A GUIDE TO LIGHT AND COLOUR DEMONSTRATIONS 2015

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LIGHT & COLOUR GROUP

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A GUIDE TO LIGHT AND COLOUR DEMONSTRATIONS

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In this publication we will give a short description of fundamental phenomena of light and colour and how they can be demonstrated in front of a small audience. Some of the demonstrations were originally developed by Karl Miescher and his coworkers in the Laboratory of Colour Metrics at the University of Basel (Switzerland). The equipment was later moved to the Norwegian University of Science and Technology (NTNU) in Trondheim (Norway) by Arne Valberg and used for many years in his interdisciplinary lectures on "Light Vision Colour". Other demonstrations were developed by Torger Holtsmark and Jan Henrik Wold at the University of Oslo. The equipment is now available in the Light Laboratory at the Faculty of Architecture and Fine Art at NTNU and is being used e.g. in the courses "Light and lighting", "Light and colour" and "Light and lighting environment" by the editors. The main idea behind this project is to bring the students in contact with real phenomena, not to simulate them by digital means.

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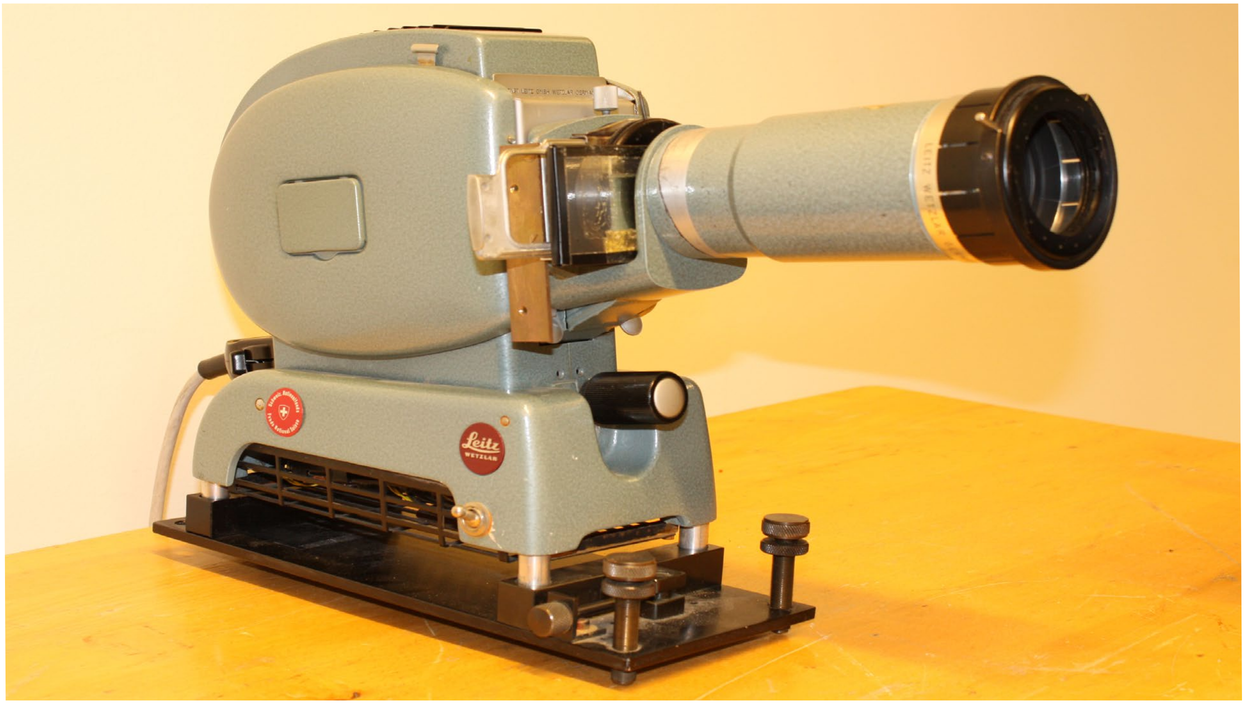

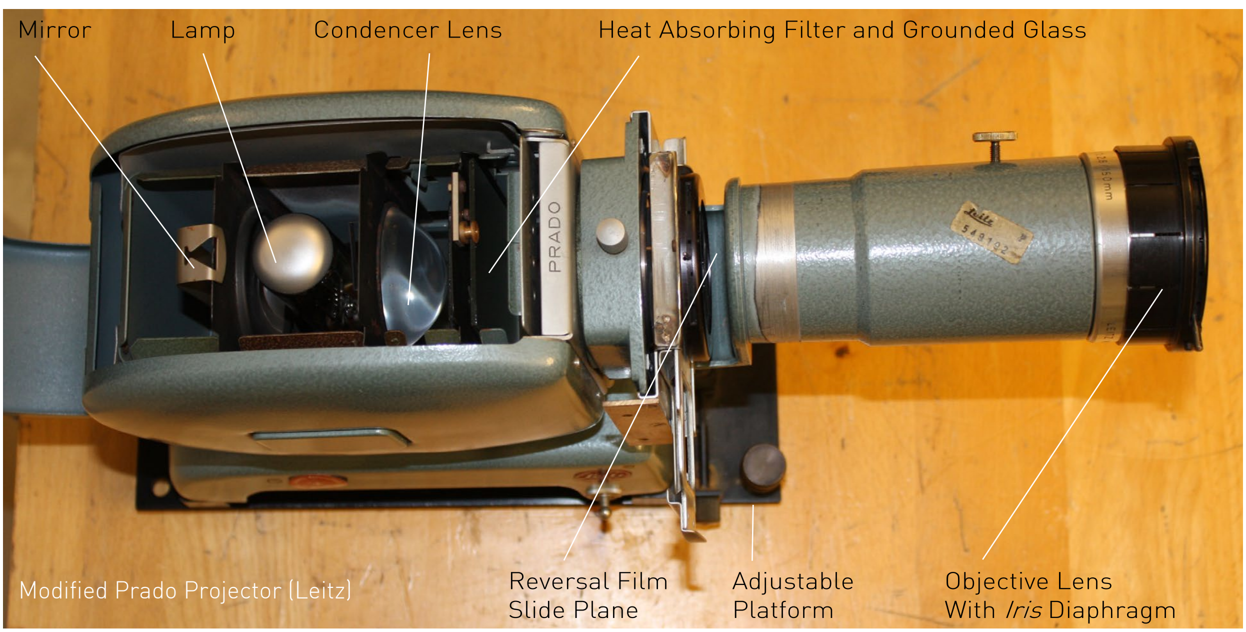
Mirror
Lamp
Condencer Lens
Heat Absorbing Filter and Grounded Glass
PRADO
Modified Prado Projector (Leitz)
Reversal Film
Slide Plane
Adjustable
Platform
Objective Lens
With *Iris* Diaphragm

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Fig. 1a

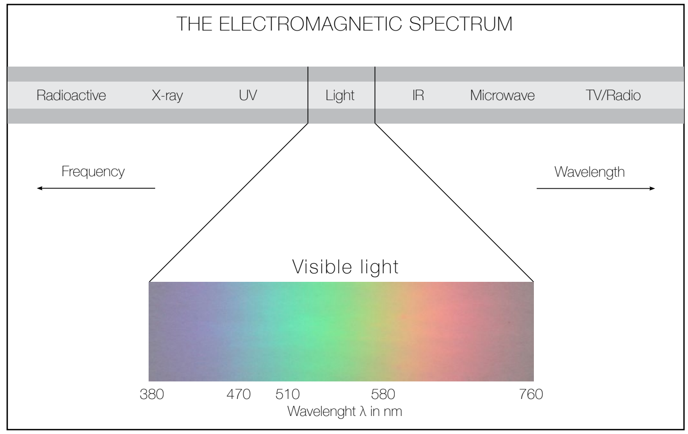

Fig. 1b

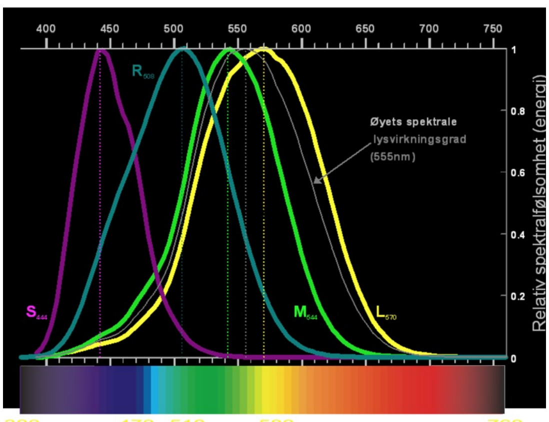

Fig. 1c

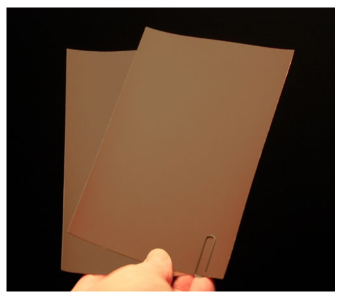

Fig. 2a

Fig. 2b

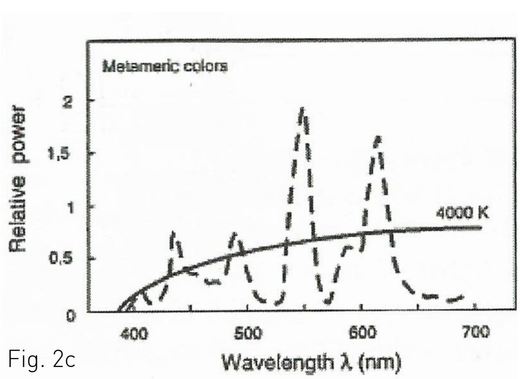

Fig. 2c

Figures to section 1: Fig. 1a Pocket Spectroscope.
Fig. 1b The electromagnetic *spectrum*.
Fig. 1c The spectral sensitivities of the three human *cone* types L, M, and S, the luminosity function V_λ (thin curve), and of the rods (drawn in blue).

Figures to section 2: Fig. 2a Metameric samples viewed under an incandescent lamp. Fig. 2b Metameric samples viewed under an artificial overcast sky. Fig. 2c Metameric spectral power distribution of two lights.

1. SPECTRAL DISTRIBUTION AND THE SPECTROSCOPE

A spectroscope (or *spectrophotometer*) is used to analyze the spectral composition of electromagnetic radiation, including "visible light". Only a small band of radiation is capable of stimulating the eye. The limits of this band depend on the spectral energy available, but for most practical purposes the visible *spectrum* can be regarded as reaching from 380 nanometer at the short wavelength side, to 780 nanometer (nm) at the long wavelength side (1nm = 10^{-9} m). Only radiation within this wavelength range is properly described as light.

The hand-held spectroscope shows the *spectrum* of reflected and emitted light, its wavelength composition (wavelength distribution) and relative intensity. The instrument is based on the principle of *refraction* in a prism, the phenomenon that the propagation of light changes its direction when it enters a transparent medium of different optical density, for example in passing from air to glass. Short wavelength bluish and green lights are refracted more than middle- and long wavelength orange and reddish lights. This phenomenon is called *dispersion*. White light consists of many different wavelengths, and these wavelengths will be separated at the border between two media with different refraction indices.

When you look at natural surface colours through the spectroscope, dark colours tend to have a narrow spectral *bandwidth*, while bright colours have a broad-band wavelength distribution.

Note to the instructor:

- Look through the spectroscope at the light from fluorescent tubes and other light sources. How do the spectra differ?

2. METAMERISM

In *colourimetry* (the discipline of colour measurement), *metameric colours* characterize different colour stimuli (e.g. coloured surfaces) that match in colour appearance, but have different spectral distributions (fig. 2c). Colours that match (appear identical) in this way are called *metamers*.

Spectral wavelength distribution is an expression that describes the relative spectral proportions of light emitted by a light source (I), or the light reflected (R), absorbed (A), and transmitted (T): (I = R+A+T); the RAT law.

The human eye contains three types of daylight *receptors* (the L, M, and S *cone receptors*) that are activated by light from different regions of the *spectrum*: the long-wavelength (L), middle-wavelength (M), and the short-wavelength (S) parts (see Fig. 1c). This means that colours can be described by three sensory quantities, called the *cone excitations* (or the *CIE tristimulus values*), proportional to the light absorptions in the pigments of the *cone receptors*. Metamerism occurs because each type of *cone* responds to the cumulative energy in a broad range of wavelengths. Whenever different spectral distributions (combinations of light across all wavelengths) produce the same three *receptor* excitations, L, M, S, metamerism is the result.

Notes to the instructor:

- In the daylightlab there are 6 *metameric colour* samples. Show these under different illuminations, for instance regular artificial fluorescent illumination and incandescent light.
- For example, take the samples to an incandescent lamp and compare them. Two of them now appears to have the same dark colour (Fig. 2a).
- Take the same samples to the artificial sky or compare them in daylight. Those that were equal have now become different (Fig. 2b), and two other samples has become equal.
- If available use a spectrophotometer to show what happens.

