diagram showing the frequency distribution of cones (dark) and rods (light). Cones are more highly concentrated within the fovea centralis, while the highest concentration of rods is found outside it.

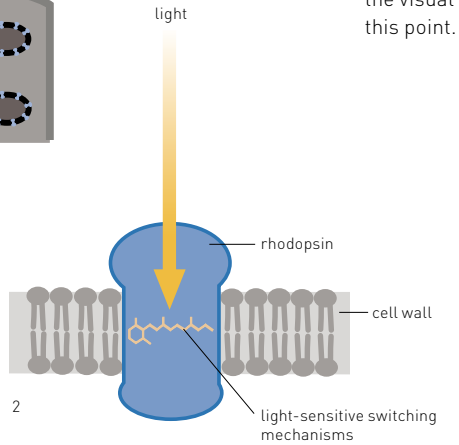
1 Vgl. Erik R. Kandel, James H. Schwartz, Thomas M. Jessell: *Princip-les of Neural Science*. East NorwalK1991, S. 402.

K52 LIGHT REACTION

Rhodopsin, the photopigment in human light-sensing cells, is a large protein molecule equipped with a light-sensitive switch mechanism. The protein consists of a long, folded chain of amino acids. The nature of the folding determines the degree to which light wavelengths are absorbed. The difference between proteins in the red and green cones results from only three individual amino acids.[1] The switch, which is activated under exposure to light, is the same in all human photopigments. When it is struck by light, its form changes. This is the only step in the process of vision that is directly dependent upon light. Only here does the physical effect of light trigger a biochemical reaction. Once the chain has been activated, the process intensifies like an avalanche in accordance with the snow-ball principle. The activated switch in a single protein excites 3,000 other enzymes, which in turn activate 2,000 others, producing a 6-million-fold amplification. This accounts for the light-sensitivity of a light-sensing cell.[2]
Following the reaction to light, the molecule of the activated switch is detached from the protein and is regenerated in the pigment layer, i.e. it is reinserted into the protein of the photopigment. The light-sensing cell cannot begin to absorb light again until this regeneration process is complete. This is the reason why the eye adapts so slowly to sudden changes in light conditions and complementary afterimages appear.

1 Cf. Josef Dudel, Randolf Menzel, Robert F. Schmidt, *Neurowissenschaft. Vom Molekül zur Kognition,* Berlin, Heidelberg, New York, 2001, p. 399.
2 Cf. ibid., caption for Fig. 17b, p. 393.





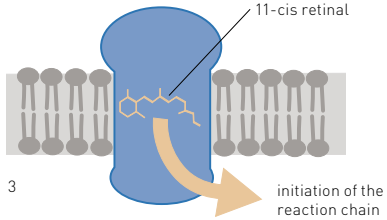


Fig. 1 This overview shows the location of light reactions,
Fig. 2 Schematic diagram of the cell wall in an outer segment of a light-sensing cell. The wall contains the protein molecule of the rhodopsin photopigment. The light-sensitive switch (11-cis-retinal) is located inside the molecule.
Fig. 3 Once light has been absorbed, the switch appears in its physiologically active form (11-trans-retinal). All subsequent reactions which produce the visual impression are triggered at this point.

K53 LIGHT SIGNAL

A physiological switch is activated in the light-sensing cell in reaction to incoming light. This causes the complete closure of all other open sodium-ion channels in the outer segment of the light-sensing cell. Dark current, i.e. electrical current through the cell, is interrupted.[1] This change in activity is reproduced at the contact point to the nervous system (synapse), where it becomes detectable as a chemical process. The next nerve cell in the chain recognizes the state of the sensory cell and forwards this information in the form of an electrical signal. The signal is transmitted into the brain. Even single light particles are registered in this way.[2]

1 Cf. Robert F. Schmidt, Gerhard Thews, *Physiologie des Menschen,* Berlin, Heidelberg, New York, 1995, p. 289.
Cf. N. Welsch, C. Liebmann, *Farbe,* Heidelberg, 2003, pp. 243 – 249.
Cf. Erik R. Kandel, James H. Schwartz, Thomas M. Jessell, *Principles of Neural Science,* East Norwalk, 1991, p. 407.
Cf. John G. Nicholls, A. Robert Martin, Bruce G. Wallace, *Vom Neuron zum Gehirn. Zum Verständnis der zellulären und molekularen Funktion des Nervensystems,* Stuttgart, Jena, New York, 1995, pp. 379 – 381.
Cf. Josef Dudel, Randolf Menzel, Robert F. Schmidt, *Neurowissenschaft. Vom Molekül zur Kognition*, Berlin, Heidelberg, New York, 2001, p. 391.
2 Cf. Nicholls, Martin, Wallace, *Vom Neuron zum Gehirn, op. cit.*, p. 382.

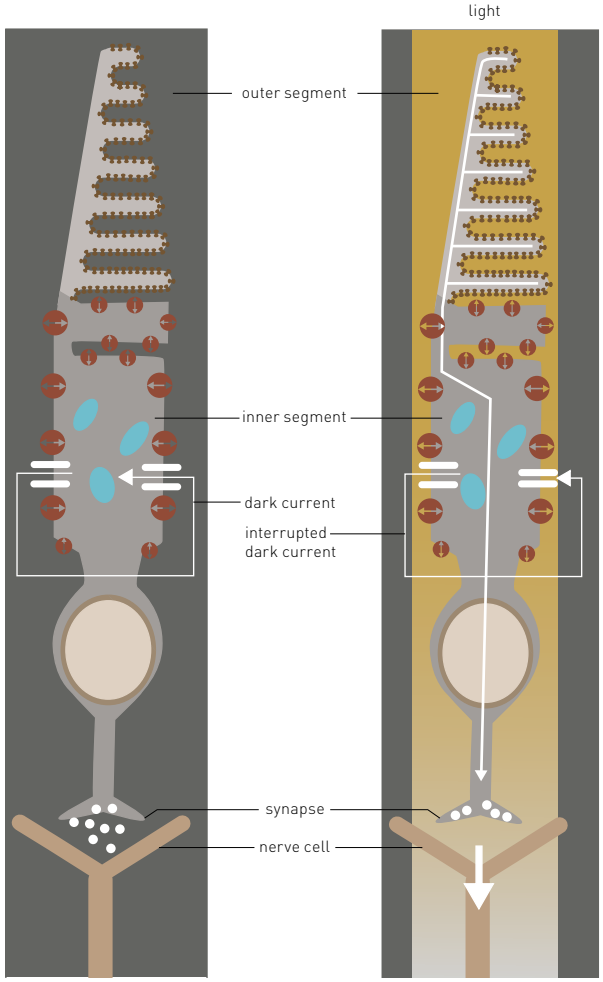


Fig. The dark current that flows through the light-sensing cell is interrupted by incoming light. This signal is transmitted to the next nerve cell in the chain and to the nervous system.

K54 PURKINJE PHENOMENON

If one looks at a blue bowl filled with red cherries in daylight, the fruits appear vivid red, the bowl dark blue. At dawn or dusk, the picture looks different: black cherries shimmering darkly in a bright, radiant bowl. This situation describes the Purkinje phenomenon, which is named for the Austrian physiologist Johannes Evangelista Purkinje (1787-1869).[1] The phenomenon reflects the change from the activity of cones to that of rods. Daylight vision relies on cones, which require a great deal of light. In contrast, the night vision system is based upon the activity of highly light-sensitive rods. This type of cell does not evoke colour impressions but provides only information about degrees of lightness.[2] Rods are most sensitive in the blue-green range of the visible spectrum of light. Thus blue or green objects appear much lighter than red ones. No light signal is generated in the red range, however, as rods cannot absorb these light waves. If no light is absorbed, black is perceived.

1 Cf. Richard Gregory, *Auge und Gehirn. Psychologie des Sehens,* Hamburg, 2001, pp. 116 – 117.
Cf. Margaret Livingstone, *Vision and Art. The Biology of Seeing,* New York, 2002, pp. 40 – 45.
2 Cf. Prof. Gernot Böhme, article in this book, p. 115 – 133

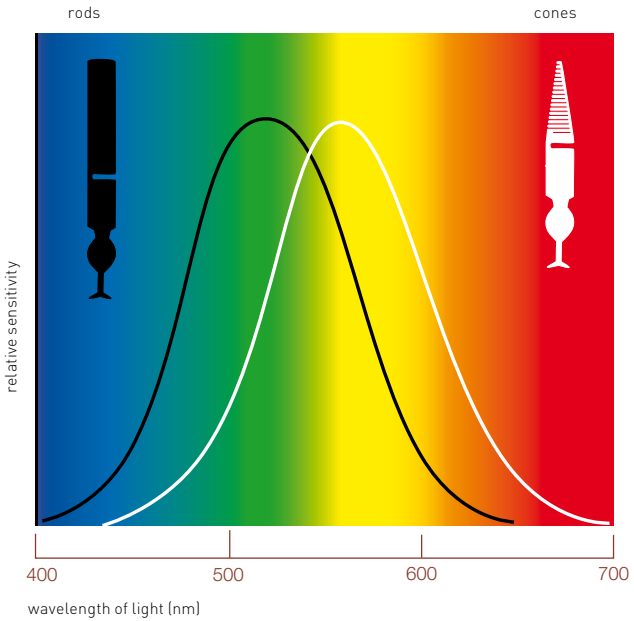


Fig. Representation of the wave spectrum of light with the corresponding colours. The degree of light absorption by the light-sensing cells is shown for each colour.
The white curve represents the sensitivity of the cones, the black curve that of the rods. The curves show the shift into the blue-green range that occurs in the Purkinje phenomenon.

K55 THREE-COLOUR THEORY

In his reflections on the basic principles of human colour vision published in 1802,[1] Thomas Young proceeded from the assumption that there cannot possibly be as many types of sensory cells in the retina of the eye as there are different colour hues. Through experiments with colour mixtures based on Newton's research, he developed the hypothesis that there must be three types of light-sensing cells in the retina, which exhibit a maximum reaction to blue, green or red colour stimuli, respectively. Sixty-five years later, the physicist and physiologist Hermann von Helmholtz refined Young's hypothesis, and thus we speak today of the Young-Helmholtz Theory.[2] Helmholtz expressed the opinion that colour is not a property of light but rather an achievement of the nervous system. Any given colour is registered by all three types of light-sensing cells, each in its own way. The colour hue that is perceived is determined by the specific excitation ratio.[3]
Colour television screens use three types of light phosphors which are capable of generating every colour with red, green and blue light rays through the process of additive colour mixture. Together, these three base colours form the RGB colour spectrum. Computer screens and beamers function in the same way, which is described by the CIE colour model.

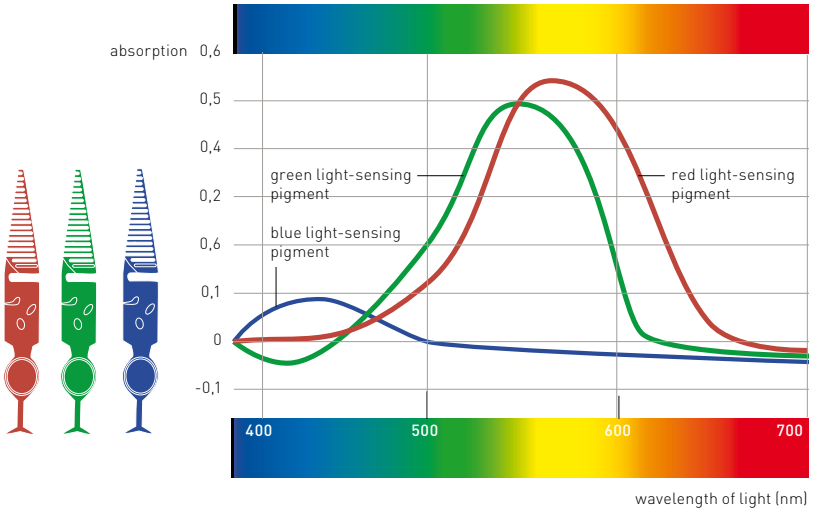


Fig. Georg Wald was able to prove the existence of three photopigments which absorb light in the blue, green and red ranges of the wavelength spectrum. The figure shows the absorption curves as computed by W. D. Wright.