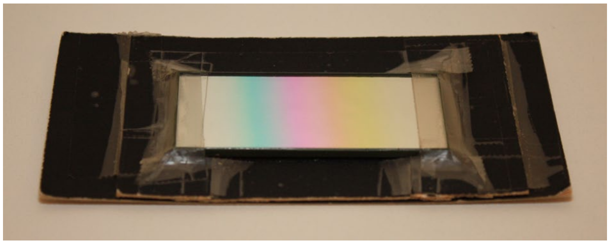

Fig. 3a

Fig. 3b

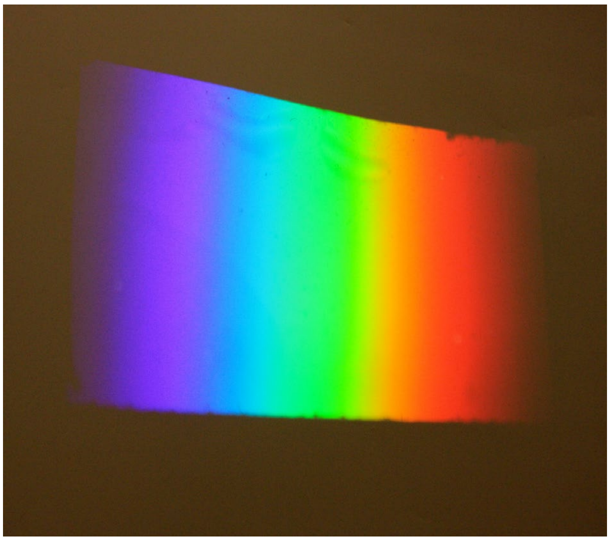

Fig. 3c

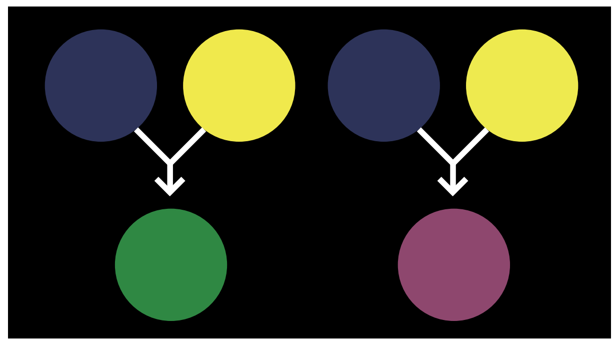

Fig. 4a

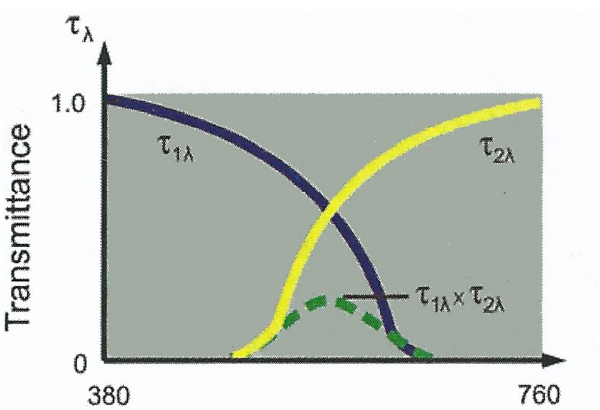

Fig. 4b

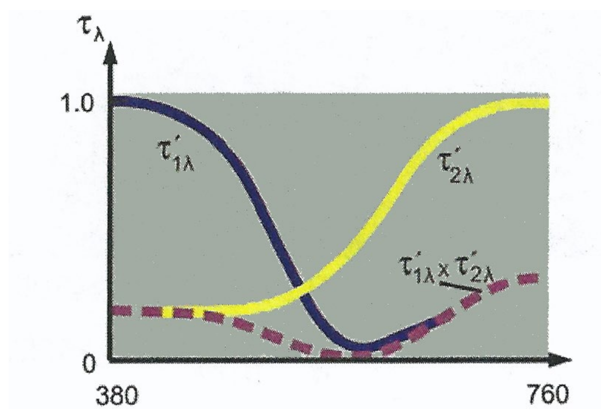

Fig. 4c

Figures to section 3: Fig. 3a Picture showing the *interference filter*. Fig. 3b *Interference filter* placed in the slide plane of the projector. Fig. 3c Picture of the interference *spectrum* of the projected light projected on the screen.
Figures to section 4: Fig. 4a Subtractive or *multiplicative colour mixture* of yellow and blue lights.
Fig. 4b and c Subtractive (multiplicative) colour mixing depends on spectral transmissions.

3. INTERFERENCE

In physics, the visible *spectrum* (also called Newton's spectrum) is a succession of colours due to refraction and *dispersion* of the transmitted light in a glass prism (see section 1). A *spectrum* can also be produced by interference in a thin film, like in oil on water (Newton's rings) or in the reflection of light from some insect wings, and from the feathers of birds (e.g. peacock). The modifications of intensity obtained by the superposition of two or more beams of *monochromatic lights*, we call interference. If the resultant intensity is zero, we have destructive interference, while if it is greater than zero, we have constructive interference. The phenomenon is caused by the wave character of light. The spectral *interference filter* used here shows the linear succession of wavelengths with equal wavelength-steps in *nanometer* (nm) being proportional to steps measured in cm across the *spectrum*. Interference filters can be made to have relative narrow spectral bands of transmission (e.g. 20 or 50 nm at half width).

Notes to the instructor:

- Use one projector, and place the spectral *interference filter* in the slide frame. Focus the *spectrum* on the screen.
- With this interference *spectrum* there is a linear relationship between wavelengths in nanometers (1 nm = 10^{-9}m) and distances in cm (= 10^{-2}m) on the screen.

4. ABSORPTION / TRANSMISSION

The consequence of absorption is the disappearance of light. The absorbed energy is converted into heat motion of the molecules of the absorbing material. Lights reflected, absorbed, and transmitted are all important in generating colours. The colours of painted wooden houses are generated by reflecting paints (they absorb some wavelengths and reflect others). The reflected light is the more important one for appearance of *object colours*.

Notes to the instructor:

- Using the *spectrum* projected from one projector (Fig. 5, p. 8), we place a homogeneous colour filter in front of that objective and observe which colours disappear from the *spectrum* on the screen. The colours that disappear are the ones that correspond to light at wavelengths that are absorbed in the colour filter. The colours remaining correspond to wavelengths that are transmitted. For instance, an orange filter absorbs the shortest wavelengths, and the colour blue in the *spectrum* disappears.
- Place a coloured paper on the whiteboard (or screen) and project the *spectrum* upon it. The wavelengths that turn black are those that are absorbed the most by the paper.
- When the *spectrum* of a colour is relatively wide (contains a broad range of wavelengths), the intensity of the colour will, generally be high and its saturation low. If the reflection *spectrum* is narrow (contains a narrow range of wavelengths), its appearance will be dark (blackish). For surface colours, light green has a broader spectral *bandwidth* than dark green, and a narrow "monochromatic" green stimulus would appear black.

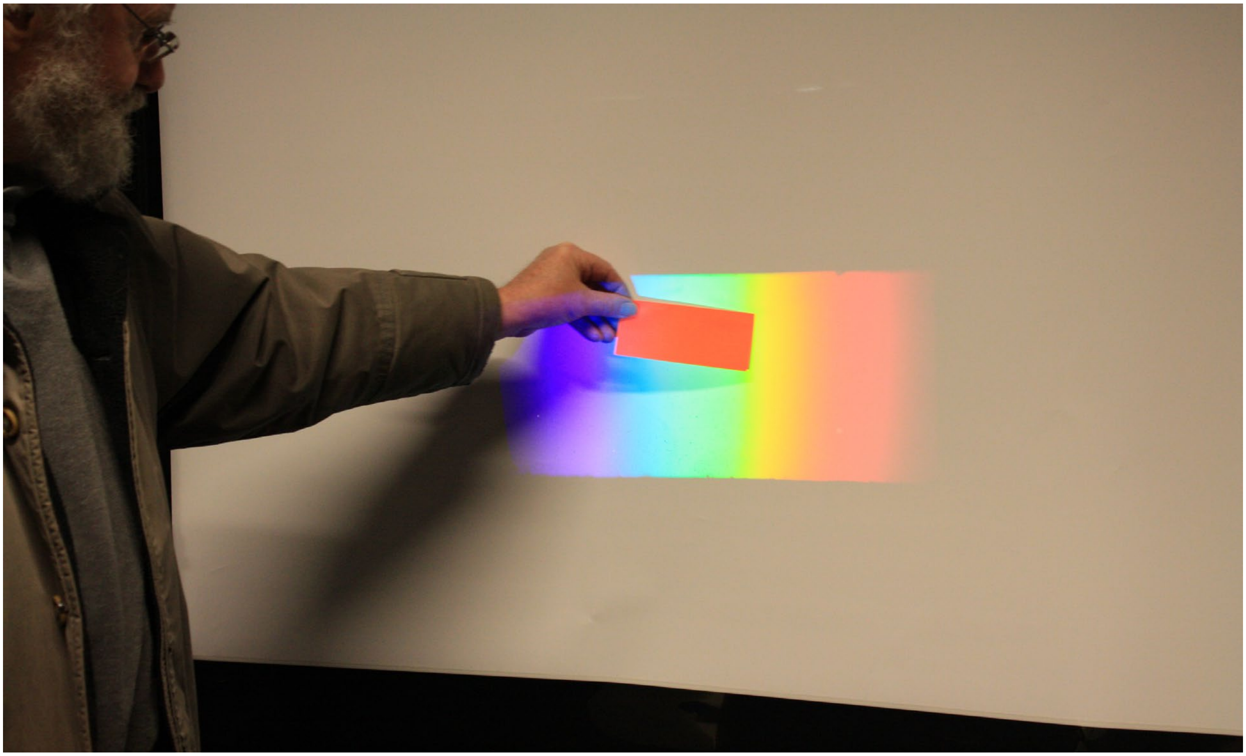

Fig. 5a

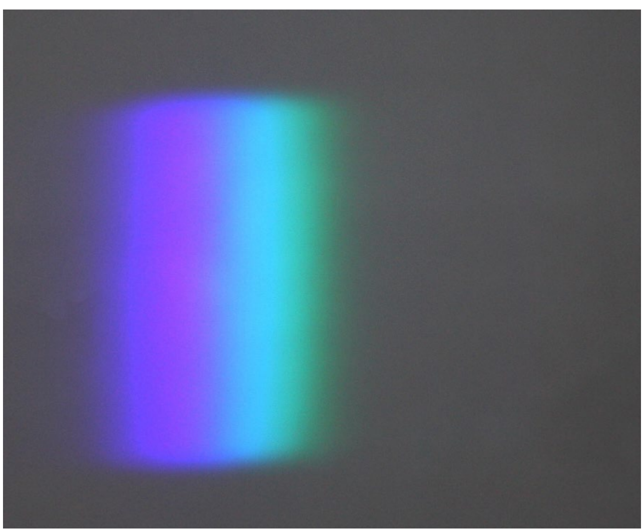

Fig. 5b

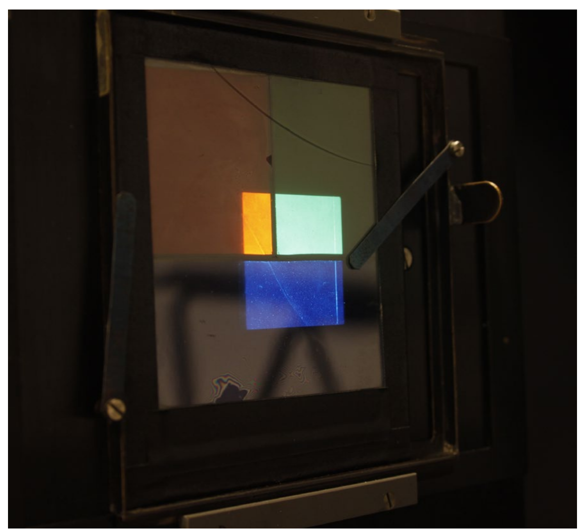

Fig. 6a

Figure to section 5: Fig. 5a Fluorescent sample illuminated by spectral lights.
Fig. 5b A blue colour filter subtracts light (here yellow, orange and red) from the beam and the transmittet light (green, blue and violet) determines its colour.
Figures to section 6: Fig. 6a Colour mixture frame with colour filters.

5. REFLECTION AND FLUORESCENCE

In some cases the light reemitted from an absorbing material may have a longer wavelength than the incident light. This is called *fluorescence*. Thus, fluorescent colour samples reflect more light over the whole *spectrum* than do non-fluorecent surfaces. They are therefore brighter, and for this reason they are used as reflecting signal colours. Note that fluorescence is a physical phenomenon different from a *fluorent* (*selfluminous*) appearance. *Fluorence* characterizes the appearance (perceived effect) of an intensity between a highly reflecting surface and a light source (Evans,1964).

Note to the instructor:

- Place e.g. an orange fluorescent colour sample on the *spectrum* that is projected on the whiteboard. When the orange sample is placed on the blue part of the *spectrum*, the short wavelength light is absorbed and reemitted as orange light (fig. 5a). This extra reflected light makes the surface look fluorent (brighter).

6. MULTIPLICATIVE (or SUBTRACTIVE) COLOUR MIXTURE

Under normal lighting conditions, the colour that an opaque surface displays depends largely on which wavelength ranges of the electromagnetic *spectrum* it reflects. For a translucent filter, the transmitted *spectrum* is the most important for its appearance. When two or more colour filters are positioned one behind the other in the same light path, a multiplicative (subtractive) colour mixture will occur. Each filter alone will subtract (absorb) a part of the incident light, allowing less light to get through (the RAT law, section 2). Contrary to common belief, the resulting colour of the mixture does not depend on the colour appearances of the two filters, but on their spectral transmission.

Subtractive colour systems start with white light from which some wavelengths are partly or wholly removed. Coloured inks, water-colours, paints, or filters situated between the viewer's eyes and the light source reduce (absorb) light of some wavelengths and transmit or reflects others, giving the objects their colour appearance.

It is a common experience from playing with water-colours that a subtractive mixture of yellow and a blue becomes green. However, this is not always the case. The mixture colour depends on the spectral distribution of each of the two colours (yellow and blue) that are mixed, and can, in some cases, become magenta (reddish blue, Fig. 4c).

Notes to the instructor:

- Using just one projector, place both filters (blue + yellow) next to the iris diaphragm and observe the light on the screen (which should be reddish or magenta).
- Using a second set of yellow and blue colour filters, the mixture colour becomes more greenish. These two different results for yellow/blue colour mixtures demonstrate the physics of the light transmission and that "subtractive mixtures" are actually "multiplicative mixtures". Multiplication of the spectral transmission curves $t_1(\lambda) \times t_2(\lambda)$ of the yellow and blue filters (in Fig. 4b) gives a maximum transmission in the middle (green) part of the *spectrum*, and Fig. 4c gives a minimum.

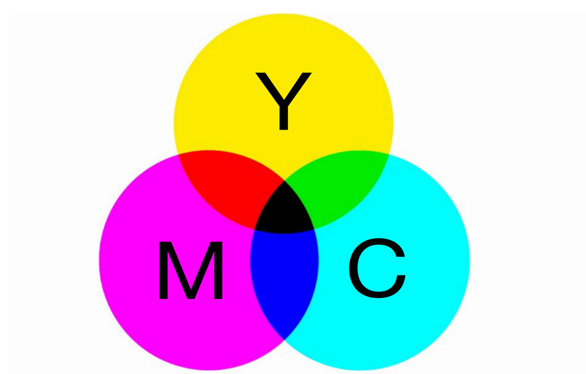

Fig. 6b Typical subtractive mixture of magenta, yellow and cyan (used in printing).

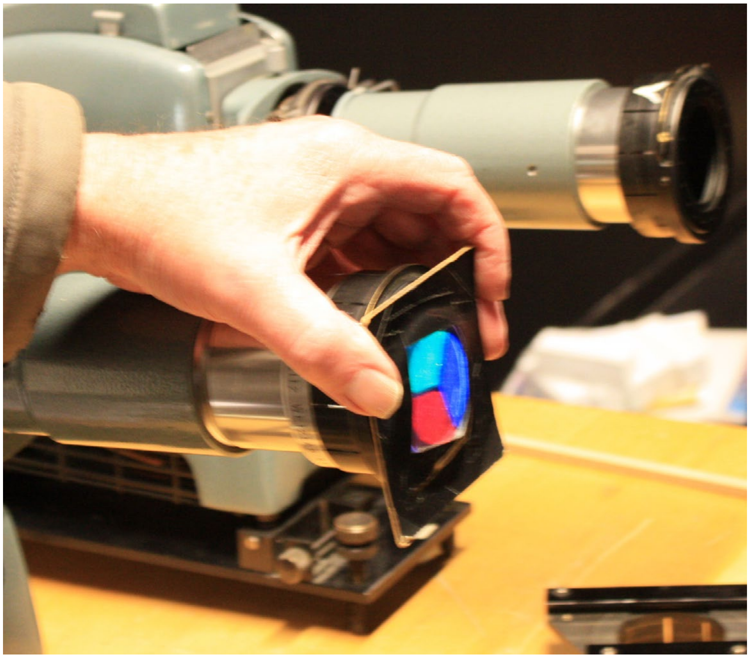

Fig. 7a

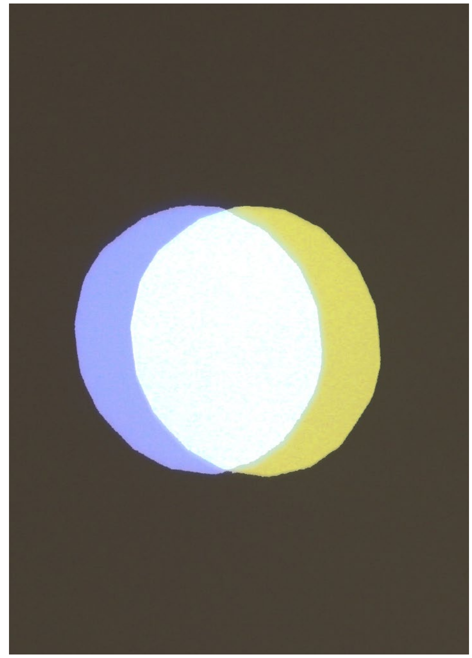

Fig. 7b

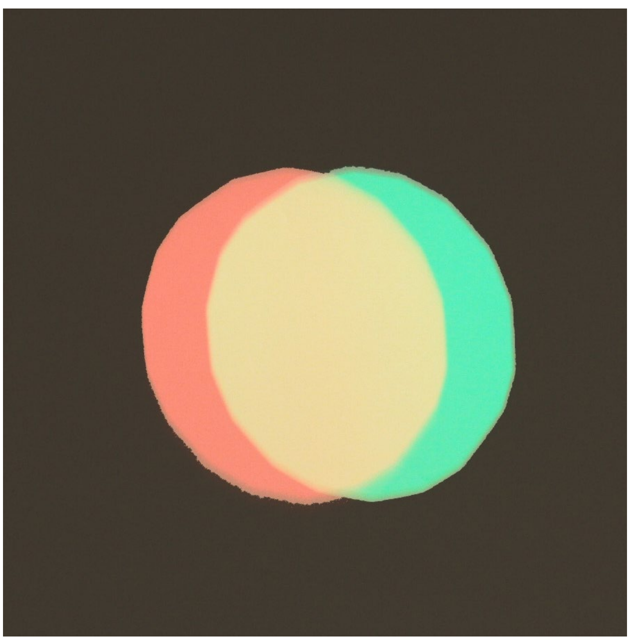

Fig. 7c

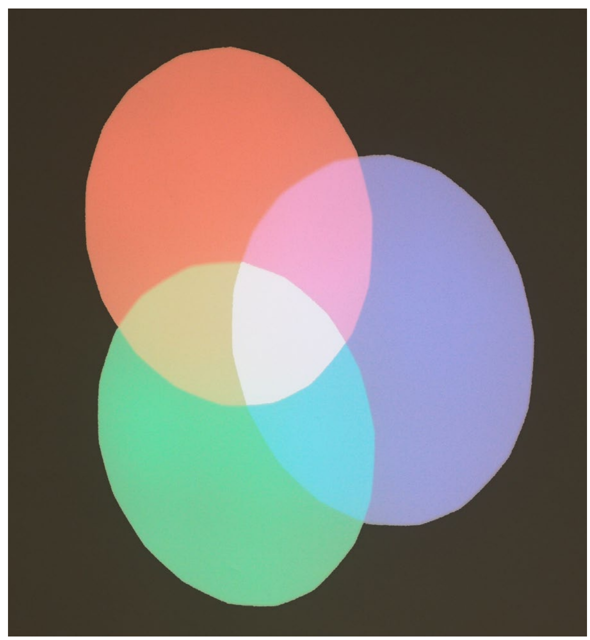

Fig. 7d

Figures to section 7: Fig. 7a Placing the tri-prism in front of the objective of the projector. Fig. 7b The bi-prism adds blue and yellow. Fig. 7c The bi-prism mixes red and green. Fig. 7d Tri-prism and additiv colour mixtures of red, green and blue. See also Fig. 7e. Often used *additive colour mixture* of red, blue and green (as used in television screens).

7. ADDITIVE COLOUR MIXTURES

7.1 Additive Colour Mixture/Tri-prism
Additive colour mixture describes the process when colours are created by mixing (adding) the lights emitted from different objects (light sources, surfaces, etc.). This is in contrast to a subtractive (multiplicative) process, where mixture colours are produced by removing light from various parts of the visible *spectrum*. Electronic displays, computer monitors, and television screens are the most common sources of *additive colour mixture*s, while *subtractive colour mixture*s are caused by mixtures of paints, pigments, and lights transmitted through colour filters. The additive reproduction process usually combines red, green and blue lights (often called *primary colours*) to produce new colours in an additive mixture. Combining one of these additive "primary" colours with another "primary" in equal amounts produces the additive secondary colours cyan, magenta, and yellow. Combining all three *primary colours* produces white. The coloured pixels of an electronic display do not overlap on the screen, but when they are small, or viewed from a sufficiently long distance, the lights from the pixels diffuse and overlap (add) on the retina (see also section 7.6).

The tri-prism splits the light beam into three channels. Using three colour filters (R, G and B) on these weakly deviating prisms positioned in front of the projector's objective, the three "primary" colours R, G and B can be separated on the screen. Superimposed they give the mixture colours Y, M and C (yellow, magenta and cyan). The colours R, G and B added together give white (as do Y, M and C together); see Fig 7e.

Notes to the instructor:

- Project the image of a small diaphragm opening on the screen.
- The "tri-prism" with red, green, and blue filters is placed in front of the projector's objective. You will now see three small separate circular images of the diaphragm on the screen: a red, a green and a blue one.
- Increase the size of the opening in the iris diaphragm to obtain a superposition (additive mixture) of the three colours. Due to the tri-prism, we only need one projector to produce three separate colour channels.
- When the tri-prism with its three colours (RGB) are in the right positions before the objective (such that equal amounts of white light enter the three filters) a white colour should be visible in the centre of the projected image.

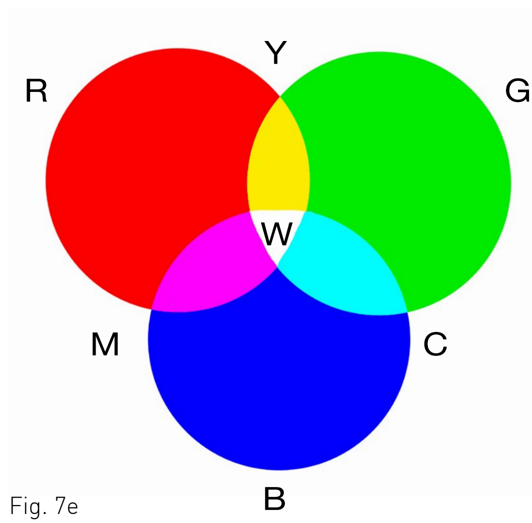

Fig. 7e

7.2 Bi-prism
A bi-prism mounted on the Prado objective splits the light beam into two channels. These channels can be brought to overlap, and mixing for instance yellow and blue by a bi-prism produces white on the screen (Figs. 7b and 7c; the principle is the same as for the tri-prism).

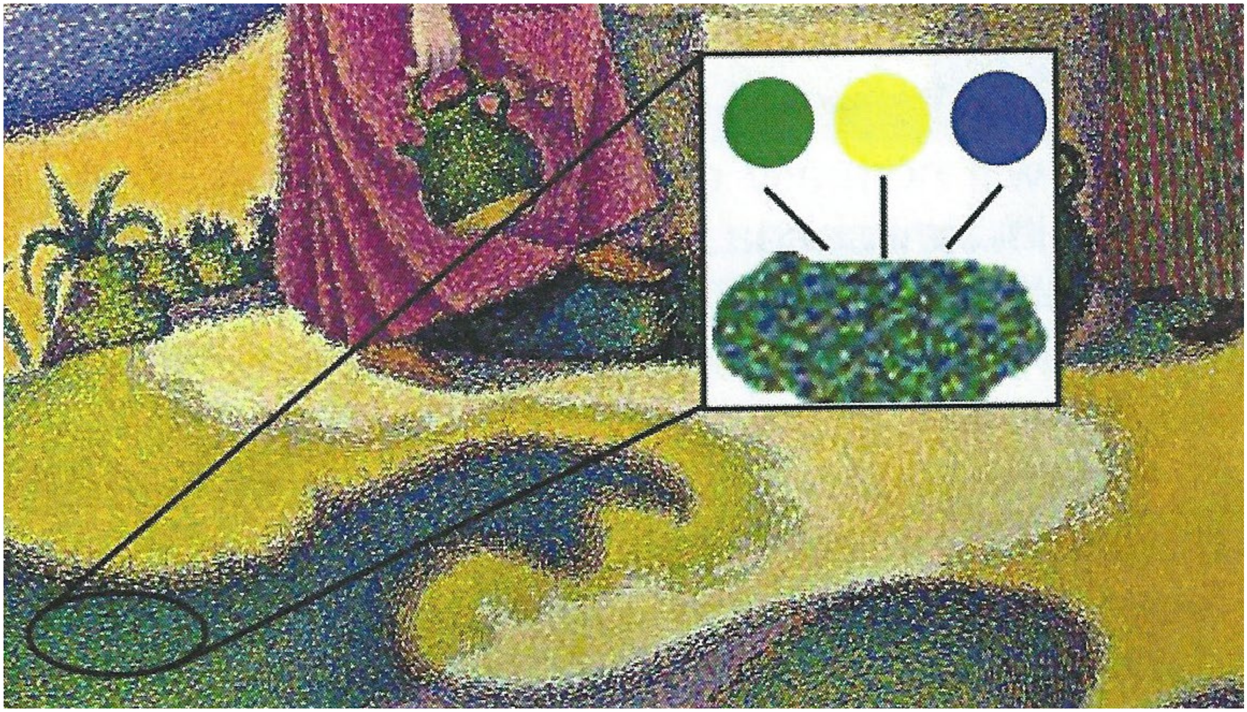

Fig. 7.6a

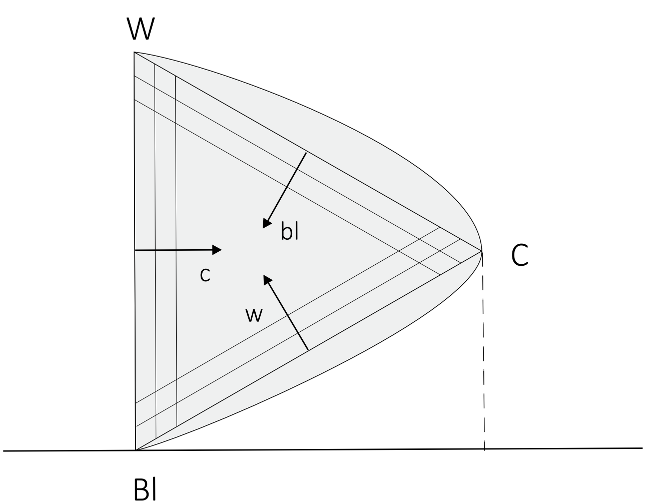

Fig. 7.6b

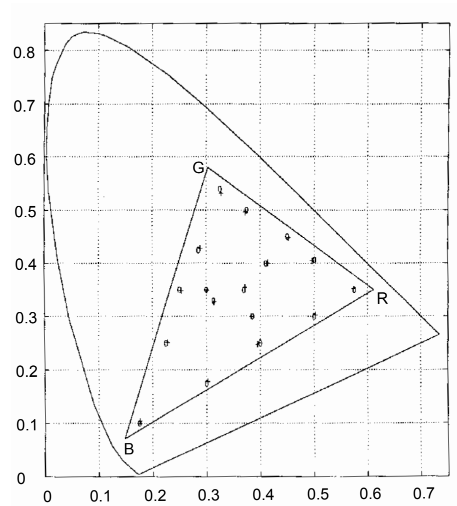

Fig. 7.6c

Figure to section 7.6: Fig. 7.6a Paul Signac, Femmes au Puits, 1892, showing a detail with constituent colours. Image taken from Wikipedia.
Fig. 7.6b and c Colour coordinates of the Ostwald system (Fig. 7.6b) and the CIE (x,y) system (Fig. 7.6c).