1 Thomas Young, *"On the theory of light and colors"*, in D.L. Adam (ed.), *Sources of Color Science,* Cambridge, 1970, p. 51.
Cf. Werner Schmid, *Biophysik des Farbensehens, Constance, 1999, p 25.*
2 Cf. Werner Backhaus, *Color Vision. Perspectives From Different Disciplines,* Berlin, New York, 1998. p. 189.
3 Cf. John G. Nicholls, A. Robert Martin, Bruce G. Wallace, *Vom Neuron zum Gehirn. Zum Verständnis der zellulären und molekularen Funktion des Nervensystems,* Stuttgart, New York, 1995, p. 384.

K56 FOUR COLOUR THEORY

The physiologist and neurological researcher Ewald Hering expressed criticism of the three-colour theory in 1871, noting that it failed to consider the pure colour yellow as one of the primary colours.[1] He found no transition from the substantive colour blue to yellow nor from red to green, i.e. neither bluish yellow nor greenish red. His theory proposes that the complementary colours red-green and blue-yellow are products of human colour perception. They counteract one another in order to achieve a balance. In a state of imbalance, they generate colour perceptions. Hering also attributed the achromatic opposing pairs of light/dark and black/white to these processes.

Today, three- and four-colour theories are viewed as different stages in a single process of colour perception. The input situation at the level of the cones is based upon the three base colours (RGB). The output situation represents the results of cone signal processing and works on the basis of complementarity.[2] The addition of red and green signals produces the yellow signal. It contrasts with the blue signal. The opposing pair of red and green is produced through the subtraction of red and green signals. Brightness values are also processed through the addition of red and green cone signals.[3]

The complementary actions of the retina can be experienced in the form of complementary afterimages.

1 Cf. Werner Schmid, *Biophysik des Farbensehens,* Constance, 1999, p. 27.
Cf. Werner Backhaus, *Color Vision. Perspectives From Different Disciplines,* Berlin, New YorK1998, pp. 23 and 189 – 190.

2 Cf. Schmid, *Biophysik des Farbensehens*, op. cit., p. 28.
Cf. Margaret Livingstone, *Vision and Art. The Biology of Seeing,* New York, 2002, p. 86.

3 Cf. Schmid, *Biophysik des Farbensehens*, op. cit., p. 29.
N. Welsch, C. Liebmann, *Farbe,* Heidelberg, 2003, p. 252.

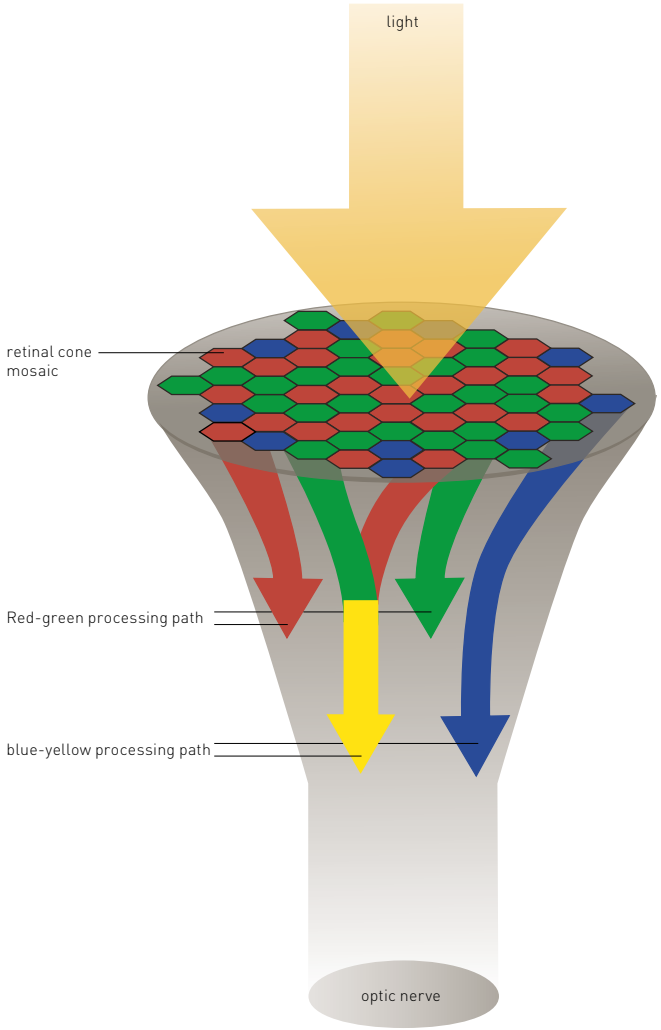


Fig. Schematic diagram of a section of the retina exposed to light. All three types of cones are stimulated. Their signals are processed together for transmission. Yellow signals result from consolidation of red and green, analogous to additive colour mixture.

K57 RETINAL COLOUR-BLINDNESS

The presence of three different photopigments in the cones, which provide for daylight vision, is the essential determinant of colour vision.

Malformations resulting in certain types of colour-blindness can occur in all three photopigments. Retinal colour-blindness is an inheritable trait. Nearly 5% of all European men suffer from the disorder or from an impairment of their ability to distinguish colours.[1] The most common form is red-green colour-blindness. If the red or green cones are partially inactive or defective, red-green processing cannot occur. This results in colour vision which depends entirely upon blue-green or blue-red colour oppositions.[2]

The biochemical structures of the red and green pigments differ at only three points. Accordingly, the corresponding genes also differ only at three positions, and these positions are also very close to each other on the female sex chromosome. This leads in some cases to genetic aberrations or defects during germinal cell development. In men, defective genes are not replaced by a second gene copy, as they are in women, and thus the genetic defect is expressed.

A person who lacks red photopigments is referred to as a protanope, one without green pigments as a deuteranope, and one without blue pigments as a tritanope.

In protanopic vision, only very dark brown to black shades are perceived in place of red. Recognition of lightness and perception of all other colours is ensured by the activity of the green and blue cones.

If the green cone is lacking or inactive, short- and love-wave light rays are processed. Deuteranopic people perceive lightness in the red range and confuse red and green. Many mammals see in a similar way, as they do not have green cones. Tritanopia, or blindness in the blue range, is very rare. It involves the absence of impairment of the blue-yellow processing channel. Yellow and green are missing in the colour spectrum when two types of cones are absent or inactive. This form of daylight vision is just as colourless as night vision. If all three types of cones are absent or defective, the entire daylight vision system does not function at all.

1

2

3

4

Fig. 1 The photo shows the colour spectrum perceived by people with normal vision.
Fig. 2 Special colour filters make it possible to process photographs in such a way that they reproduce the visual impressions of colour-blind people. This processed photo simulates the absence of red cone function. The image shows only very dark shades where red would ordinarily appear. Green and red are not clearly distinguishable.
Fig. 3 The same image is perceived in this way by a person with defective green cones. Reddish hues are hardly distinguishable from greenish tones, and reddish hues look somewhat lighter than greenish ones, as the red cones are active.
Fig. 4 All shades of yellow and green are eliminated in vision without blue cones.

1 Cf. Werner Schmid, *Biophysik des Farbensehens,* Constance, 1999, pp. 68 – 71.
2 Cf. Karl R. Gegenfurtner, Lindsay T. Sharpe, *Color Vision. From Genes to Perception,* Cambridge, 2001, pp. 24 – 51.

K58 COMPLEMENTARY AFTERIMAGE

When an individual focuses for an extended period of time on a coloured surface, specific light-sensing cells are activated. They adapt to the active colour stimulus and become insensitive. The result is known as local colour adaptation.[1]
If the same person then looks at a white surface, the eye sees an afterimage in the complementary colour of the first surface. The sensory cells that evoke the perception of the complementary colour were not stimulated while looking at the coloured surface and can respond immediately to white light. Once the bleached photopigments have been regenerated, the afterimage disappears again.
The complementary colours observed in this process are those produced by additive colour mixture.

1 Cf. G.A. Agoston, *Color Theory and its Application in Art and Design,* Berlin, Heidelberg, New York, London, Paris, Tokyo, 1987, pp.195ff.

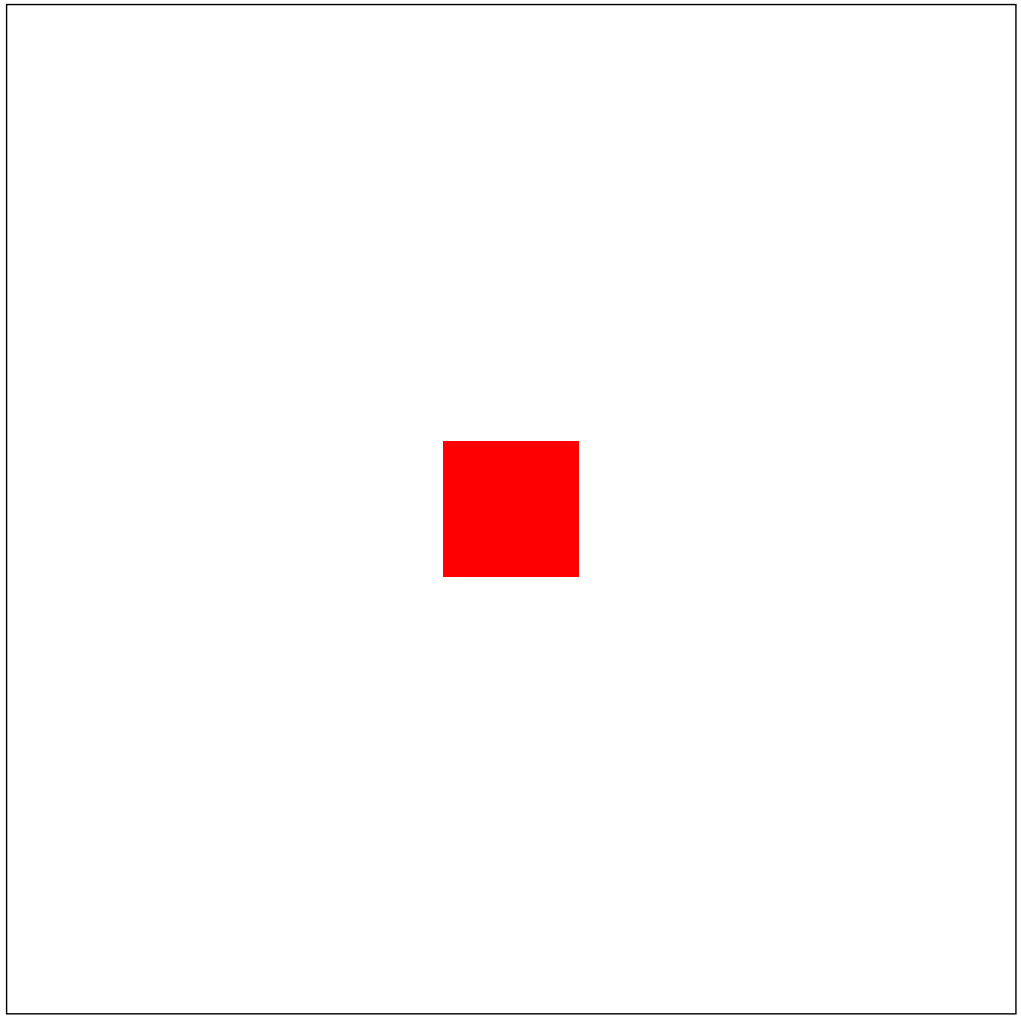


Fig. The red rectangle begins to flicker at the edges after being viewed for a certain period of time. When the viewer shifts his gaze to the white surface next to it, the cyan-coloured afterimage appears.

K59 ADAPTATION

Adaptation is both a general process of adaptation by all light-sensing cells to a given degree of brightness and a process of adaptation to the dominant illuminating light. Cell sensitivity is continuously adjusted in response to incoming light through adaptation. Both processes – brightness and colour adaptation – are continuous and contribute along with other processes to constancy in visual perception.[1]

Light-sensing cells are active within a broad range of light intensities. Exposure to bright light stimulates their biochemical activity. However, they are accordingly insensitive to low light intensities following such stimulation. Only after a moment of adjustment is the eye capable of distinguishing weaker light stimuli. In contrast, the light-sensitivity of the eye increases under exposure to weak light. This results in the blinding glare effect that occurs when the eye is suddenly exposed to brighter light. The eye achieves maximum adaptation to darkness after an extended period of darkness.