7.3 Colour Reproduction and Colour Measurement
The demonstration above illustrates how one can produce different colours as an additive mixture of three "*primary colours*" (R, G, B). When the mixture colour matches an unknown colour, the intensity (e.g. luminance) of each of them can be regarded as colour coordinates in a three-dimensional "colour space".

7.4 A subjective colourimeter
As we have seen above, additive mixtures of several colours using only one projector can be obtained by using R, G, B filters mounted on a flat, moveable x-y frame colour coordinates are the relative amounts R, G, B (proportional to their illuminated areas), or the proportions (r = R / (R+B+G), g = G / (R+G+B)), together with the luminance L of the *primary colours*. Moving the frame produces a continuous change of colour within the (r, g) triangle. The principle can be used to make precise, subjective colour matches with human observers. The instrument together with the observer works as a colourimeter (a colour matching instrument).

7.5 Additive colour mixtures with black
When using a x-y frame on the objective with white (w), black (bl), and chromatic colour (c), this mixture can, according to the German chemist Wilhelm Ostwald, be described as:

$$w + bl + c = 1$$

These coordinates can be visualized in a triangle where black is situated at one of the corners, with white and the chromatic colour on the two other corners (see Fig. 7.6b). Remember that in order to perceive black you need a bright, white surround enclosing the focused test area. The triangle also visualizes the coordinates of mixture colours when using a spinning wheel with colour sectors (Maxwell's method).

7.6 Pointillism
The "spatial melting" of small coloured dots, together with subtractive mixtures, are frequently used mixing methods in colour reproduction, such as colour printing and TV-screens. The methods, applying spatial *additive colour mixture* of melting dots, is often used in art (pointillism), and on the electronic displays used by modern TV-screens, mobile telephones etc. At some distance from the subject's eyes the dots cannot be resolved (separated), but instead "melt" by spreading into each other. Their colours will add. Within the "melting area" the luminance will be the average of the dots' luminance.


Fig. 7d Key personalities in colour science. The German scientists and antagonists Ewald Hering (left) and Hermann von Helmholtz (right).Pictures from Wikipedia.

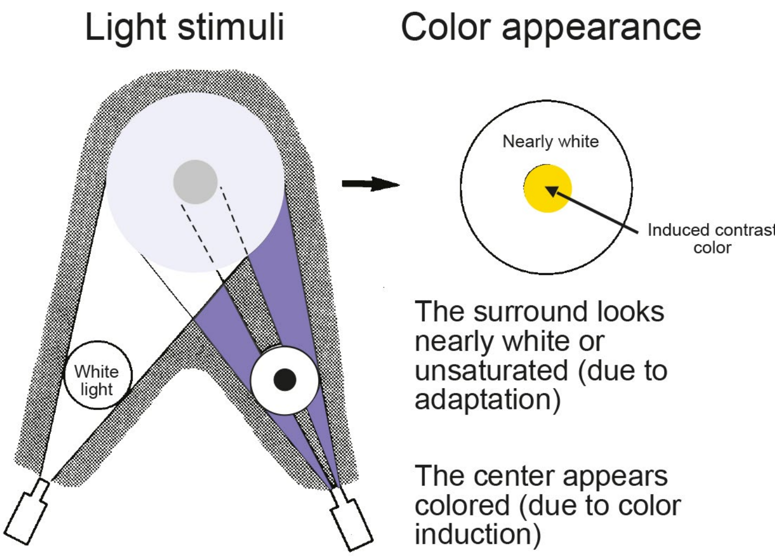

Fig. 8

Figures to section 8: Fig. 8 Coloured shadows. When a blue and a white light illuminate the same object, the object casts two shadows on the wall (see also Fig. 10a).

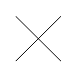

Fig. 9a

Figure to section 9: Fig. 9a Afterimage example. Look at the picture for 15 seconds and shift focus to the cross. Blinking helps you to see the afterimage.

8. ADAPTATION

If you look steadily at an object (fixate), it will disappear after some time. When you enter a room where the illumination is not white, it will tend to become white after some time. When you walk out of a well lit room and go into the night, adaptation to the new light condition will take some time, but the eye is able to deal with more than 10 decades (10^{10}) of light levels.

After looking for a while at an unsaturated colour projecting the surround (annulus) to a white central disk, it will become nearly white (due to adaptation). At the same time the centre appears tinted with the opponent afterimage complementary colour due to colour induction from the annulus (see Fig. 8).

Similarly, when you enter a room where the illumination is somewhat off-white, it will tend to become more neutral white after some time. When you walk out of a well lit room and go into the night, total adaptation to the darker light condition will take about 30 min. The area of the pupil (that regulates the illuminance on the retina) can only change the light hitting the retinal *receptors* by one decade in response to this vast range of light levels. Daylight vision is mediated by the *cone receptors* in the retina, while night vision relies on the rod *receptors* (see Fig. 1c). Totally, the human retina has about 6 million cones and 120 million rods.

9. AFTERIMAGES

Afterimages appear when you fixate an object for about 15 seconds and then shift your gaze to a homogenous background. If you have, for instance, fixated a green spot, the afterimage will become a reddish spot, and if you have fixated a reddish spot, the afterimage becomes greenish. The afterimage of yellow is bluish, and blue generates a yellowish afterimage. Strong afterimages that change their colour over time after stimulus exposure are the results after a short look at the sun (not to be recommended). The colours of the afterimages have been called the "afterimage-complementary" because they differ somewhat from the additive complementaries to the stimuli generating them.

Fig. 9b. The Scotisch Physicist James Clerk Maxwell holding one of his colour wheels. Picture from Wikipedia.

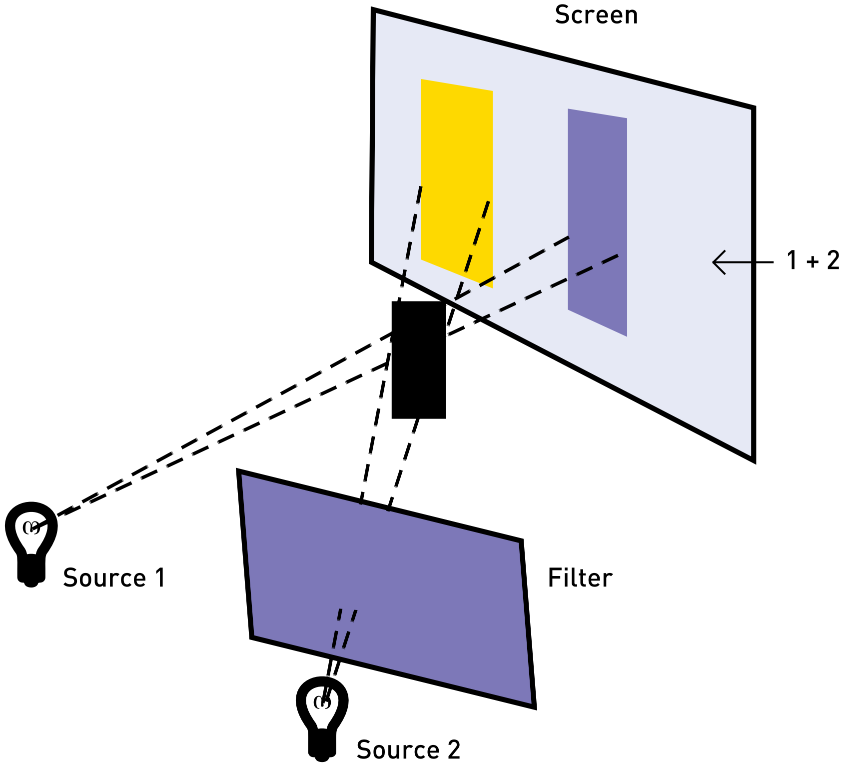

Fig. 10a

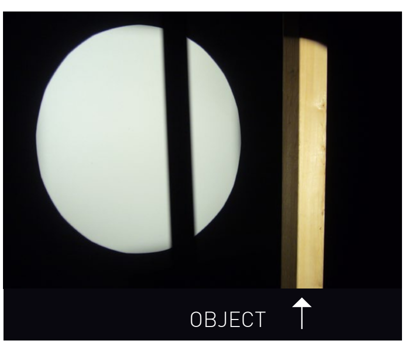

Fig. 10b

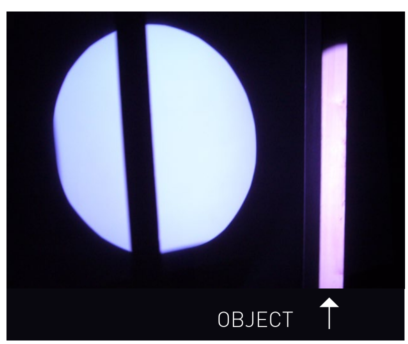

Fig. 10c

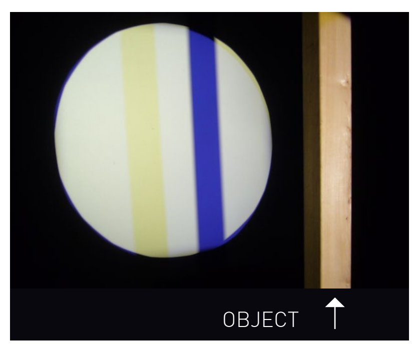

Fig. 10d

Figures to section 10: Fig. 10a Coloured shadow and simultaneous contrast (yellow).
Fig. 10b Obstacle illuminated by white light from source 1.
Fig. 10c Obstacle illuminated by bluish light from source 2.
Fig. 10d Obstacle illuminated by both sources.

10. SIMULTANEOUS COLOUR CONTRAST

"*Simultaneous contrast*" refers to the phenomenon that colours affect each other laterally. The phenomenon is also called induction. The contrasting effect that a surrounding area has on a central test field seems to happen at once, but in reality it develops somewhat over time. A centre is affected by the colour and the *lightness* or *brightness* of its surround. A bright surround induces *blackness* into the centre. In fact, black is an induced contrast colour and not merely absence of light. A reddish surround induces greenness in its centre and so on (see also section 11).

Both achromatic and chromatic contrast effects are combined products of neurophysiological and psychological processes. That the contrast effect depends more on the surround than on the centre field can be proven by measuring the *CIE* (x,y) coordinates of the centre field by a spot photometer. Even for surround manipulations that display drastic contrast effects in the centre the measured (colourimetric) colour coordinates are constant.

To create coloured shadows: Two projectors; one with bluish light and one with white light. When an object is illuminated by the mixture of blue and white two shadows occur, the yellow one is only illuminated by white light and appear yellow through induction.

The induction process tells us that lateral interactions are taking place in the nervous system.

Notes to the instructor:

- Work with 2 projectors and start without using colour filters. An object illuminated by the two projectors will normally cast two similar "gray/white" shadows on the screen. They are somewhat different because of different colour temperatures of the light bulbs in the projectors (due to different age).
- One person makes a shadow by replacing the object with her/his own hand.
- Place a blue filter in one of the projectors. Instead of the expected one gray and one blue shadow, you will see a blue and a yellow shadow (adjust the relative intensities of the two lights to get a bright and saturated yellow colour).
- The longer you look, the stronger the effect will become (the phenomenon gets more prominent due to adaptation). If you replace the blue filter with, e.g. a red filter, the contrast colour on the screen will be greenish, despite the fact that physically it has not changed and a naïve observer would expect one shadow to become neutral white and the other one red.

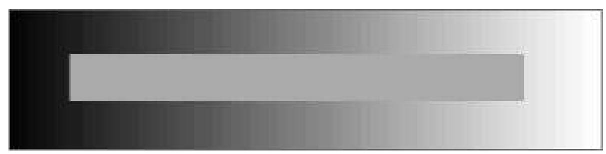

Fig. 10e Simultanious lightness contrast.

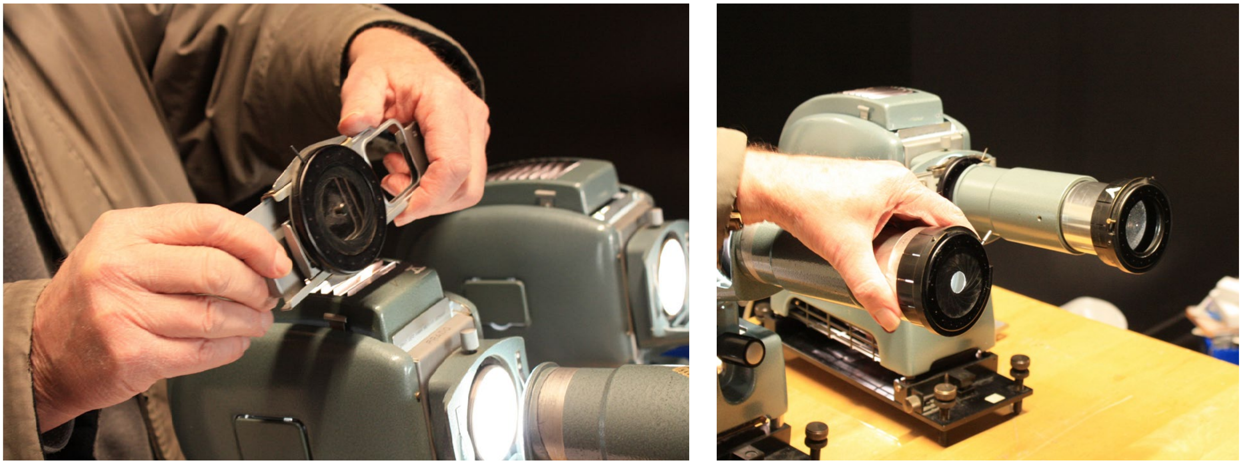

Fig. 11a

Fig. 11b

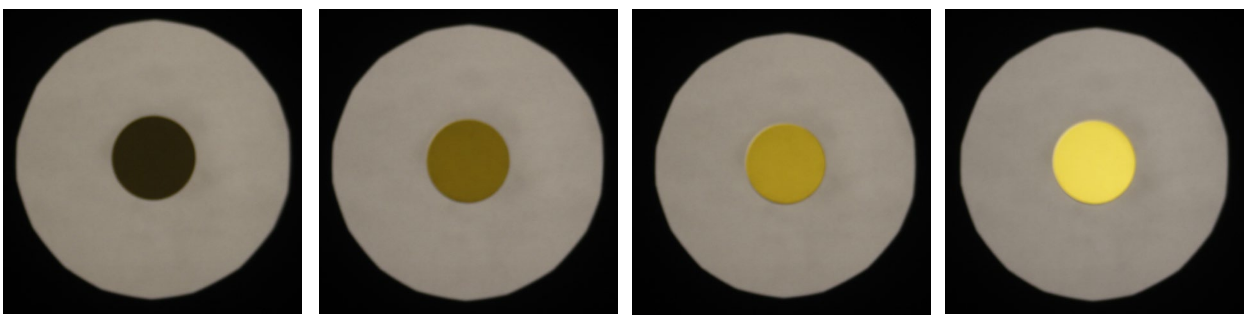

Fig. 11c

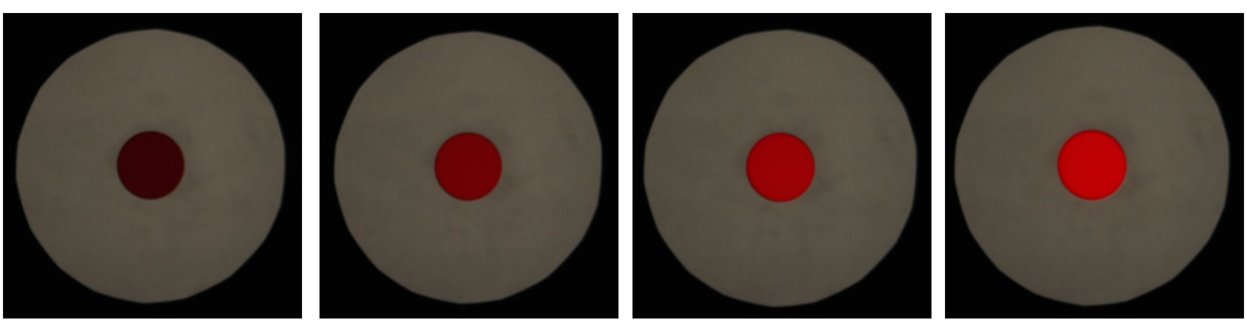

Fig. 11d

Figures to section 11: Fig. 11a Equipment to demonstrate centre- and surround effects.
Fig. 11b Disk with different luminance, from dark (left) to bright (right). Saturation changes as luminance increases.
Fig. 11c and d Disks in surrounds. *Related colours*. *Lightness* and *brightness* change *hue* and saturation in the centre disk.

11. CENTRE/SURROUND

11.1. Centre/Surround
Most of the *colours* in our natural environment come from reflecting surfaces of objects. According to Wilhelm Ostwald (1923), 99,9% of all colours in the natural environment were of this kind (in the 19th century), and he called them "*related colours*". They are also often called *object colours* in order to distinguish them from light sources. A striking feature of natural *related colours* is their *black-content.*

The same phenomenon of *related colours* can be observed with flowers like Ladies' delight (stepmother's flower). Some of them look close to black in the middle because, compared to the surround, little *light* is reflected here. But if you illuminate a small black area of the flower with a narrow pencil of bright white light, you will see a saturated chromatic colour that was masked by black.

Fig. 11c also illustrates the Bezold-Brücke effect. This effect is one where *hue* is influenced by the luminance ratio of the centre disk relative to its surround. In the example of Fig 11c the yellow disk turns greener as luminance ratio decreases

Notes to the instructor:

- Use the centre/surround diaphragm (Fig. B7 in the Appendix B) in the slide plane.
- The two projectors must be precisely adjusted. One projector projects a bright central disc and the other a surrounding annulus around the disc. The inner diameter of the annulus on the screen should be the same as the diameter of the disc.
- Reduce the *lightness*/*brightness* of the centre by increasing the light intensity of the surround only. A range of grays in the central disc will result – this is a series of "*lightness*". If we successively decrease the luminance of the surround, we get a series of "*brightness*" in the centre. This proves that grayness is an effect of the relative luminance between centre and surround, or between an area and its environment. *Colour*s that are affected laterally by a bright surround resemble "*related colours*" in nature.
- Put the yellow filter in the projector providing the centre field and manipulate the surround-projector's intensity and size. For bright surrounds, the yellow centre turns olive and finally "black".
- Block the surround projector (then no black will be induced into the centre field) and the centre field will turn yellow again. This demonstrates how a bright surrounding annulus affects the *perception* of light and *colour* in the centre through induction. You should also manipulate the outer diameter of the surround, its intensity, and its colour in order to observe the complicated behaviors of "*related colours*". From this we conclude that black is not just absence of light.

Fig. 11e

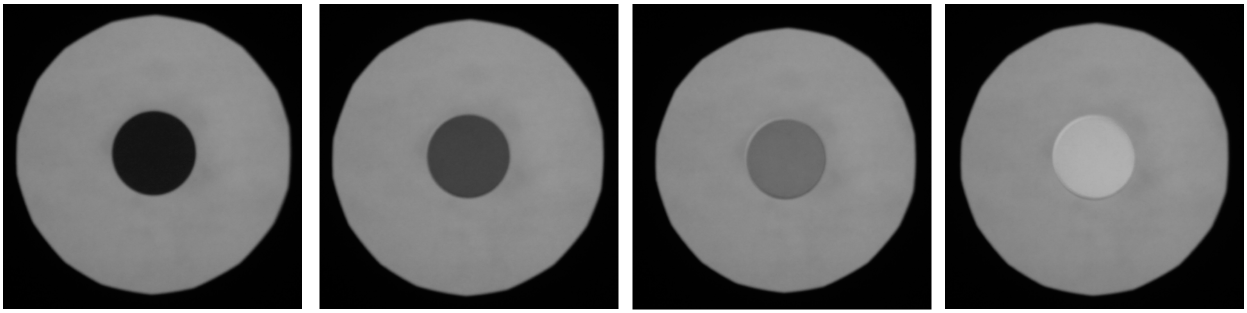

Fig. 11f

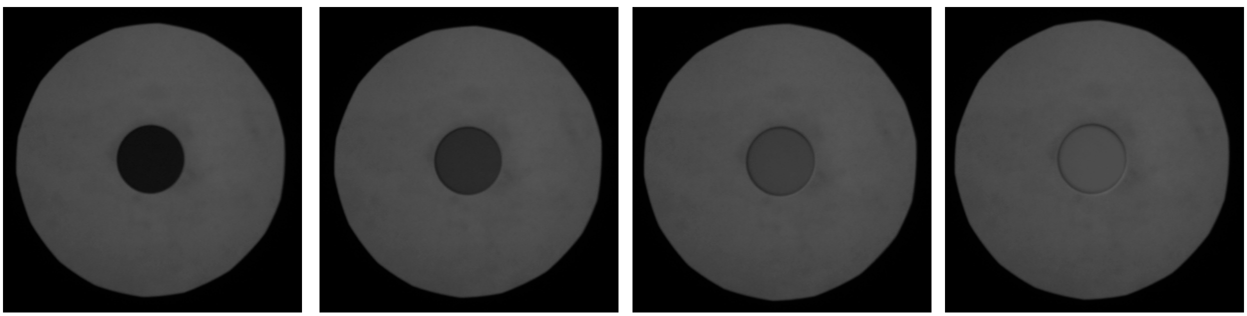

Fig. 11g

Fig. 11h

Figures to section 11: Fig. 11e, f and g The same figures as in page 18, here shown in black and white.
Fig. 11h Series of pairs of chromatic lights with the same lumninance, but different colours.
Note the *isoluminance* of Fig. 11d (far right) and 11g (far right).

11.2. Isoluminance
Isoluminance describes the situation when two different adjoining *chromatic colours* have the same physical luminance, measured in cd/m^2. Their appearance may in some cases remind us of fluorence (see section 13). This phenomenon has not been well studied, but it may be related to the fact that certain cell types in the human retina respond well to luminance borders and cease firing for borders between isoluminant stimuli.

Note to the instructor:
- Adjust the luminance of the chromatic centre and *achromatic* surround in the projected image on the screen and measure the luminance of centre and surround with a spot photometer. Adjust until there is no luminance difference.

11.3. Brightness/Lightness
Perceived intensity of a chromatic colour (of the same *chromaticity*) is often called *brightness*. At relatively low intensities and brighter surroundings, the colour contains black and the perceived intensity dimension is one of *lightness* (with *blackness* as its opposite).

Note that expressions such as *lightness* and *brightness* refer to qualities of *perception*, whereas intensity and luminance refer to a physical description.

12. FLUORENCE (NOT FLUORESCENCE)

A fluorescent surface has a *colour* coating of a higher luminance than those with a normal reflection *spectrum* (see section 5). A simple centre/surround demonstration can simulate the physical condition required for perceiving fluorence (the characteristic "shiny" appearance of a fluorescent surface). This demo proves that fluorence depends on the relative luminance between the object's surface and that of its surroundings. The visual impression is called fluorence (Evans, 1948). It normally appears for a luminance ratio greater than 1.0 between centre and surround, but is somewhat dependent on the centre's colour saturation (since the *brightness* of isoluminant colours is also dependent on their saturation).

13. OBJECT COLOURS

We have seen that characteristic appearances of *object colours* can be simulated and manipulated on a screen by a projected centre/surround pattern from 2 projectors. The centre can be coloured, as well as white. The familiar daylight appearance of *light* reflected from an object's surface can, for instance, be mimicked by the luminance of the centre field being lower than that of the white surround. When the centre field's luminance is lower than that of the surround, we have the typical viewing condition of reflecting *object colours* called *related colours* or *surface colours*. Both fields' luminance can easily be changed by *iris* diaphragms on the projectors' objectives.

The size of the surrounding area can also be changed, and size-effects on the *lightness* of the centre be demonstrated.

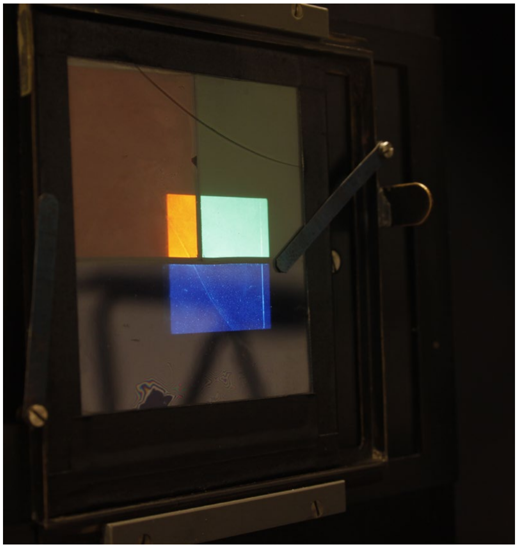

Fig. 14a

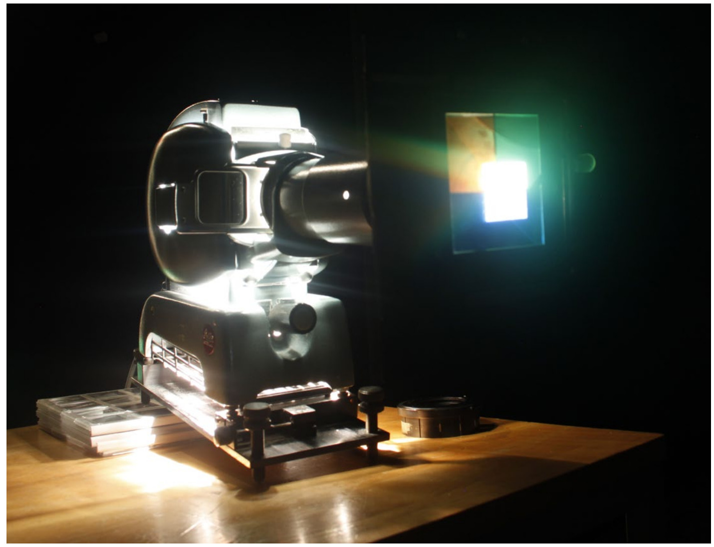

Fig. 14b

Fig. 14c

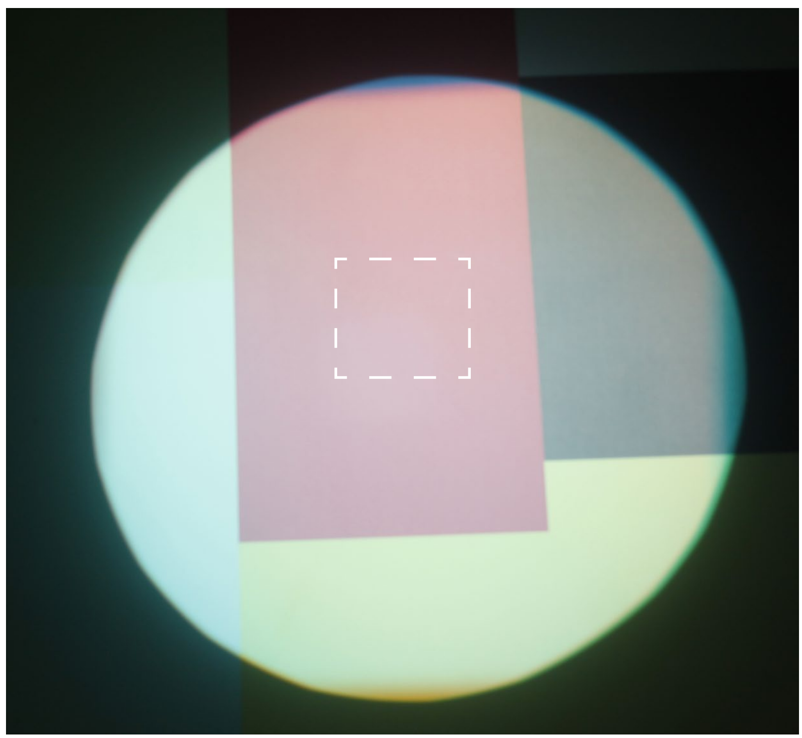

Fig. 14d

<u>Figures to section 14</u>: Fig. 14a and b Equipment used to demonstrate colour constancy.
Fig. 14c The square colour "window" in the black velvet appears to be white when seen in isolation.
Fig. 14d The greater Mondrian with the same square (the frame indicates the area) which is pink.