This process of light-dark adaptation occurs, for example, when a person enters a dark tunnel on a bright, sunny day. Following the initial impression of complete darkness, individual details gradually become perceptible. Because the light-sensing cells have adjusted to the high light intensity, they must now develop a more differentiated response to the weak light. The opposite process unfolds when leaving the tunnel. Having adjusted to the weak light, they eye is initially blinded by the glare and must adjust physiologically to the sudden increase in light quantity. This take place more rapidly than the reverse process, however.

The "colour-sensing cells" (cones) adapt to coloured light in much the same way. This is known to perceptual psychologists as chromatic adaptation, but is actually nothing more than the process of white balancing in the eye.

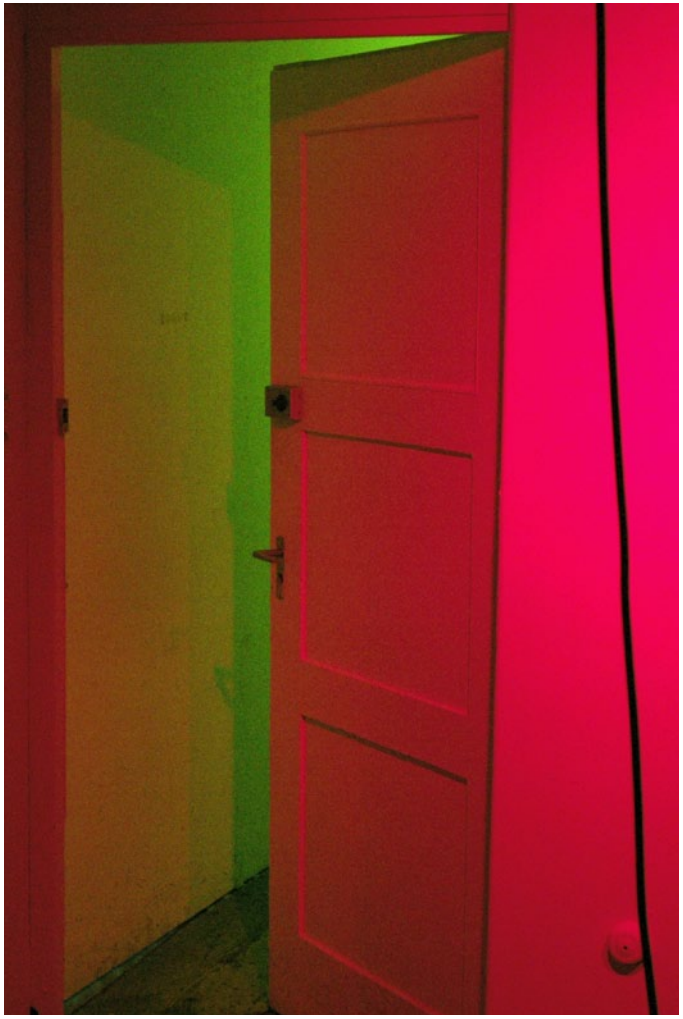


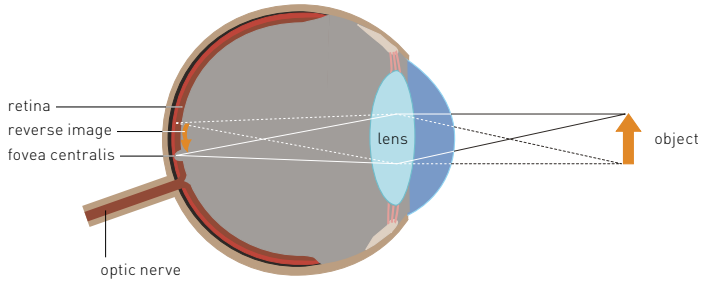
Fig. This photograph taken in the ColourLightLab under exposure to strong coloured light simulates chromatic adaptation by the eye. When a person looks into neutral light, the complementary colour is immediately perceived. The computation signals of the digital camera used to take this photograph are programmed in analogy to the chromatic adaptation of the eye.

1 Cf. Josef Dudel, Randolf Menzel, Robert Schmidt, *Neurowissenschaft vom Molekül zur Kognition*, Berlin, Heidelberg, New York, 2001, p. 395. Cf. Ralph M. Evans, *An Introduction to Color, New York, London, 1948, pp. 130 – 135 and 173 – 185.*

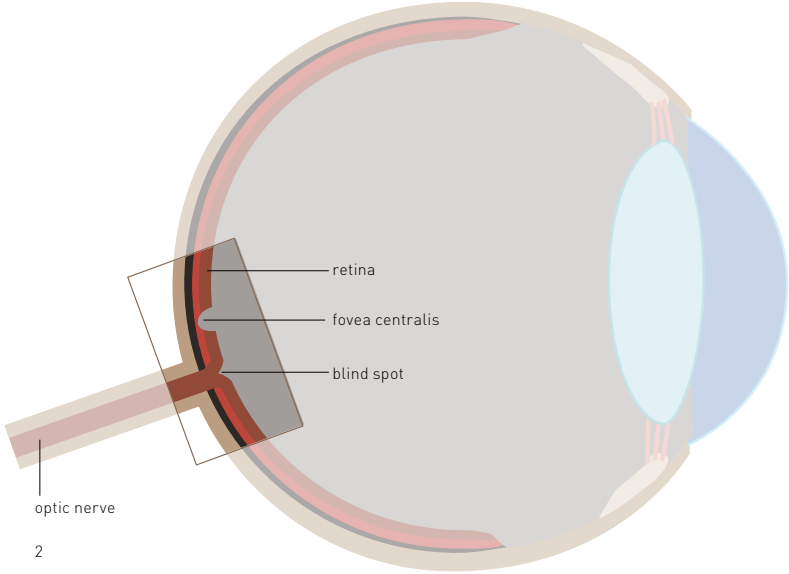
K60 RETINA

The retina is the light-sensitive layer of the eye. It is a complex network of nerve cells which represent an outpost of the brain. Its most important components are the light-sensing cells located on the undersurface of the retina above the pigment layer, which is turned away from the light.
The blind spot – an area in which there are no light-sensing cells – is located at the point at which the optic nerve exits the eye. This "hole" in the retina is not perceived, however.
All parts of the retina are represented in the brain. The fovea centralis, which is the centre of sharp, colour daylight vision, is linked to a particularly large area of the brain. A look at the rear wall of the eye reveals the fovea centralis in its yellow colouration. It is referred to as the macula.[1]
Optical illusions, which cannot be controlled deliberately, are traced to pre-conscious processing within the retina. The process involves the initial processing of light signals entering the eye. The light-sensing cells are linked horizontally. Contrast enhancement in particular, is attributable to interaction between groups of light-sensing cells.

1 Cf. N. Welsch, C. Liebmann, *Farbe,* Heidelberg, 2003, pp. 250ff.



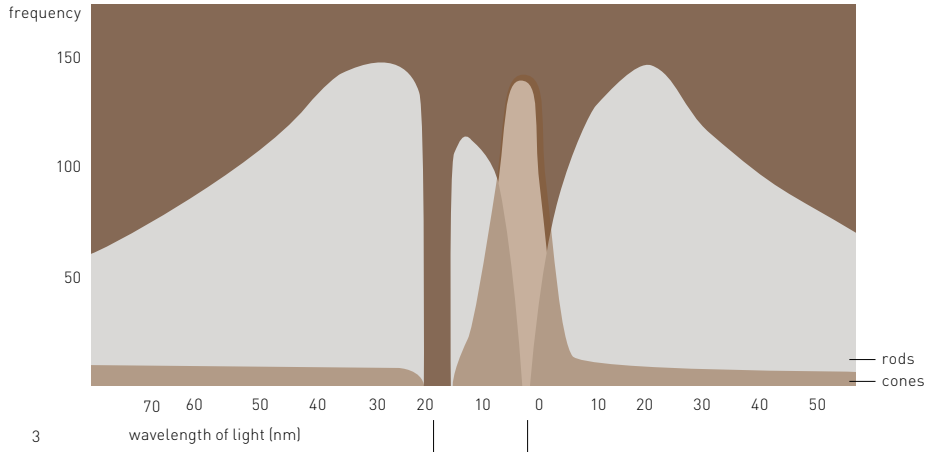
1



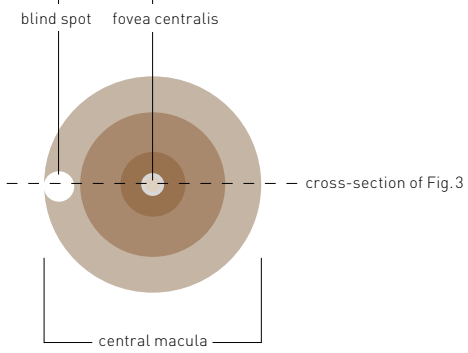
2

Fig. 1 The image projected onto the retina is upside-down. The fovea centralis is positioned at the focal point of the path of light. The thin layer of the retina which contains the light-sensing cells is shown in red. The pigment layer nourishes the retina and envelops it in a light-impermeable shell.
Fig. 2 View of the central region of the retina showing the fovea centralis (macula) and the blind spot.

Fig. 3 – 4 Vertical section of the retina along the dotted line shown in Fig. 4. Since the eye is spherical in shape, the scale is subdivided by degrees. The zero-degree point is located within the fovea centralis. The blind spot lies between 10 and 20 degrees adjacent to the fovea centralis to the left. Each point in the sectional image is assigned the number of the light-sensing cells found there. The rods are shown as light-grey, the cones as dark-brown. Cones are most highly concentrated in the fovea centralis, whereas no rods are located there but appear in maximum concentration on the periphery of the retina.



3



4

K61 RETINAL STRUCTURE

The retina is composed of clearly distinguishable layers of nerve cells. Layers which contain cells alternate with layers devoted solely to signal transmission. The electrical signals generated by light-sensing cells are processed and modified within this complex network of alternating layers.
Horizontal networking is accomplished by so-called horizontal and amacrin cells. Vertical networking is achieved through bipolar nerve cells. They serve as the direct link between light-sensing cells and the optic nerve.
Light does not strike the light-sensing cells directly. These cells are embedded in the light-impermeable pigment layer on the underside of the retina, where they are protected. The retina is very thin only in the region of the fovea centralis, where the cones are directly exposed to incoming light.
Located in the uppermost region of the retina are the ganglia cells that form the optic nerve. The entire retinal network with all electrical signals leads into the comparatively few ganglia cells. This means that signals must be highly bundled. All sensory cells which generate signals that influence a given ganglia cell form a receptive field.

1 Cf. N. Welsch, C. Liebmann, *Farbe,* Heidelberg, 2003, pp. 251 – 254.
Cf. John G. Nicholls, A. Robert Martin, Bruce G. Wallace, *Vom Neuron zum Gehirn. Zum Verständnis der zellulären und molekularen Funktion des Nervensystems,* Stuttgart, Jena, New York, 1995, pp. 377 and 389.
Cf. David S. Falk, Dieter R. Brill, David G. Stork, *Ein Blick ins Licht. Einblicke in die Natur des Lichts und des Sehens, in Farbe und Fotografie,* Basel, Boston, Berlin, 1990, p. 192.
Cf. Erik R. Kandel, James H. Schwartz, Thomas M. Jessell, *Principles of Neural Science*, East Norwalk, 1991, p. 409.