14. COLOUR CONSTANCY

Colour constancy is a process that allows us to see and recognize a familiar object as being of the same or similar colour, regardless of the colour of the illuminant (if it is indoor fluorescent light or outdoor daylight). *Colour constancy* works best if the incident illumination contains a relatively broad range of wavelengths (being not too far from white light). The ability of an illumination (e.g. a fluorescent lamp) to reproduce colours as seen in daylight is given by its colour rendering index (CRI). An CRI index of 90 or 95 is regarded as very good, whereas 80 is acceptable for most purposes.

The three different *cone receptor* cells of the eye register different ranges of wavelengths of the *light* reflected by every object in the visual scene. From this information, it looks like the visual system attempts to neutralize (adapt or subtract) the chromatic component of the illuminant (Land, 1959). This illumination is discounted in order for us to see the object's "true colour" when illuminated with white light (usually daylight). The pattern of areas in a Mondrian display plays an important role in this demonstration of *colour constancy*.

The experiment described below can be done using a spot spectrophotometer. It will prove that the centre's *chromaticity* coordinates (x,y) do not change when going from a small isolated centre field to a large field (from Fig. 14c to Fig. 14d).

Notes to the instructor:

- Use a Mondrian, one projector, a velvet board, and the x-y colour mixture frame.
- Show just one square colour "window" in the velvet, the others must be covered. The background must be completely black, and the room must be dark.
- The *light* coming from the projector should illuminate the coloured square "window".
- Change the position of the x–y, "colour mixture frame" on the projector until the reflected light from the square appears an acceptable white. Take away the black velvet to illuminate the Mondrian pattern by the same colour. The square patch that appeared white while isolated (Fig. 14c) and viewed in a dark surround, no longer does so. It has regained some of its appearance in daylight (Fig. 14d).

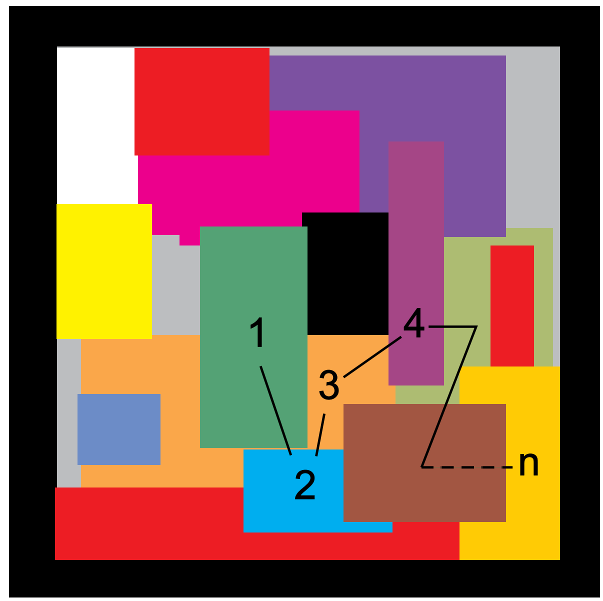

Fig. 14e A display similar to that used by Edwin Land to demonstrate his retinex hypothesis.

Fig. 15a

Fig. 15b

Fig. 15c

Fig. 15d

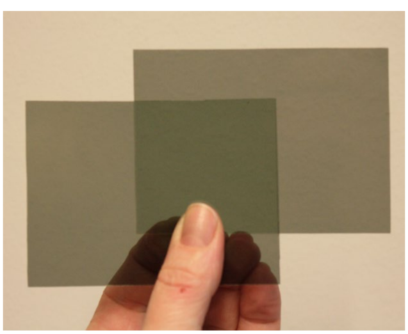

Fig. 16a

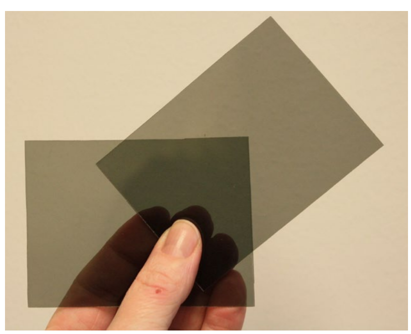

Fig. 16b

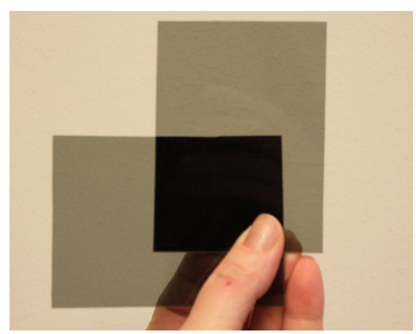

Fig. 16c

Figures to section 15: Fig. 15a and b Simulation of the effect of *cataract*. Reduction of chromatic and achromatic contrast after diffusion of the image, for example due to *cataract*.
Fig. 15c Street view as seen with healthy eyes. Fig. 15d Street view as seen with *cataract*.
Figures to section 16: Transparent polarization filters. The transparancy depends on orientation.
Figures to section 17: Fig. 17a A grating of the same spatial frequency, but different contrast.
Fig. 17b Gratings of different spatial frequencies (cycle/degree), but with the same contrast.

15. VIEWING THE WORLD WITH CATARACT

If you look through a diffusing medium (for instance a plastic foil or grounded glass), you will notice that *lightness* contrasts (of gray surfaces and shadows of a certain size) become much more reduced than chromatic contrasts of the same size (see Fig. 15). The vividness and distinctiveness of the remaining *chromatic colours* are striking – they stand out against a grayish wash of the background. *Chromatic colours* thus appear more independent and less attached to objects compared to how they appear with normal eye sight. This phenomenon resembles a visual ailment called *cataract* where the light scatter within the eyeball is caused by defects in the eye lens. Most people over 60 years of age show some sign of *cataract*. Today it can be removed by surgery where the old lens is replaced by a new one.

16. POLARIZATION

Light reflected from the wet road, from a calm water surface, from windows and from all sorts of glass is polarized (as in Polaroid sunglasses). Transmitted light is also polarized. In polarized light the amplitude of the electromagnetic vector has only one direction of oscillation whereas in un-polarized light all directions are present. The intensity of transmitted and reflected polarized light can be even more reduced by adding another filter. By using two transparent polarizing filters, one after the other in the light path, the intensity of the transmitted light will change depending on the angle of the two filters relative to each other (Fig. 16). Polarizing filters can therefore be used as light attenuators in optical instruments.

17. SPATIAL CONTRAST SENSITIVITY (VIGRA-C)

A computer with a particular graphics card, built by Thorstein Seim, has been programmed to test various visual functions, such as *achromatic* and chromatic spatial contrast sensitivity. This is done by determining contrast thresholds using sinusoidal or square wave gratings (where the contrast is periodically changed across the screen; see Fig. 17). The number of repeating periods on the screen is expressed in cycles/degrees. Simple forms like squares, circles, and rings can also be used.

Notes to the instructor:

- A test of *achromatic* achromatic and cromatic contrast sensitivity can be performed by changing the contrast of the pattern on the screen. The observer is answering yes/no for having seen, or not seen, a grating pattern. The high frequency domain consists of narrow stripes and can be used to determine the subject's limit of resolution in cycles/deg. Testing at a distance of 2 m usually gives optimal results. Subjects should not fixate the grating for too long because adaptation may cause the grating to vanish.

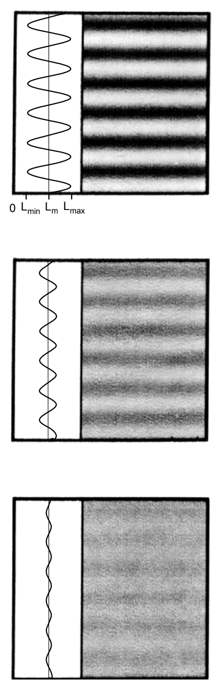

Fig. 17a

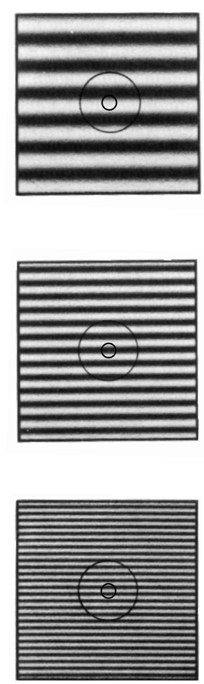

Fig. 17b

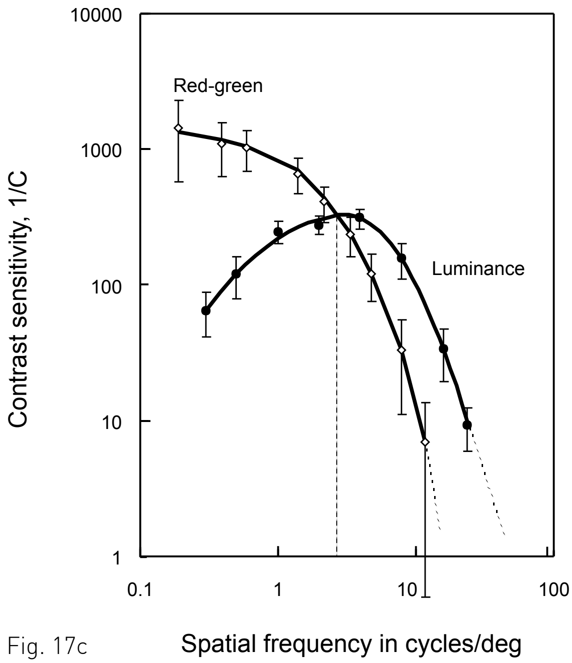

Fig. 17c

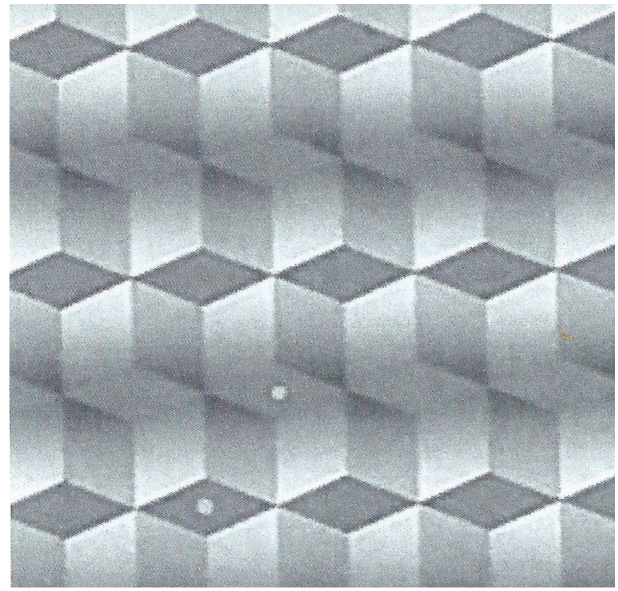

Fig. 18.1 Logvinenko illusion. The luminance of the two diamonds marked by a small circle is equal.

Fig. 18.2a

Fig. 18.2b

Figures to section 17: Fig. 17c Typical spatial contrast sensitivity for the detection of a static sinusoidal grating modulated either in luminance or in red-green *chromaticity* at *isoluminance*.
Figures to section 18.1: Fig. 18.2a Hand illuminated by a square light source.
Fig. 18.2b Illuminated by a cross-shaped light source.

18. ILLUSIONS

18.1. The Logvinenko Illusion
The small dots of Fig. 18.1 mark two surfaces in the figure that are physically equal in reflectance and thus have equal luminance (Logvinenko, 1999). This seems hard to believe, and it is one of the strongest illusions of *achromatic lightness* contrast known to us. The reason why the diamonds look so different is not clear. Note also that the dots themselves are influenced by contrast, in the same directions as are the diamonds on which they appear.

18.2 Shadow Effects
The geometrical form of the light source (if it is e.g. circular, elongated, or a square) is reflected in the form of the shadows of the objects it illuminates. For instance, a triangular light source produces a triangular shadow, even though the object that casts the shadow is circular (demo developed by Torger Holtsmark). Long fluorescent tubes form shadows that are different from spherical light bulbs. The border of shadows are important for recognizing their form, and here *Mach bands* play a role.

18.3 Mach bands
Mach bands have their name from the Austrian physicist Ernst Mach who studied them at the end of the 19th century. They denote the illusory contrast enhancement that occurs in the transition zone between a dark and a lighter stripe of *light* (Ratliff, 1965; Holtsmark and Wold, 1980-2005). Close to the border, a dark shadow will be locally darker while the lighter part becomes even lighter. This contrast enhancement is a perceptual phenomenon caused by neural processes in the visual system. It may offer an advantage to the viewer in that it compensates somewhat for the optical blur that always occurs in the eye (see Fig. 18.3).

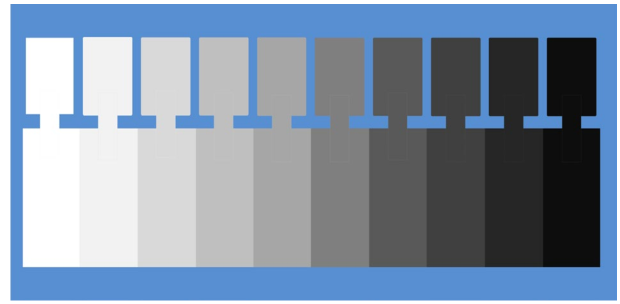

Fig. 18.3: *Mach bands*.

18.4. The Pinna Watercolour Illusion
The Italian psychologist Banjo Pinna has provided several illustrations where narrow coloured boundaries and enclosed areas influence an area's colour by spreading the border colour out into the interior of the figures (Pinna et al., 2001). This kind of diffusion of the border colour seems different from *simultaneous contrast*.