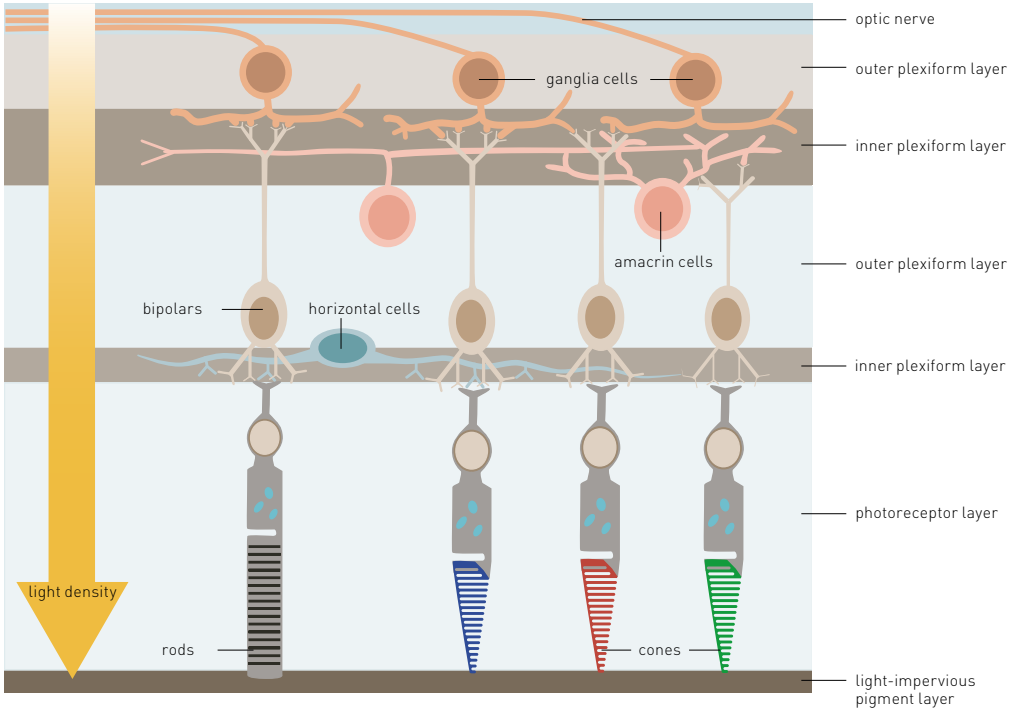


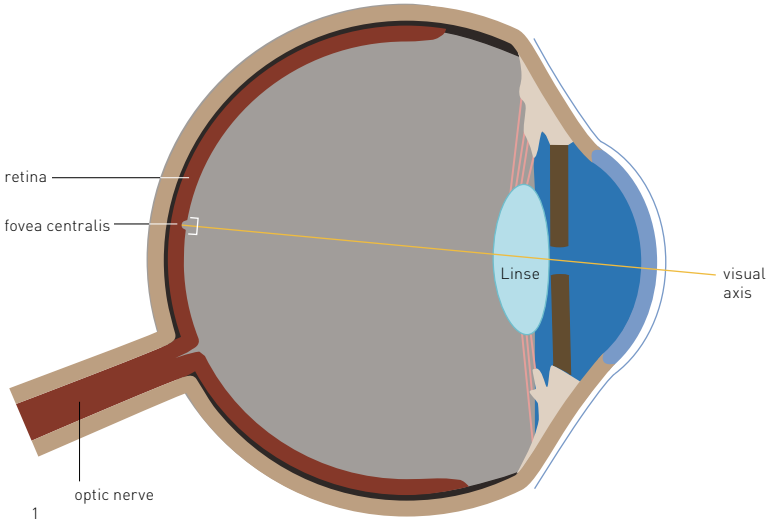
Fig. Schematic diagram of the cellular structure of the retina. The path of light is indicated. The light-sensitive outer segments of the rods and cones are oriented downward toward the pigment layer. All retinal outputs are consolidated in the optic nerve. All retinal cells are simultaneously active and communicate with one another.

K62 FOVEA CENTRALIS

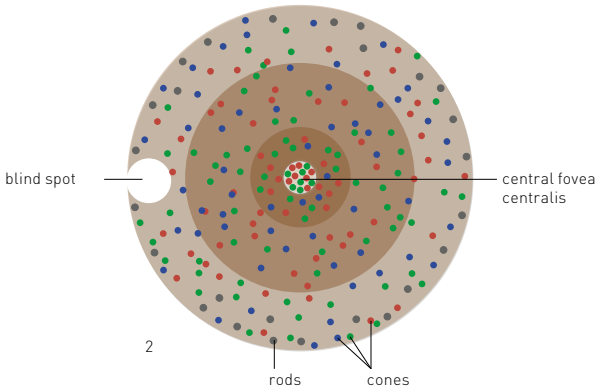
In the focal point of the lens, where the visual axis converges with the retina, lies the fovea centralis. The layers of nerve cells are very thin at this point. The quantity of light striking the light-sensing cells is especially large.[1] The fovea is the point in the eye at which resolution is the highest, and it is responsible for daylight vision.[2] Cone density is highest in the fovea centralis. Only red and green cones are found in the centre, while blue cones appear only near the edges.[3] This is one of the adjustments the eye has made to an imaging error in the lens, which refracts high-energy light more intensely.
Rods appear in maximum concentration outside the fovea centralis. This explains why sharp vision is always peripheral at night. As the fovea is essential night-blind, a star in the sky is recognizable only on the periphery of the eye, i.e. when it is not viewed through the fovea.
The fovea measures 1.5 mm in diameter, its centre only 0.33 mm. As small as this part of the retina is, it is represented by a very large region of the brain. In order to maximize resolution, each light-sensing cell in the fovea is directly linked to the brain. Cells outside the fovea are consolidated to a much greater extent. Peripheral night vision is much less sharp, in contrast.
The eye constantly orients the fovea toward the most highly-contrasting areas of the field of vision through saccadian eye movements, thereby refreshing the perceived image continuously.

1 Cf. N. Welsch, C. Liebmann, *Farbe,* Heidelberg, 2003, p. 251.
Cf. Margaret Livingstone, *Vision and Art. The Biology of Seeing, New York, 2002, p. 70.*
2 Cf. Moritz Zwimpfer, *Farbe – Licht, Sehen, Empfinden. Eine elementare Farbenlehre in Bildern von Moritz Zwimpfer,* Bern, Stuttgart, 1985, Sections 241 and 259.
3 Cf. Welsch, Liebmann, *Farbe*, op. cit., p. 250.
4 Cf. Livingstone, *Vision and Art*, op. cit., p. 70.

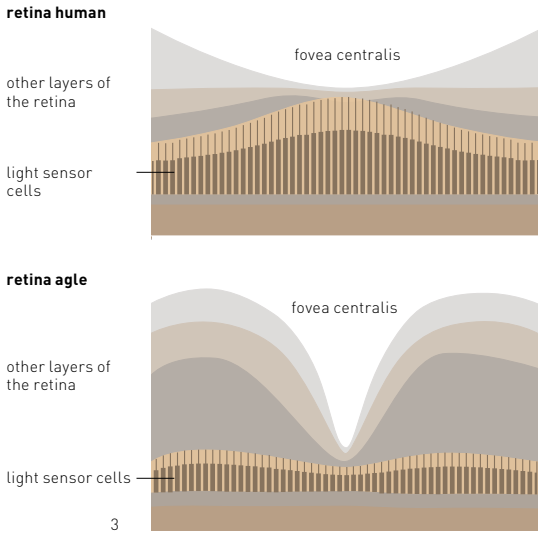
Fig. 1 The cross-section of the eye indicates the position of the fovea.
Fig. 2 Schematic view of the fovea from above. Only red and green cones are located in the central area. The number of rods increases to its maximum value toward the edge. The position of the blind spot is also indicated.
Fig. 3 The visual acuity of the eagle is far superior to that of the human being A comparison of a human fovea with the fovea of an eagle clearly reveals that the eagle has a much deeper fovea.



1



2

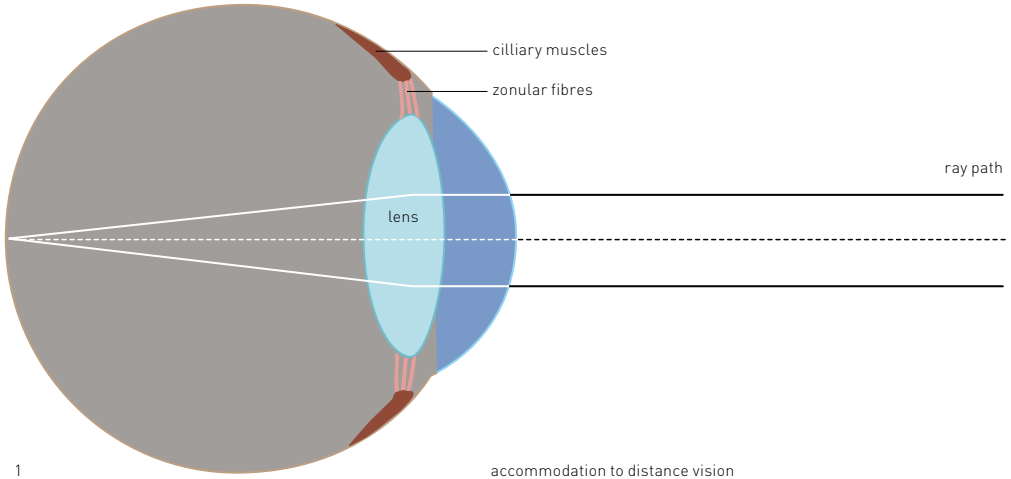


3

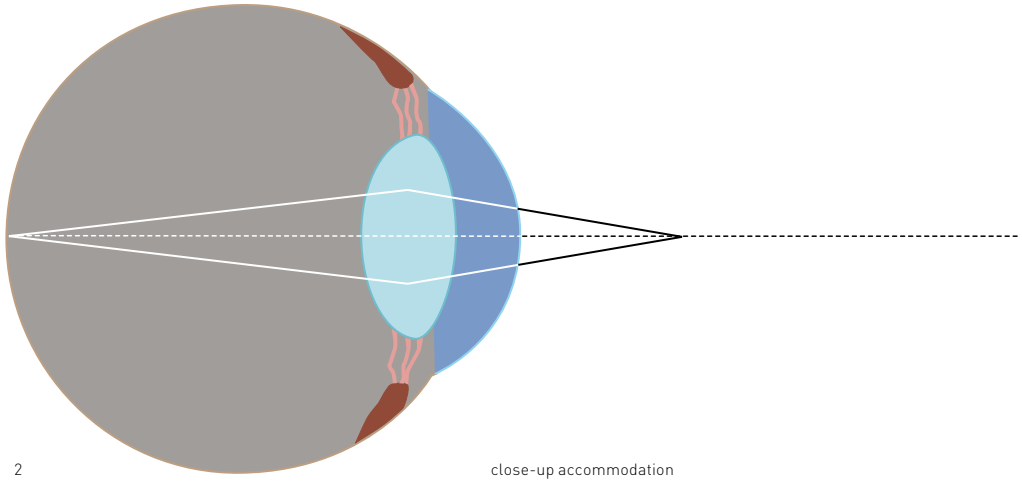
K63 ACCOMMODATION

By making a rapid adjustment, the eye is capable of focusing on both distant objects and those at close range. This adjustment is referred to as accommodation. In order for this process to work, the focal point of the light rays entering the eye must coincide precisely with the point of sharpest vision (fovea). That is insured by the elastic, flexibly bulging lens, the heart of the optical system of the eye.
The lens is suspended on zonular fibres which are connected to ciliary muscles. When the muscles are relaxed, the fibres are tensed and the lends is flattened. The eye sees objects sharply in the distance. Conversely, the contraction of ciliary muscles relaxes the zonular fibres, allowing the lens to bulge by virtue of its intrinsic elasticity. Its refractive power increases, and points close to the eye are presented in sharp focus on the retina.[1]

1 Cf. Moritz Zwimpfer, Farbe – Licht, Sehen, Empfinden. Eine elementare Farbenlehre in Bildern, Bern, Stuttgart, 1985, articles 226 – 229.
Cf. David Falk, Dieter Brill, David Stork, Ein Blick ins Licht. Einblicke in die Natur des Lichts und des Sehens, in Farbe und Fotografie, Basel, Boston, Berlin, 1990, p. 155.



1 accommodation to distance vision



2 close-up accommodation

Fig. 1 The illustration shows an idealized image of the eye and the path of light bundled in the lens during accommodation to distance vision. When the zonular fibres are stretched, the lens assumes a flatter shape.
Fig. 2 During close-up accommodation, the lens exhibits a rounded bulge as no pull is exerted on the zonular fibres.

K64 SACCADIAN EYE MOVEMENTS

The word "saccadian" means "abrupt". Saccadian eye movements are small, constantly repeated, unconscious movements with which the eye causes the fovea centralis, i.e. the point at which vision is sharpest during the day, to move across the field of vision.[1] Controlled by the overall view of a scene, the eye continuously registers the areas of greatest contrast (both colour and light-dark contrasts).[2] Saccadian eye movements play a very important role in visual perception. If the eye is hindered in its movement, the perceived image disappears. The photopigment bleaches out and the sensory cells cannot regenerate. Vision would be impossible without constant eye movements which transmit a continuous series of new images to the visual centre of the brain, where they are processed into a total impression. Thus the perceived image is continuously refreshed in order to maintain perception.[3]

1 Cf. Richard L. Gregory, *Auge und Gehirn. Physiologie des Sehens,* Hamburg, 2001, pp. 63 – 67.
2 Cf. Margaret Livingstone, *Vision and Art. The Biology of Seeing,* New York, 2002, pp. 78 – 83.
3 Cf. A. Terry Bahill, Lawrence Stark, *"Sakkadische Augenbewegungen"*, in *Spektrum der Wissenschaft: Verständliche Forschung. Wahrnehmung und visuelles System,* Heidelberg, 1986, pp. 68–77.