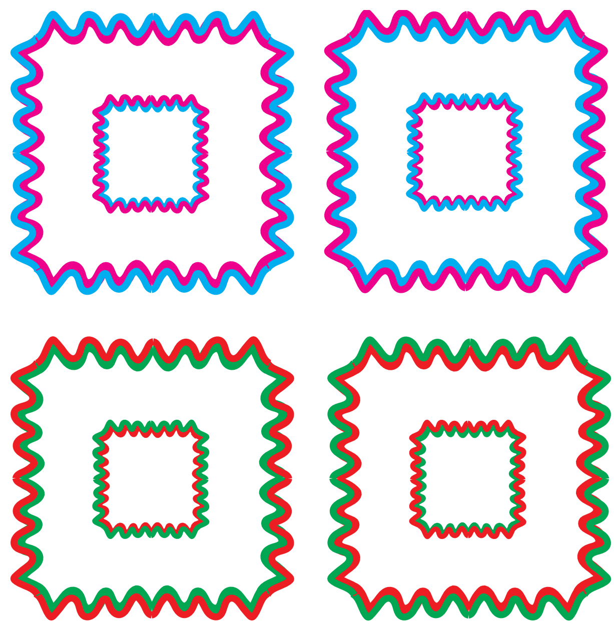

Fig. 18.4 Examples of watercolour illusions. Colours spread within the frame.

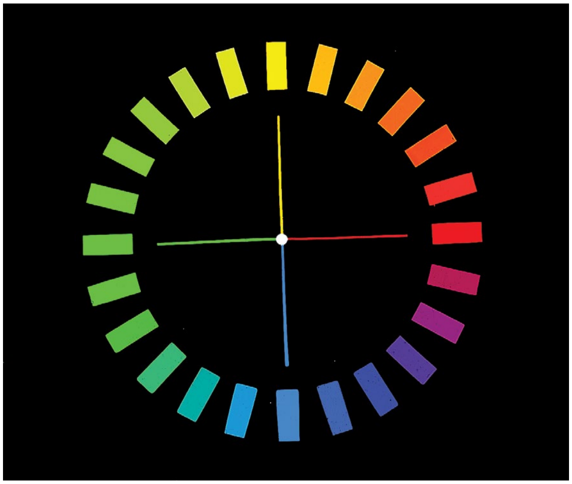

Fig. 19.1

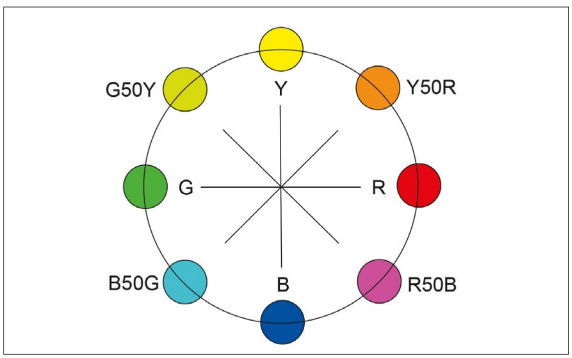

Fig. 19.3a

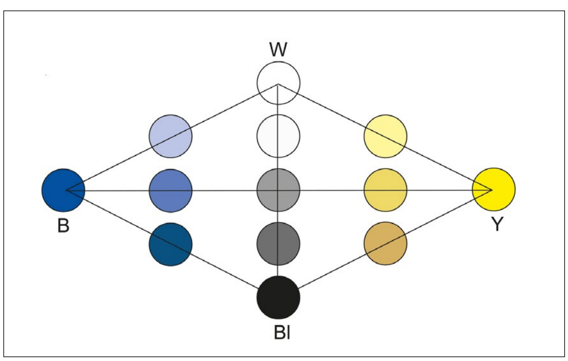

Fig. 19.3b

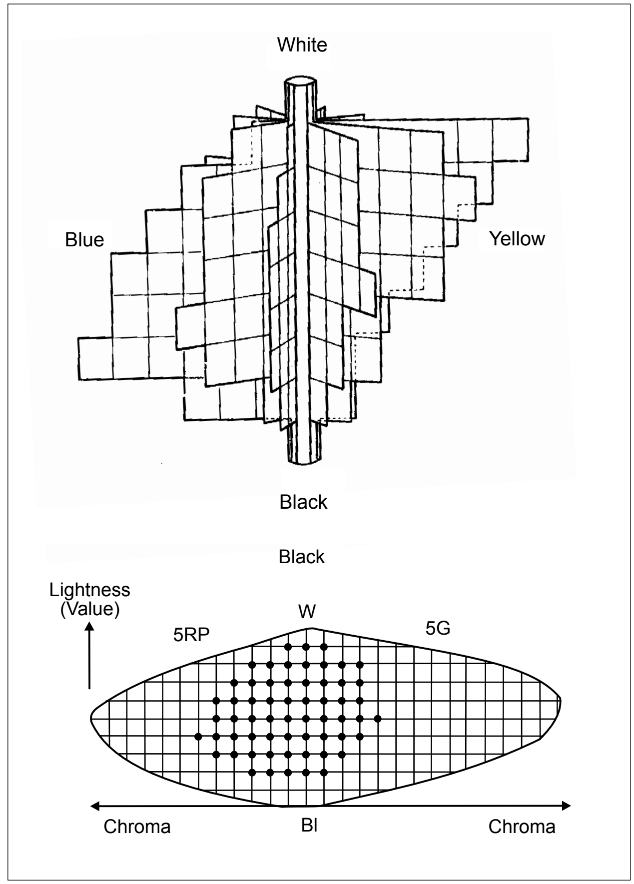

Fig. 19.2

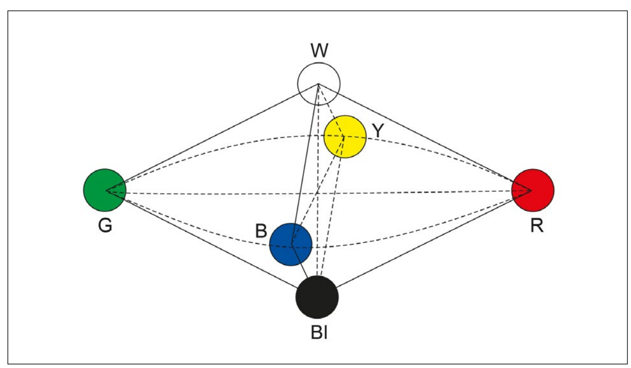

Fig. 19.4

Fig. 19.1 The symmetric Miescher *hue* circle with 24 steps. Opposing unique *hues* on the axes.

Figure to section 19.2: Top The three-dimensional arrangement of colour chips in the *Munsell system*. Bottom The colours in a *hue* plane of the *Munsell system*.

Figures to section 19.3: Fig. 19.3 A *hue* circle with the elementary *hues* Y (yellow), R (red), B (blue) and G (green) on the axes.The *hues* in between contain proportions of the two nearest elementary hues. Fig. 19.3b *Hue* plane of the colour solid.

Figure to section 19.4: A three-dimensional colour solid in the form of a double *cone*.

18.5. The Wright Illusion
The Wright illusion displays a remarkable strong *simultaneous contrast* effect, and the complex lateral interactions behind it are not fully understood. Blue and yellow stripes in a grating are overlaid by a red, a green and a grey square. The square changes appearance dependent on which stripe it is on and with the distance to the observer (changing the angle of view).

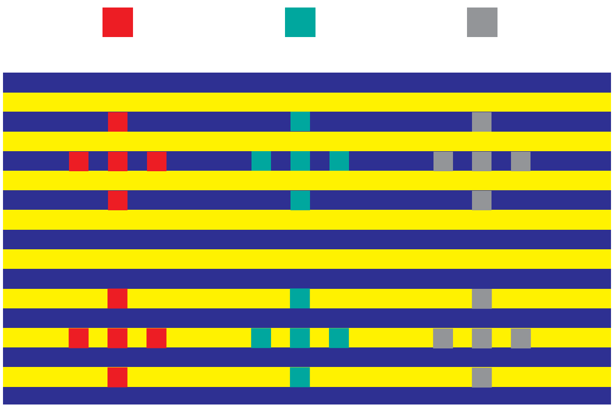

Fig. 18.5 The Wright Illusion.

19. THE PRINCIPLES OF COLOUR ORDER SYSTEMS
Colour systems have been developed in an attempt to order the abundance of colours, not only for commercial paints, but also for those found in nature. Colour systems can be psychological, based on human *perception*, or physical based on measured colourimetric properties. For instance, *hue* is a perceptual reality, while wavelength is the corresponding physical entity. Equally, *lightness* or *brightness* are perceptual, whereas luminance and luminance ratio are physical magnitudes. Precise language requires that this difference is kept in mind.

19.1 The CIE XYZ Tristimulus Colour Space
The colour matching space of the International Commission on Illumination (*CIE*) is based on *trichromatic* colour matches and uses the tristimulus coordinates X, Y, and Z, and the *chromaticity* coordinates x, y, z developed from them. A common way to characterize colours within this linear system is by (x,y,Y), where Y represents the relevant photometric unit, such as luminance in cd/m2. x = X/(X+Y+Z) and y = Y/(X+Y+Z).

19.2. The Munsell System
The coordinates of the *Munsell system*, as exemplified in the Munsell Book of Colours, are *hue* (H), chroma (C) and Value (V). Equal steps in each of these three dimensions represent the same visual difference by good approximation. *CIE* has developed a non-linear, opponent transformation of X, Y, and Z called (L, a, b) to represent the *Munsell system*.

19.3. The Ostwald coordinates
The German chemist Willhelm Ostwald, like the Scottish physicist James Clerk Maxwell, used a spinning disk to study *additive colour mixtures*. With three colour sectors w (white), s (black), and c (chromatic colour) on the rotating disk, a mixture of all three fractions could be written as c + w + s = 1, where the w, s, and c represented the angels or relative areas of each colour in the mixture. The mixture can be represented in a triangle (Fig. 7.6b).

19.4. The Natural Colour System
The *NCS* system is a subjective scaling system based upon the German physiologist Ewald Hering's original idea of *opponent colour* processing in the neural system. It uses *hue* (H), chromaticness (C) and *blackness* (S) as the basic coordinates. The basic *opponent colours* are red – green, yellow – blue, and white - black. Like for the Ostwald colourimetric system, perceived colours can be represented mathematically in a triangle of constant *hue*. Within the triangle C + W + S = 1 chromaticness C and *blackness* S are the basic coordinates.

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21. TECHNICAL COMMENTS

Appendix A: Glossary

Words/expressions	Explanation
Accommodation	Changing the eye's focus from far to near by decreasing the radius of curvature of the lens. Expressed in diopters. The ability to accommodate is more critical at low light levels than in bright light (due to the reduced depth of field when the pupil expands).
Achromatic	Not chromatic.
Achromatic colours	Colours with no chroma; i.e. black, grey and white.
Adaptation	The ability of the visual organ to adjust its sensitivity and function to the prevailing light level and colour. The term can be used for the process itself or for the final state. The retina is said to be light adapted (corresponding to *photopic vision*) or dark-adapted (scotopic vision). The size of the pupil plays only a minor role in adaptation.
Additive colour mixture	When two or more coloured lights are added (overlaid), either on a screen or otherwise superimposed on the retina.
Bandwidth	Range of wavelenghts (or frequencies) represented in a stimulus, or to which a system is sensitive.
Bezold-Brücke phenomenon	The *hue* of a colour stimulus of constant *chromaticity* changes when its luminance changes.
Blackness	Blackness is a property of reflecting *object colours*. It depends on the luminance ratio of a target relative to its surround.
Border colours	Colours that arise at black and white borders due to *dispersion*, e.g. by a prism or an imaging lens. When the beam of light is too wide to produce a *spectrum* of *monochromatic light* upon refraction, a partial *spectrum* of *optimal colours* may still be seen at black and white borders.
Blind spot	A spot in the monocular visual field that is blind because it corresponds with the position on one retina where the nerve fibers leave the eye, and where there are no photoreceptors.
Brightness	Apparent amount of light emitted by a surface.
Cataract	An ailment of the optic media of the eye. The eye lens becomes less clear and the imaging on the retina more diffuse. Removing the eye lens and replacing it with an artificial lens is now a routine operation in this situation.

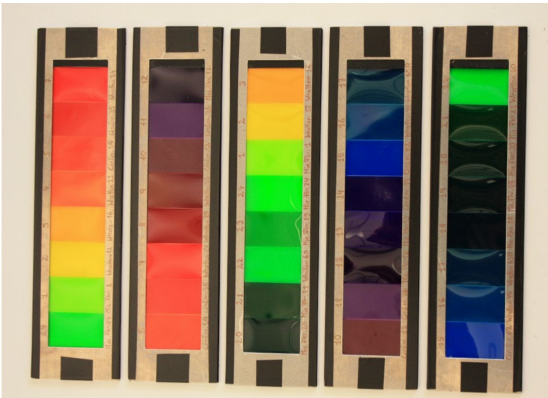
Words/expressions	Explanation
CIE	Commission Internationale de l'Eclairage (french). International Commission on Illumination (english).
Chromatic adaptation	The self-adjustment of the visual system to the colour of the prevailing illumination in such a way that object-surfaces appear to have the same colour for all daylight phases and for most artificial lights. The visual system works towards neutralizing (in a still unknown way) the effect of the colour of the illumination. For example, a white surface appears white even if the illumination changes from bluish daylight to yellowish incandenscent light. See Colour constancy.
Chromatic colours	Colours are divided into achromatic colours (black, greys, and white) and chromatic colours (yellow, red, blue, green and their transitions).
Chromaticity	Two dimentional colour coordinates (r,g) in a unit colour triangle R+G+B = 1, or the (x,y)-coordinates in the *CIE* system for colour measurement, in a plane where the sum of *tristimulus values* X+Y+Z = 1.
Chrominance	Colour stimuli of equal luminance are characterized by their chrominance and luminance ratio. Chrominance is their difference in *tristimulus values* divided by the luminance.
Complementary colours	Pairs of colours that yield white in an *additive colour mixture*.
Cone	*Receptor* cell in the retina that operates at photopic light levels
Colour	Physical: Electromagnetic radiation between 380 and 780 nm. Psychological: Perceptual quality characterized for instance by yellow, red, blue, green, white and black.
Colour constancy	To see and recognize a familiar object as being of the same or similar *colour*, regardless of the colour of the illuminant.
Colourimetry	Measuring of *colour*.
Dispersion	The index of refraction, n, of a medium (e.g. glass, water) varies with the wavelength of light. The refraction at the boundary between two translucent media (glass and air, for example) is therefore wavelength-dependent. White light that is refracted by a glass prism gives rise to a *spectrum* where the short wavelengths are refracted more than the long ones. One consequence is that images of white/black borders produced by a simple lens have coloured borders (see *Border colours* and *Spectrum*).