Fig. When we observe a face, we see that the eyes are constantly wandering between different points. The paths of these movements is inscribed on the face.

K65 RECEPTIVE FIELDS

A receptive field is a region of the retina through which the activity of a nerve cell in the optic tract is influenced.[1] The formation of receptive fields is an inevitable consequence of the fact that millions of light-sensing cells are linked to a comparatively small number of optic nerve cells. A given cell in the optic tract is always assigned to multiple, often very large numbers of light-sensing cells. Receptive fields increase in size from the fovea to the periphery of the retina.

The phenomena of contrast perception and contrast enhancement, optical illusions, based upon light-dark and colour contrasts, and optical colour mixture, assimilation and simultaneous contrast, are more easily explainable with reference to receptive fields.

The simplest receptive field in an optic nerve cell is nearly circular in shape. It originates in all of the cross-links in the retina.[2] All such fields have a centre and a surround, which function in opposite ways. When, for example, light falls on the centre of the field, nerve cell activity is stimulated. A correspondingly large number of signals are transmitted along the optic tract to the brain. When light falls on the surround, signal transmission is inhibited. A ring-shaped illumination of the surround actually results in total inhibition. Yet the reverse effect also occurs, i.e. that central light has a marked inhibiting effect on signal transmission and peripheral light has an activating effect. The signal channel responds with a clear signal to a clearly perceived distribution of light in the centre or the surround, but no response is triggered by diffuse illumination. The system of receptive fields in the retina is extremely sensitive to the smallest contrasts. Boundaries and colour transitions generate computations in the nerve cells which further intensify the sensation of contrast.[3] Areas that do not change are not computed again by the nerve cells, thus reducing the

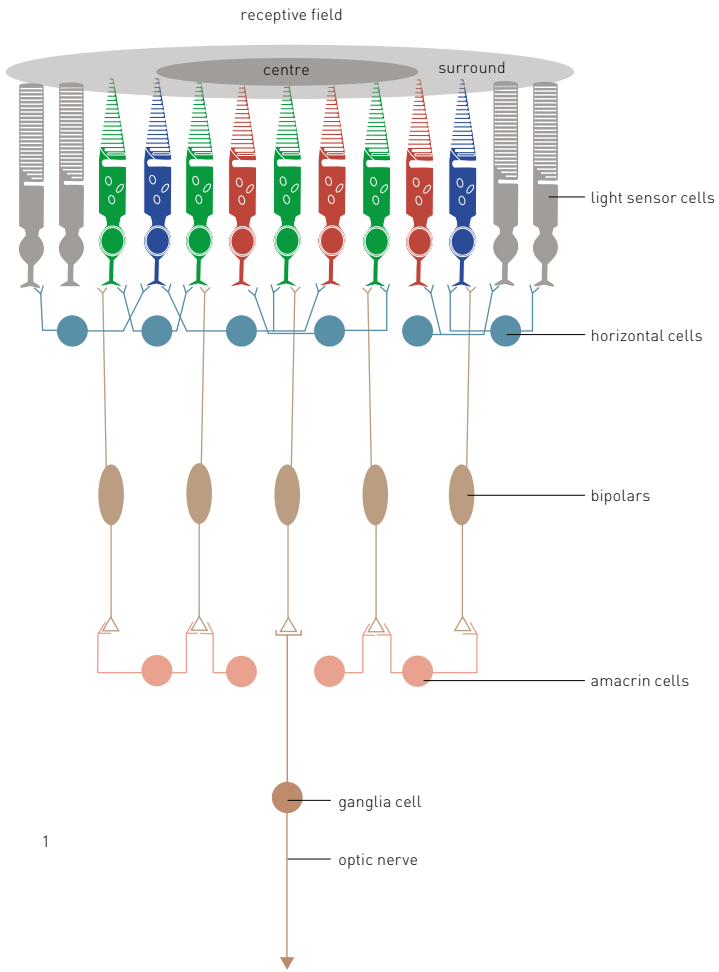


Fig. 1 A simple receptive field in an optic nerve cell. Lateral inhibition of nerve cells farther along the chain is responsible for the opposite responses of the centre and the surround.

total workload, much in the same way that JPEG images are computed by a computer.
Receptive fields and stimulation patterns grow increasingly complex at higher levels of the optic tract toward the brain.[4] Specific movements, line patterns, shapes and even facial features are required to stimulate these nerve cells.
In processing colour stimuli at the level of the optic nerve, the function of the retina, i.e. the structure of simple receptive fields, confirm Hering's four-colour theory of the existence of receptive fields that are responsive to red-green, yellow-blue and light-dark.[5]

1 Cf. David Hubel, Torsten Wiesel, *Brain and Visual Perception.The Story of a 25 Year Collaboration,* Oxford, 2005, p. 93.
2 Cf. John G. Nicholls, A. Robert Martin, Bruce G. Wallace, *Vom Neuron zum Gehirn. Zum Verständnis der zellulären und molekularen Funktion des Nervensystems,* Stuttgart, Jena, New York, 1995, p. 388.
Cf. N. Welsch, C. Liebmann, *Farbe*, Heidelberg, 2003, p. 253.
Cf. Margaret Livingstone, Vision and Art. The Biology of Seeing, New York, 2002, pp. 53 – 55.
Cf. Roger Eckert, *Tierphysiologie,* Stuttgart, New York, 1993, pp. 254 – 271.
Cf. Nicholls, Martin, Wallace, *Vom Neuron zum Gehirn, op. cit.,* pp. 392 – 393.
Cf. Ernst Peter Fischer, *Die Wege der Farben,* Constance, 1994, p. 95.
3 Cf. Stephen E. Palmer, *Vision Science. Photons to Phenomenology,* Cambridge, 1999, p. 115–118.
4 Cf. Livingstone, Vision and Art, *op. cit.,* p. 60.
Cf. Nicholls, Martin, Wallace, *Vom Neuron zum Gehirn, op. cit.*, p. 416.
5 Cf. Livingstone, *Vision and Art, op. cit., p.* 60.

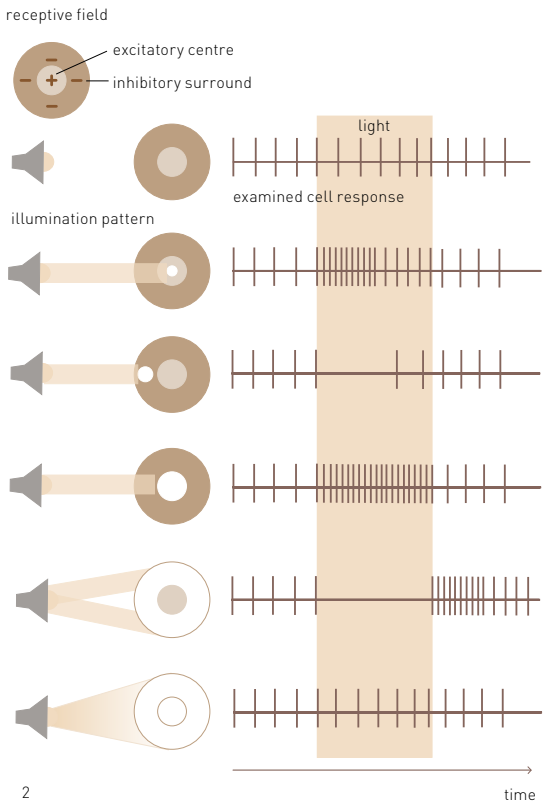


Fig. 2 A series of experiments performed on an optic nerve cell. The cell responds to certain illumination patterns with electrical impulses, which it transmits to the brain. These electrical signals were measured over a specified period of time. The receptive field of this nerve cell has an excitable centre and an inhibiting surround.

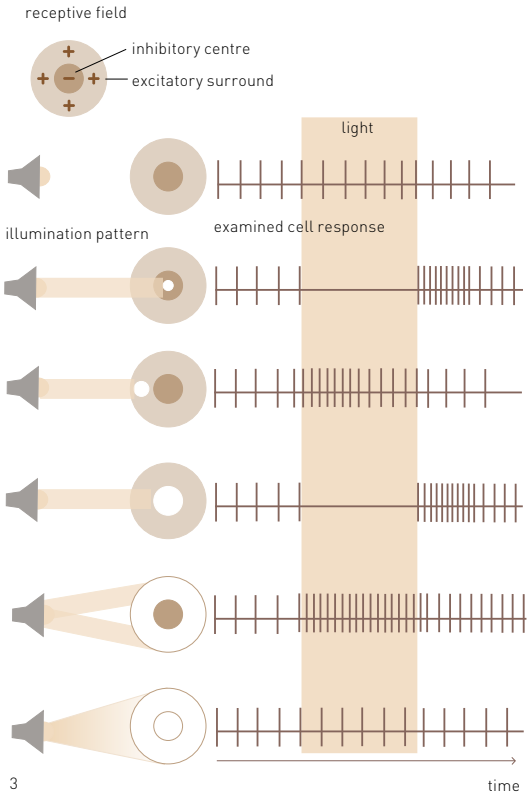


Fig. 3 The same experiment performed with a cell that responds in precisely the opposite way. Its receptive field is inhibited when the centre is illuminated and intensely stimulated by light falling on the surround.

K66 OPTICAL PARTITIVE COLOUR MIXTURE

A close look at a poster printed using the four-colour printing method reveals countless small dots of colour. In some places, they appear to have been printed clearly apart from one another; in others, they appear to overlap. Viewed from a distance, the dot pattern forms a unified colour impression.

Reflected coloured light is processed into an overall image depending upon the size of the observed dots and the distance between the viewer and the image, Since no substantive mixture of the colours has taken place, the process unfolds in the eye and is therefore known as optical partitive colour mixture. Some of the colours appear more radiant, as reflected light is mixed additively. But because the colour dots are applied to a substrate (canvas, paper), they are less radiant than the additive colour mixture composed of pure light.

If the dot patterns are larger than the receptive fields in the retina, the eye can discern the individual dots. The colour contrasts enhance each other at the point of transition from one colour dot to the next and begin to flicker brightly. This was the effect aimed for by the pointillist painters. They sought to create a radiant colour impression by applying dots of pure colour next to each other.[1] Maximum colour intensity is achieved when dots fill only the centres of the receptive fields with their stimulating light. At this point, the colours are mixed additively in the eye. However, if the dots fill the entire receptive field, this brilliant colouration is extinguished, as the responsible sensory cells cannot respond to the diffuse impression. That is why it is so important to observe pointillist paintings from precisely the right distance. If the distance is too great, the brilliant radiance of the colours gives way to a greying effect.

Fig. The greater the distance of the dot pattern from the eye, the smoother the colour progressions appear. Individual dots can be distinguished in a close-up view

1 Cf. Margaret Livingstone, *Vision and Art. The Biology of Seeing,* New York, 2002, pp. 176 – 187.
Cf. Werner Backhaus, Reinhold Kliegel, John Werner, *Color Vision. Perspectives From Different Disciplines,* Berlin, New York, 1998, pp. 27 – 30.

K67 CONTRAST ENHANCEMENT

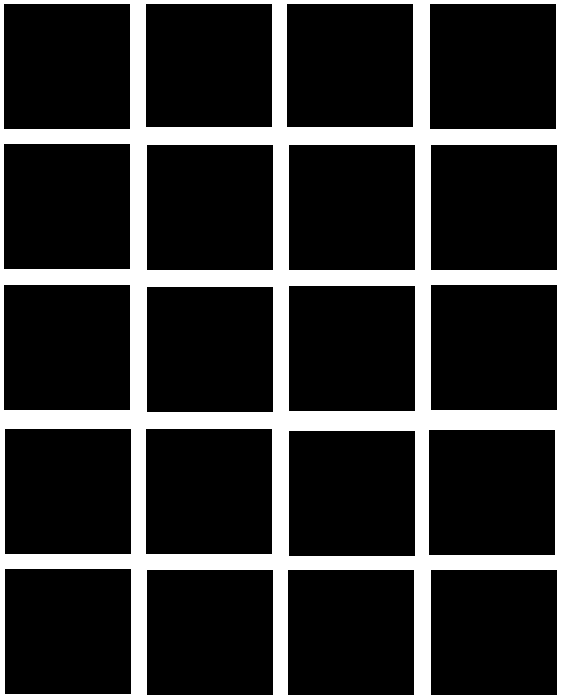
Simple optical illusions such as the Cornsweet, Hermann grid and Elke Lingelbach-illusions reveal the underlying structures of human visual perception in the light-dark range. They also demonstrate the functional principles of receptive fields.

An image of the outside world is initially processed on the retina and transmitted in filtered form to the brain. The smallest contrasts are overinscribed, and constant stimuli are toned down by surface areas. The Cornsweet illusion shows that visual systems are more sensitive to abrupt changes than to gradual ones.[1] The grey hue of the two areas is identical on the two sides, but the shade changes slightly toward the middle. What is interesting is that the light-dark impression is applied to the entire area, so that we have the impression of looking at a lighter field on the left and a darker one on the right.

The other two illusions are attributable to a specific characteristic of retinal cells known as lateral inhibition. These cells are stimulated and inhibit neighbouring cells at the next processing level at the same time. This inhibiting effect is particularly noticeable at the points of transition between the centres and the surrounds of receptive fields.

The Hermann grid exhibits dark-looking areas in the white points of intersection when observed through the peripheral field of vision. The perceived white area of the points of intersection is inhibited four-fold by the adjacent dark corners and darkened as a whole. Thus the grid line appear lighter. They are inhibited only two-fold by the adjacent dark areas.[2]

1

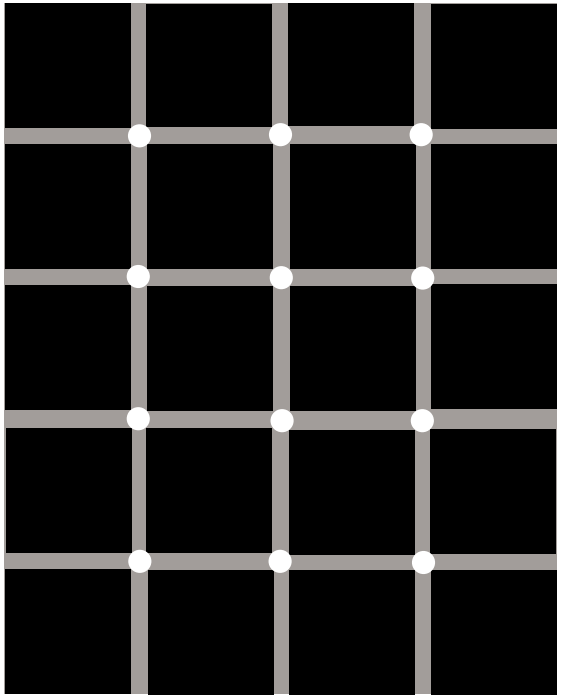


2

Fig. 1 Cornsweet illusion
Fig. 2 Hermann grid illusion

The Elke Lingelbach illusion is a refined version of the Hermann grid with slightly darkened lines and white circular areas at the points of intersection. The illusion always shows circular fields filled with grey. The light-dark contrast between the white circular areas and the overall surrounding area, which is much darker, overlaps with the impression of the grid illusion and intensifies it in addition.[3]

1 Cf. Margaret Livingstone, Vision and Art. The Biology of Seeing, New York.2002, p.58.
2 Cf. ibid., pp.56 – 57.
Cf. Stephen Palmer, Vision Science. Photons to Phenomenology, Cambridge, 1999, pp.116 – 117.
3 Cf. Livingstone, Vision and Art, op.cit., inside front cover flap.



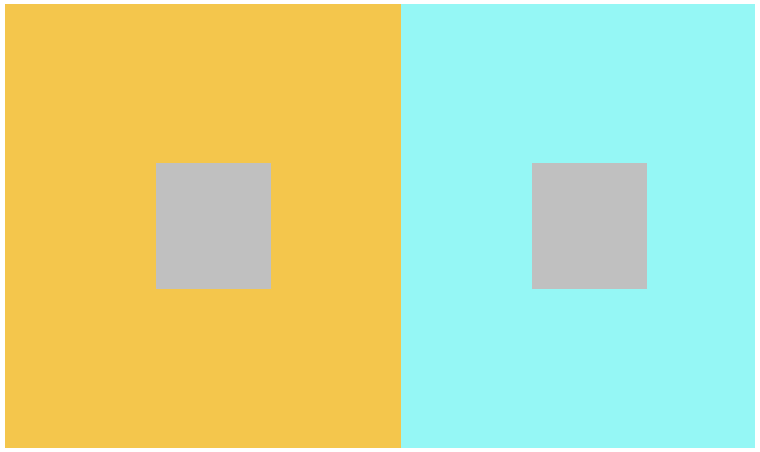
3

Fig.3 Elke Lingelbach illusion

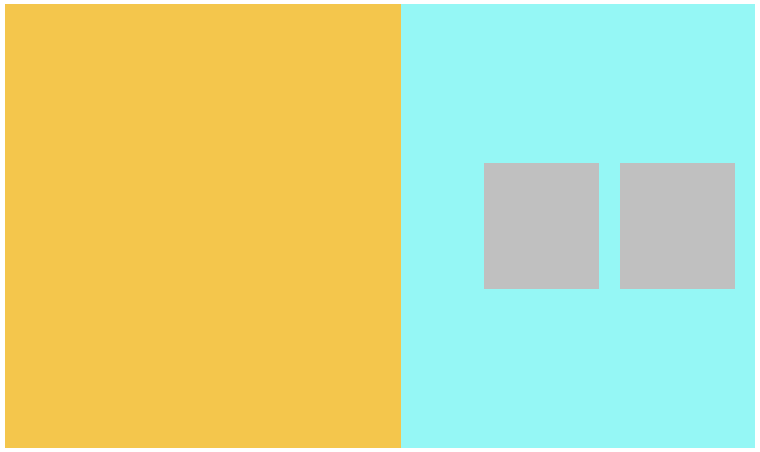
K68 SIMULTANEOUS CONTRAST

The perceived brightness and colour of an object is not determined by the spectral composition of the light reflected by a surface alone but depends to a substantial degree on its surroundings.
If for example, a small, neutral, grey field is completely surrounded by a large, vividly coloured area, the smaller field appears to have the complementary colour of the large area. This phenomenon of colour induction is known as simultaneous contrast.[1] A neutral field is seen in a colour approaching the complementary colour of the surrounding area. The intensity of this impression is determined by the degree of saturation of the surrounding colour. As in optical partitive colour mixture, the size of the fields and their distance from the eye play an important role in the perceived impression.

1 Cf. Anatol Julian Kallmann, *Farbkonstanz und Farbkontrast. Eine Untersuchung mit Hilfe der farbigen Schatten,* Mainz, 2003, p. 3.
Cf. G. A. Agoston, *Color Theory and its Application in Art and Design,* Berlin, Heidelberg, New York, London, Paris, Tokyo, 1987, pp. 199 – 203.



1



2

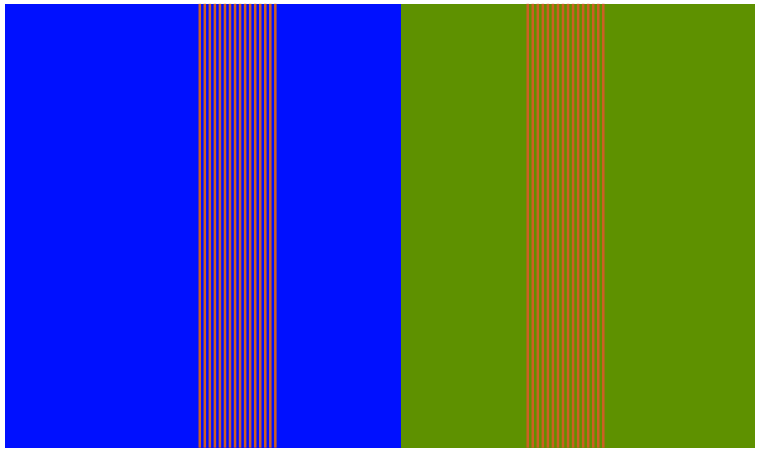
Fig. 1 Screenshot from the tool Simultaneous contrast (see DVD-ROM). The neutral grey of the small square appears warmer and reddish against a cyanblue background. Viewed against a yellowish background, however, it looks colder and bluish.
Fig. 2 Simultaneous contrast is eliminated immediately when the two squares are viewed in the same colour field.

K69 ASSIMILATION

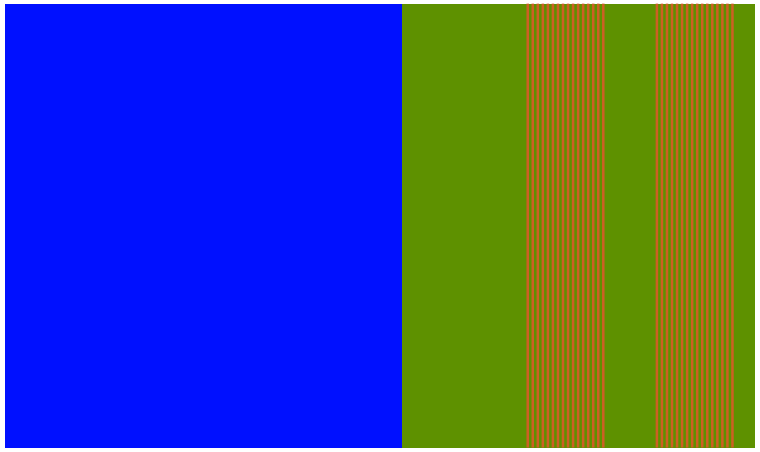
Scientists were quite familiar with the effect of assimilation even in the 19th century. Michel Eugene Chevreul, Director of the Royal Gobelin Factory in Paris, was confronted with the problem that finished woven carpets made of threads dyed using the finest substances and methods exhibited dull colours.[1] Even the black in blue and purple designs was extremely weak. Chevreul realized that this was the effect of how the individual colours and their contrasts were perceived. He undertook a scientific study of the problem and discovered the phenomena of simultaneous, successive and "mixed" contrast. Wilhelm von Bezold, a professor of physics, also described the effect of light and dark contours as an important aspect of various ornaments in his theory of colours, published in 1874. Wherever a colour is "outshone" and significantly altered in colour and brightness by a neighbouring colour, a golden, silver or black contour can be added to eliminate interaction between the two completely.[2]

The mixture and blending of colours of neighbouring fields with different hues and brightness are effects that counteract the appearance of contrast, as they diminish rather than intensify the difference between neighbouring colours. The phenomenon is referred to as assimilation and the "Bezold spreading effect."[3]

Assimilation plays a crucial role in the process of distinguishing figures from backgrounds. It closes off a form and sets it apart from the background. An interior field is interpreted as lighter than it actually is if it is part of a light-coloured total form viewed against a darker background. Conversely, an interior field appears darker because it is seen as a darker figure against a lighter background. Narrow bands on a coloured background are also not perceived in the complementary colour of simultaneous contrast but are integrated instead into the background colouration, although the width and distance between the



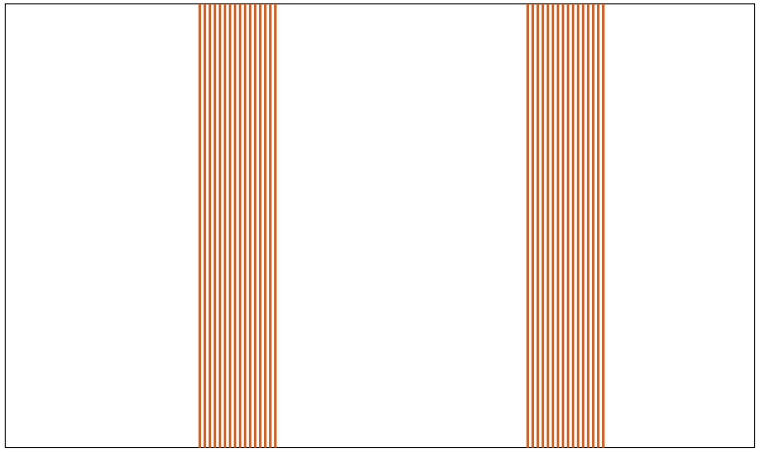
1



2

Fig. 1 Screenshot from the tool Bezold spreading effect (see DVD-ROM).
The colour of the narrow bands are assimilated into the background colour, thus diminishing the contrast. The bands are of identical colour but look very different.
Fig. 2 – 3 All coloured bands look identical against the same background. A different effect is achieved when the bands appear on different-coloured fields.

individual bands plays an important role in this context. Another key factor is the distance between the observed field and the observing eye. Research on the perception of assimilation, the processing of the phenomenon at the level of the retina and the subsequent processing steps in the brain is still in progess.[4]



3

1 Cf. Albert B. Costa, *Michel Eugene Chevreul: Pioneer of Organic Chemistry,* Department of History, University of Wisconsin, Madison. Wisconsin 1962, pp. 6–11.
2 Cf. Dr. Wilh. v. Bezold, *Die Farbenlehre im Hinblick auf Kunst und Kunstgewerbe*, 2nd edition, Braunschweig 1921, pp. 118 – 119, 132–133, 162, 163 – 165.
3 Cf. Dorothea Jameson, Leo M. Hurvich, "Essay concerning color constancy", in *Ann. Rev. Psychol.,* 1898, 40: 1-22, pp. 11 – 14.
Cf. Robert W. Burnham, "Bezold's Color-Mixture Effect", in *American Journal of Psychology*, 66, 1953, pp. 377–385.
4 Cf. Harry Helson, Frederick H. Rohles, "A Quantitative Study of Reversal of Classical Lightness-Contrast", in *American Journal of Psychology* 72, 1959, pp. 530 – 538.
Cf. Charles M. M. De Weert, Lothar Spillmann, "Assimilation: Asymmetry between Brightness and Darkness?", in *Vision Res.*, vol. 35, no. 10, 1995, pp. 1413 – 1419.
Cf. Charles M. M. de Weert, "Assimilation versus Contrast", in Arne Valberg, Barry B. Lee (eds.), *From Pigment to Perception. Advances in Understanding Visual Processes*, New York, London, 1990, pp. 305 – 311.
Cf. Werner G. K. Backhaus, Reinhold Kliegl, John S. Werner, *Color Vision. Perspectives From Different Disciplines,* Berlin, New YorK1998, pp. 19 – 21, 28.

K70 COLOUR SHADOW – COLOURED SHADOW

If an object is illuminated against a white background by a coloured and a white light source, the result is a striking optical illusion. Two shadows are produced. The shadow cast by the white light is tinted by the coloured light from the second source. This is referred to as a coloured shadow. The shadow cast by the coloured light from the one source is illuminated by white light and is colourless in a physical sense. However, a powerful colour sensation is evoked in the viewer's perception: the shadow appears in the complementary colour of the coloured light. This phenomenon is known as colour shadow.[1]

The colour shadow covers the entire field of vision. Unlike simultaneous contrast, it is not restricted to a small area.[2] The human eye performs continuous white balancing, much like a digital camera. The dominant light colour in the surroundings is defined in terms of colour constancy as "white". The consequence is a shift in colour sensation on the entire retina. This process exchanges white, i.e. the white point, with the colour of the dominant lighting (chromatic adaptation).

When such an adapted vision system encounters a white surface – for the shadow of the coloured light effectively reflects white light – the colour shift in the eye compels the complementary colour to appear in the field of the "colour shadow".

Since the CIE chromaticity diagram provides a good description of the characteristic features of the perception of coloured light, it can be used to explain this shift:

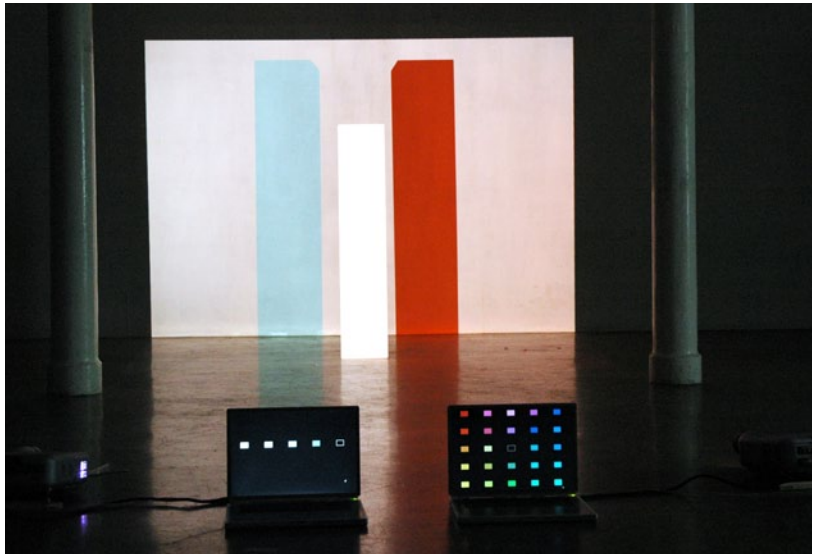


Fig. With the installation of "Shadow colours", consisting of 2 light sources (beamers) and a wooden stele, intensely coloured shadows and pale colour shadows can be generated. Thus, for example the shadow of the wooden stele, which is produced by white light (left Beamer), appears in the same colour as the red light (right beamer). The shadow that is produced from the red light appears cyan.

All highly saturated colours are connected by a straight line through the white point to their complementary colours. The adaptation of the eye shifts the white point along the spectral colour line or the purple line, moving the complementary colour into what was formerly the white point. Thus, in this situation, white is seen in the complementary colour. When, for example, the eye interprets white as red, a white field appears in the complementary colour cyan.
The coloured shadow appears only at lower light intensities, however. If the white light is too intense, the eye reverses the colour shift and the colour shadow disappears again. The colour shadow cannot be measured in physical terms. However, it can be photographed with a digital camera, which imitates the white balancing process that takes place in our eyes.

1 Cf. Anatol Julian Kallmann, Farbkonstanz und Farbkontrast. Eine Untersuchung mit Hilfe der farbigen Schatten, Mainz 2003, pp. 1 – 3.
Cf. G. A. Agoston, Color Theory and its Application in Art and Design. Berlin, Heidelberg, New York, London, Paris, Tokyo 1987, p. 203.
Cf. Eckhart Seiffert, Das Phänomen Farbiger Schatten nach Otto von Guericke, Köthen 2002, p. 12.

2 Cf. Kallmann, Farbkonstanz und Farbkontrast, op. cit., p. 175.

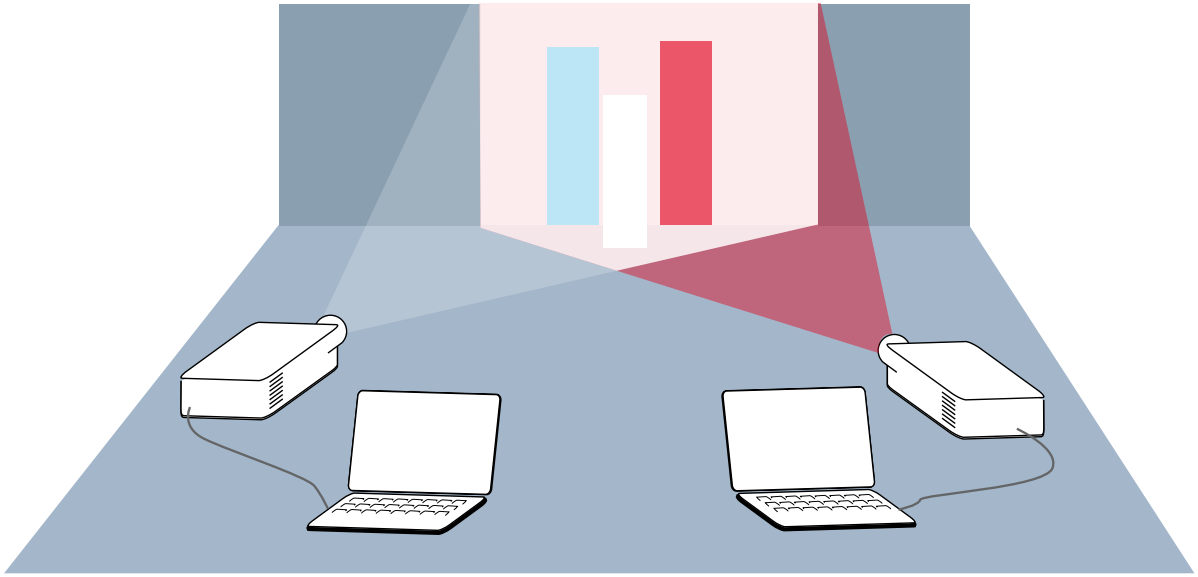


Fig. Installation "Shadow colours".
-Beamer on the left: White light
-Beamer on the right: Red light
-Colour shadow on the left: cyan
-Coloured shadow on the right: red

INDEX

Aberration, chromatic K45
Aberration, spherical K25
Absorption K01 K05 K09 K13 K22 K43 K46 K47 K52
Absorption spectrum **K46** K47
Accommodation **K63**
Achromatic point K02
Acrylic paint K13 K14
Adaptation **K59**
Adaptation, chromatic K59 K70
Adaptation, local colour K58
Afterimage, complementary K52 K56 **K58**
Amacrin cells K61
Aquarelle paint K14
Artificial light film K11 K34
Assimilation K65 **K69**
Base colours K02 K02 K04 K06 K12 K36
Base colours, virtual K02
Beamer **K32** K55
Berlin blue K13
Bezold, Wilhelm von K69
Bezold spreading effect K69
Binder K13 **K14**
Bioluminescence K10
Bipolar K61
Black K05 K06 K12 K49 K54 K69
Black point K02
Achromatic point K02
Blind spot K60
Braun's tube K31
Brightness K01 K02 K07
Brightness adaptation K59
Brightness constancy K28
Bubble eye K44
Candela K35
Candle flame K11
Carotinoid K13
Casein paint K14
Cells, light-sensitive K43 K44
Chevreul, Michel Eugene K69
Chlorophyll K13
Chrominance K31
CIE K02 K55
CIE (x, y, Y) CIEILLD$_{65}$ K02
CIE colour spectrum K02
CIE chromaticity diagram **K02** K70
Ciliary muscles K63
CMY K06
Cold pole K06
Colorimetry **K02** K04
Colour(s) **K01** K02 K04 K07 **K09** K12 K20 K23 K26 K36 K55 K68 K69
achromatic **K06** **K07**
broken K07
chromatic K06
cold K06
dim K07
prismatic K26
spectral K06 K07
warm K06
Colour adaptation K59
Colour blindness K37 K57
Colour body K02
Colour constancy K08 K28 K40 K70
Colour contrast K64 K65 K66
Colour Dimensions System K07
Colour distinction characteristics K06 K07
Colour effect K01
Colour filter K05 K22
Colour hue K01 K02 K04 K06 **K07** K08 K40 K55
Colour impression K36 K54 K66
Colour induction K68
Colour information K50
Colour location K02
Colour mixture, additive K02 K02 **K04** K10 K12 K22 K26 K31 K36 K50 K55 K58 K66
Colour mixture, external additive K04
Colour mixture, internal additive K04
Colour mixture, optical K65
Colour mixture, optical partitive **K66** K68
Colour mixture, subtractive K04 **K05** K12 K22
Colour pathway K39
Colour perception K36 K51 K56
Colour printing **K30**
Colour processing **K39**
Colour reproduction K35
Colour saturation K02
Colour sensation K01
Colour stimulus K01 K02 K39 K55 K58
Colour strength K13
Colour substance K13
Colour temperature K02 **K11** K34 K40
Colour type K02 K07
Colour valence K01 K02 K02

Colour value K02
Colour vision **K36** K47 K55 K57
Complementary colour K02 K06 K07 K22 K23
K58 K68 K70
Complex eye K44
Cone pigments K48
Cone system K51
Cones K36 K39 K45 K48 **K50**
K51 K54 K56 K57 K62
Contrast enhancement K60 K65 **K67**
Contrast perception K65
Convex lens K25
Cornea K45
Corpus geniculatum laterale K38 K39
Cyan K06
Cyan, magenta, (lemon) yellow K06 K12
Cyan, magenta, yellow, black / CMYK K05 K12 **K30**
Dark current K53
Daylight K02
Daylight film K11 K34
Daylight vision K36 K48 K50 K51 K54
K57 K60 K62
Depth of field K25
Deuteranope K57
Dichroid filter K20 K21 **K23**
Diffraction K17
Dimming K07
Diode K33
Dispersion **K26**
DLP beamer K32
Dyes **K15**
Earth pigments K13
Edge spectra **K27**
Einstein, Albert K16
Emission K09
Euclid K24
Exposure K35
Eye K01 K05 K09 K41 **K43**
K44 K55 K59 K60 K62
K63 K66 K68
Eye, concave-mirror K44
Eye, human K31 K34 **K45**
Eye, types of K21 **K44**
Eye movement, saccadian K45 K62 **K64**
Field(s), receptive K37 K39 K61 **K65** K66
K67
Filter K21 **K22** K34 K45
Fluorescence K10
Fluorescent dye K31
Focal point K25 K45 K62 K63
Focusing screen K29
Four-colour printer K02
Four-colour printing K05 K12 K66
Four-colour printing process K30
Four-colour theory **K56** K65
Fovea centralis K02 K38 K45 K49 K50
K51 K60 K61 **K62** K63
K64 K65
Ganglia cells K37 K61
Goethe K01
Grey K06 K12
Helmholtz, Hermann von K55
Hering, Ewald K56 K65
Horizontal cells K61
Illumination K02 K08
Illuminating light K08 K09 K59
Illusion, optical K60 K65 K67 K70
Image processing K38
Image scale K25
Image space K25
Image, virtual K24 K25
Imaging error K45 K62
Indigo K15
Infrared K26
Infrared radiation K17 K41
Inhibition, lateral K67
Interference K17 K20 K23
Interference colours **K20**
Intrinsic brightness K07
Intrinsic colour K22
Intrinsic shadow K28
Kelvin K02 K11
Key colour K05 K12
Land, Edwin K40
LCD beamer K32
LCD screen K31
Le Blon, Jakob Christoph K30
LED **K33**
Lens K26 K32 K45 K50 K62
K63
Lens eye K44 K45
Light K01 K04 K05 K09 K10
K12 K13 **K16** K17 K18
K21 K22 K23 K24 K28
K32 K41 K43 K47 K48
K55 K66
artificial K40
coloured K02 K02 K04 K12 K66
ultraviolet K10 K18 K41 K45
visible K41 K54
white K02 K04 K05 K12 K26
K46 K58
Light absorption K36
Light amount K35 K48

Light bulb light K11
Light efficiency K35
Light mixture K06
Light particles K09 K16 K18 K24 K33 K41 K43 K47 K49 K53
Light phosphor K10 K31 K55
Light quanta K16
Light quantum hypothesis K18
Light radiation K11
Light rays K23 K24 K26 K29 K32 K45 K63
Light reaction **K52**
Light scattering **K29**
Light sensitivity K44 K51 K52
Light, sense of K42
Light signal K53
Light source K01 K26 K28 K34 K35 K40 K70
Light, speed of K16 K19 K23
Light stimulus K47
Light wave(s) K02 K02 K04 K20 K21
Light wavelength K13 K46 K47 K52
Light-dark adaptation K59
Light-dark contrast K64 K65
Light-dark impression K47
Lighting, „cold" K33
Light-sensing cells K01 K02 K36 K38 K40 K43 K44 **K47** K50 K52 K53 K55 K58 K59 K60 K61 K65
Light-sensing cells, human **K48** K52 K65
Light-sensing cells, types K36 K55
Liquid-crystal screen K31
Livingstone, Margaret K37 K39
Lumen K35
Luminance K31 K35
Luminescence **K10**
Luminous flux K35
Luminous intensity K35
Lux K35
Macula K60
Magenta K06 K26 K27
Malus, E. L. K21
Manifest colours **K08** K40
Mineral pigments K13
Mirror K23 K32
Mirror image K24
Mirror, dichroid K32
Nanometre K41
Newton K01 K26 K55
Night vision K36 K48 K49 K57
Object point K25
Object shadow K28
Object space K25
Ochre K13
Offset printing K30
Oil paint K13 K14
Optic nerve K01 K37 K38 K39 K48 K60 K61
Optic nerve cells K65
Optic nerve junction K38
Optic tract K37 **K38** K65
Optics K16 K19 K21 K32 K45 K63
Optics, geometric **K24**
Paint K13 K14
Particle model **K18**
Penumbra K28
Perception, visual **K37** K64 K67
Photoelectric effect K16 K18
Photography K22 K34 K35 K40
Photography, digital K31 K40
Photons K16 K41 K51
Photopigments K36 K51
Photoreceptors K47
Phototaxis K42
Phototropism K42
Physical colours K12
Physical values and units K35
Pigment layer K60 K61
Pigment(s) K05 **K13** K14 K15 K22 K47 K48 K50
artificial K13
natural K13
synthetic K13
Planck, Max K16
Pointillism K66
Polarization **K21** K22 K23
Polarizing filter K22
Polarizing vision K44
Positive lens K24 **K25**
Primary colours K06 K56
Prism K01 K04 K21 K24 K25 K26 K27 K32 K46
Protanope K57
Purkinje phenomenon K49 **K54**
Purkinje, Johannes Evangelista K54
Purple colours K02
Purple hues K26
Purple line K02
Pyrometry K11
Quantum theory K18
Rainbow K26
Rainbow colours K01

Red, green, blue K02 K02 K04 K06 K32
K36
Red, green, blue cones K50
Red-green colour blindness K57
Reference light source K35
Reflection K01 K09 K13 K22 K66
Refraction K19 K21 K50
Refraction index **K19** K23
Resolution K45 K50 K62
Resolution capacity K44
Retina K36 K38 K39 K41 K45
K47 K48 K50 K55 K56
K60 K61 K62 K63 K65
K66 K67 K69 K70
Retinal image K37 K45
Retinal structure **K61**
RGB K06 **K31** K56
RGB colour spectrum K02 K36 K55
Rhodopsin/visual pigment K49 K50 K52 K64
Rod pigments K48
Rod system K51
Rods K48 **K49** K51 K54 K62
Saturation K01 K02 K07 K68
Saturation, degree of K07
Scattering K21
Screen, computer K02 K02 K04 K10 **K31**
K33 K55
Secondary colours K06
Shadow **K28**
Shadow, colour **K70**
Shadow, coloured **K70**
Simultaneous contrast K65 **K68** K69 K70
Skylight filter K22
Soap bubbles K20
Solar spectrum K22
Spectral colour range K02
Spectral colours K02 K04 K20 K22 K26
K46
Spectral photometry K46
Spectrum K02 K04 K09 K12 K17
K20 K22 K26 K41
Spectrum continuous K26
Spectrum, discontinuous K26
Standard light source K02
Substantive colour(s) K08 **K12** K35
Substance mixture K06
Successive contrast K69
Sunlight K01 K11 K20 K25 K26
K29 K45
Surface K01 K09 K12 K49
Terra di Siena K13
Three-colour theory K02 **K55** K56
Tonal values K07
Topography of the retina K38
Transmission spectrum K46
Tritanope K57
Tube screen K31
Ultraviolet K26
Ultraviolet radiation K17 K22
Umber K13
Umbra K28
UV vision K44
Vegetable dyes K13
Vermilion K06
Vision, focused K50
Visual axis K45 K50 K62
Wald, Georg K55
Warm pole K06
Wave model K16 **K17** K18 K19
Wave(s), electromagnetic K16 K17 K41
Wave spectrum, electromagnetic K16 K41
Wavelength K09
Wavelength range K42
What system K37 K39
Where system K37
White K06
White balance **K34** K40 K59 K70
White point K40 K70
X, Y, Z K02
X-ray radiation K17
Young, Thomas K55
Young-Helmholtz theory K55
Zonular fibres K63

REFERENCES FOR ILLUSTRATIONS

K02 Fig. 1 bis **Fig. 7**
Cf. *http://www.daicolor.co.jp/english/color_e/color_e01.html*

K16 Fig. 3
Cf. Jost J. Marchesi: *Handbuch der Fotografie*. Band 1: *Geschichte, Chemisch-physikalische und optische Grundlagen*. Schaffhausen 1993, S. 126

K17 Fig. 1
Cf. *http://www.vs-c.de*

K18 Fig. 1
Cf. Joachim Grehn (Hg.): *Metzler Physik*, 2. Auflage. Stuttgart 1989, S. 359, Fig. 9 – 1

K19 Fig. 2
Cf. Ekbert Hering, Rolf Martin, Martin Stohrer: *Physik für Ingenieure*, 6. Auflage. Berlin, Heidelberg 1997, S. 410, Fig. 6 – 15.

K24 Fig. 1
Cf. Ekbert Hering, Rolf Martin, Martin Stohrer: *Physik für Ingenieure*, 6. Auflage. Berlin, Heidelberg 1997, S. 410, Fig. 6.

K24 Fig. 3a und **Fig. 3b**
Cf. Ekbert Hering, Rolf Martin, Martin Stohrer: *Physik für Ingenieure*, 6. Auflage. Berlin, Heidelberg 1997, S. 410, Fig. 6 – 3.

K25 Fig. 1
Cf. Jost J. Marchesi: *Handbuch der Fotografie*. Band 1: *Geschichte, Chemisch-physikalische und optische Grundlagen*. Schaffhausen 1993, S. 156

K25 Fig. 2
Cf. Jost J. Marchesi: *Handbuch der Fotografie*. Band 1: *Geschichte, Chemisch-physikalische und optische Grundlagen*. Schaffhausen 1993, S. 158

K28 Fig. 4
Cf. Mario Bollin: *Zeichnen: Grundlagen im Vorkurs an der Schule für Gestaltung Basel*. Basel 1995, Der Schlagschatten, Darstellungen

K32 Fig. 2
Cf. http//www.chip.de

K32 Fig. 3
Cf. http//www.chip.de

K33 Fig. 3a
Cf. Friedrich Dorn, Franz Bader: *Physik Mittelstufe*, Hannover 1980. S. 358, 358.2 und 358.3

K33 Fig. 3b
Cf. Friedrich Dorn, Franz Bader: *Physik Mittelstufe*, Hannover 1980. S. 358, 358.1

K37 Fig. 2
Cf. Margaret Livingstone: *Vision and Art. The Biology of Seeing*. New YorK2002, S. 51

K39 Fig. 1
Cf. Margaret Livingstone: *Vision and Art. The Biology of Seeing*. New YorK2002, S. 51

K41 Fig. 1
Siehe K16 Fig. 3

K46 Fig. 1
Cf. Werner Schmidt: *Biophysik des Farbensehens*. Konstanz 1999, S. 37, Fig. 12

K50 Fig. 3
Cf. Richard Gregory*: Auge und Gehirn. Psychologie des Sehens*. Hamburg 2001, Tafel IX

K51 Fig. 3
Cf. N. Welsch, C. Liebmann: *Farbe*. Heidelberg 2003, S. 251, 3 – 31

K53 Fig. 1
Cf. N. Welsch, C. Liebmann: *Farbe*. Heidelberg 2003, S. 245, 3 – 25 und 3 – 26

K54 Fig. 1
Cf. Richard Gregory*: Auge und Gehirn. Psychologie des Sehens*. Hamburg 2001, Tafel VI

K55 Fig. 1
Siehe K50 Fig. 3

K60 Fig. 3
Cf. N. Welsch, C. Liebmann: *Farbe*. Heidelberg 2003, S. 251, 3-31 and 3 – 32

K62 Fig. 3
Cf. Margaret Livingstone: *Vision and Art. The Biology of Seeing*. New YorK2002, S. 70

K64 Fig. 1
Cf. Richard Gregory*: Auge und Gehirn. Psychologie des Sehens*. Hamburg 2001, S. 66, 3.15

K67 Fig. 1
Cf. Margaret Livingstone: *Vision and Art. The Biology of Seeing*. New YorK2002, S. 58

K67 Fig. 2
Cf. Margaret Livingstone: *Vision and Art. The Biology of Seeing*. New YorK2002, S. 57

K67 Fig. 3
Cf. Margaret Livingstone: *Vision and Art. The Biology of Seeing*. New YorK2002, Buchdeckel Innenseite/ inside flap