Words/expressions	Explanation
Elementary colours	Six particularly simple *colour* qualities (approximate wavelength in brackets): Black, White, Yellow (ca. 570 nm), Blue (ca. 470 nm), Green (ca. 500 nm), and Red (approx. complementary wavelength 495 nm). Also called unique colours.
Hue	The *hue* of a *colour* can be characterized by relative proportions of the closest elementary hues yellow, red, blue and green. They can be ordered along a hue circle.
Interference filter	Colour filter with a relatively narrow wavelength range of light transmission. Characterized by spectral half-width in nm at 50% transmission.
IR	Infrared electromagnetic radiation of wavelengths above 780 nm.
Iris	A smooth muscle ring controlling the size of the pupil. "The colour of the eye". Eye colour depends of the amount of pigment in the iris. Blue eyes have little pigment and brown eyes have more pigment.
Isoluminance	A situation where different *colour* stimuli have the same luminance.
Light	A stimulus that gives a visual sensation. The visible range of the electromagnetic *spectrum* is from 380 nm to 780 nm.
Lightness	The visual attribute by which one can tell if a surface reflects more or less *light*. A visual impression of intensity that increases with increasing reflectance factor.
Mach bands	The (illusory) enhancement of *lightness* contrast across contours arising from a luminance difference between two adjacent areas.
Metameric colour	*Colour* stimuli that match in colour appearance, but have different spectral distributions.
Monochromatic light	Radiation with a narrow wavelength distribution, ideally a single wavelength.
Multiplicative colour mixture	Colour mixture where *light* is absorbed in successive pigment layers. For instance, when light passes first trough a yellow filter and then trough a blue filter, light energy is removed from the path by every new filter, and the resulting spectral distribution is obtained by multiplying the spectral distribution of the incident light by the spectral transmission factors of each new pigment. See *additive colour mixture*.
Munsell system	A colour atlas that approximates the ideal of all neighboring colour chips having the same percieved colour difference. The coordinates of the system are chroma (colour strength), *hue* and value (*lightness*).

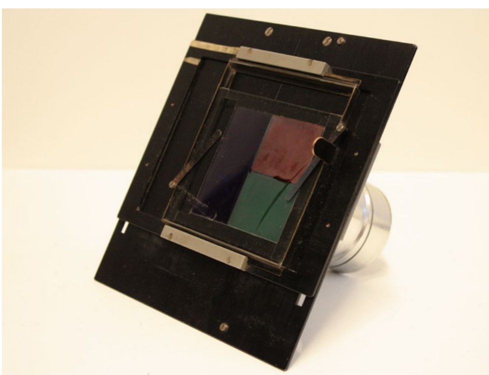
Words/expressions	Explanation
Natural Colour System, NCS	The Natural Colour System uses a perceptual scaling based on the relative proportions of unique colours. Colour differences are therefore not equal everywhere in the NCS colour space (as in the *Munsell System*). The cordinates are *hue*, chromaticness, and black content.
Object colours	Colours of reflecting surfaces (or of *related colours* viewed in lighter surroundings). In contrast to the colours of light sources, object colours posess a black component induced by a surround of higher luminance (e.g. a white reflecting surface).
Opponent colour	Opposite *elementary colours*. For example yellow and blue (there are no colours that are both yellow and blue at the same time). Red and green is another pair.
Optimal colours	*Object colours* that have a spectral distribution with only one step from 0 to 1.0 (or from 1.0 to 0) in their spectral distribution.
Perception	Subjective qualitative experience or impression of some sensory input (internal representation). Can also be used for our understanding and comprehension, and is therefore sometimes linked to hypotheses and interpretations of sensory information about the environment.
Photopic vision	Daylight vision at light levels where the rods are not active (above about 10 cd/m^2.
Photometry	The science of *light* measurement.
Primary colours	This is a term often used for the colours in a colour mixture (in additiv mixtures it is for practical reasons often red, green and blue, but in principle other combinations can be used as well).
Receptor	A neural element that transforms one type of energy to another. Most sensory cells respond selectively to specific physical stimuli, such as pressure, *light*, temperature, etc. Photoreceptors are excited by the absorption of light quanta and transform this energy into a change in the electric potential across the cell membrane.
Related- and unrelated colours	The appearance of chromatic stimuli undergo changes in *lightness*, *hue* and chromatic strength depending on the luminance of their surroundings. Object or surface colours that are viewed in a well illuminated, natural environment are examples of related colours. Since they are all darker than a white surface, they have some degree of induced *blackness*. Blackness is in itself a typical related colour. The term unrelated colour refers to the appearance of *light* sources, of bright colours viewed in the dark. They are sometimes called void colours. The luminance ratio between a surface and white (the reflection factor) determines whether its colour is related or unrelated.

Words/expressions	Explanation
Simultaneous contrast	Mutual interactions between adjacent areas and figures within the visual field. Black and grey colours are typical examples of simultaneous contrast where bright surrounds affect areas of lower luminance. Simultaneous contrast is active within the *lightness* domain (*related and unrelated colours*) as well as within the chromatic domain (coloured shadows, colour induction). Within the spatial domain it gives rise to size illusions.
Spectrum	A spatial distribution of the wavelengths of electromagnetic radiation. The visible spectrum ranges from 380 nm to 760 nm and is usually produced by *dispersion* in a prism or by interference in a regular grating pattern.
Subtractive colour mixture	See *Multiplicative colour mixture*.
Trichromatic colour vision; trichromat	Normal colour vision with all *cone* types intact; a person with normal colour vision.
Tristimulus values	Three numbers for the amount (vector length) of three basic colour stimuli (often called primaries) that match a test colour in an *additive colour mixture*. In the *CIE* 1931-system the tristimulus values have the notation X, Y, and Z. They apply to a specific triplet of (virtual) primaries.
UV	Ultraviolet radiation with a wavelength shorter than 400 nm. UV is divided into three wavelength ranges; UV-A (315 nm - 400 nm), UV-B (280 nm - 315 nm), and UV-C (100 nm – 280 nm).
VIGRA	A specific 3x10 bit computer display system (VideoGRAphic system developed around year 2000 by Torstein Seim and Arne Valgberg) for the presentation and manipulation of a variety of visual stimuli on a colour monitor

Appendix B: Equipment for Colour Demontrations



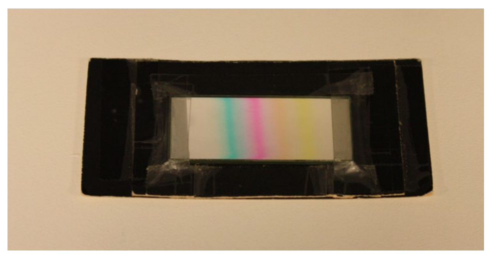
B1. 24-step colour circle to be used together with the filter holder of Fig. B8. Developed by Karl Miescher.



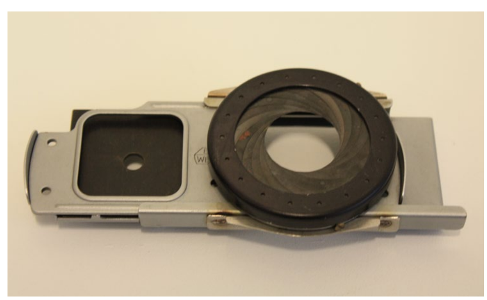
B2. Colour Mixture x-y Frame

B3. Projector Lamp

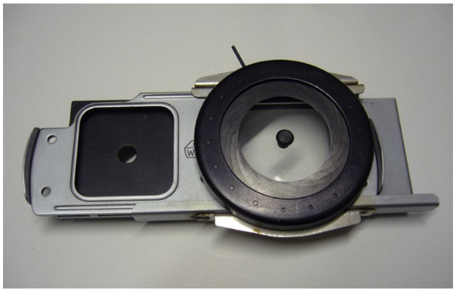
B4. Index Colour Filter



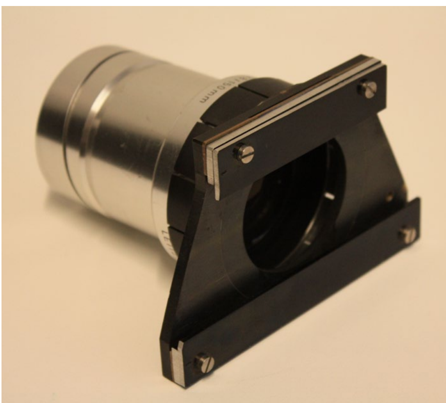
B5. Interference Filter



B6. Iris Diaphragm and Slide

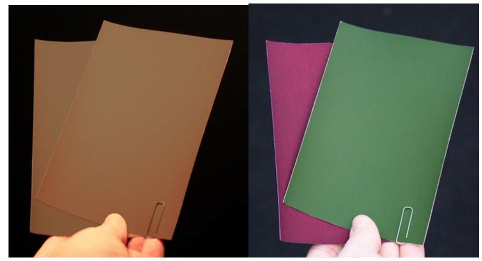


B7. Annulus



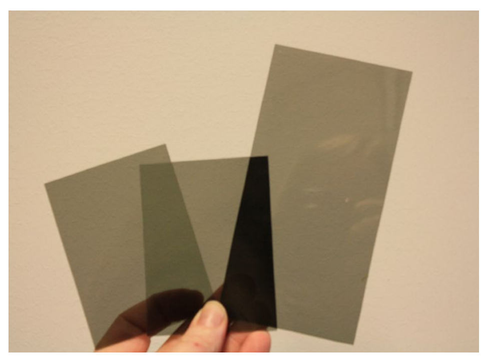
B8. Filter Holder

B9. Magnifier Lens



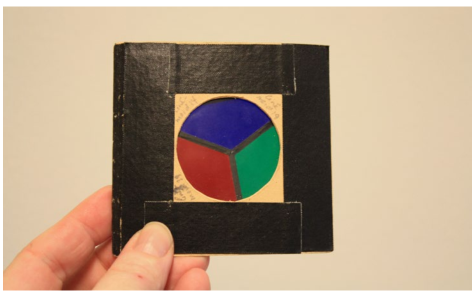
B10. Metameric Pairs

B11. Prado Objective

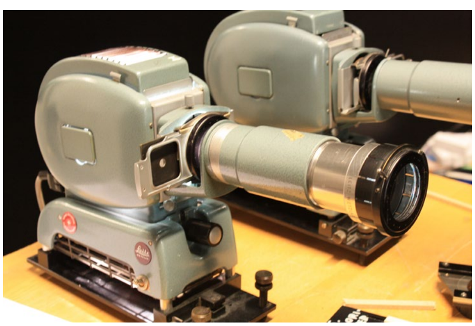


B12. Polarizing Filters

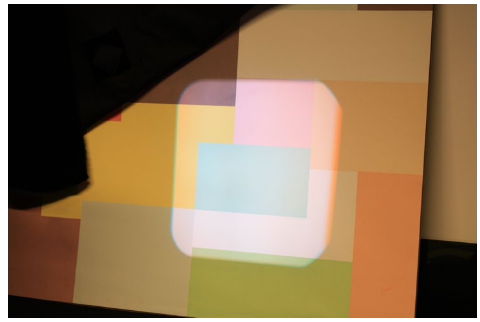
B13. Spectroscope



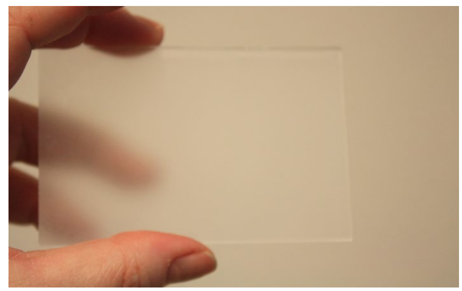
B14. Tri-prism



B15. Projectors



B16. Mondrian Board



B17. Light Diffusing Glass

22. About the Author and the Editors

Biography of Arne Valberg, professor emeritus, Institute of Physics, NTNU (Author)

Arne Valberg was trained as a physicist first in Oslo, Norway, and then in the Karl Miescher Laboratory for Colour Metrics in Basle, Switzerland. He also spent half a year in Prof. Bob Boynton's laboratory in La Jolla, California, and between 1974 and 1990 he was a visiting scientist at Lothar Spillmann's laboratory at the Neurophysiologic Clinic in Freiburg, Germany, under Prof. Richard Jung. In the 1980ies, as a visiting professor at the Max-Planck Institute of Biophysical Chemistry in Göttingen under Prof. Otto D. Creutzfeldt, he became closely associated with professor Barry Lee's laboratory. In 1990 he became a professor of Biophysics and Visual Science at the University of Oslo, and in 1993, professor of Visual Science at the Norwegian University of Science and Technology (NTNU) in Trondheim. There he was charged with building a Low Vision Laboratory in collaboration with Tambartun Centre and also became engaged in establishing a national centre for neuroscience. He thus paved the ground for a Center of Excellence in Biology and Memory and in 2008 the Kavli Institute of Neuroscience (directed by the Nobel Prize laureates May-Britt Moser and Edvard Moser).

Valberg has published 3 books, several book chapters and more then 100 papers in international scientific journals (Nature, Science, Proc. Royal Soc. London, J. Physiol., Exp. Brain Research, J. Neuroscience, J. Visual Neuroscience, JOSA, Vision Research, Amer. J. Physics, Colour Research and Application, Applied Optics) on experimental and theoretical as well as applied aspects of colour science. For a quarter of a century Valberg has been the national representative of Norway in Division 1, Colour and Vision of the Commission Internationale de l'Eclairage (CIE) and has been member of several technical committees. He is an elected fellow of the Optical Society of America and was in 2009 winner of the AIC Judd award.

Biography of Bjørg Helene Andorsen, Master Student of Architecture, Department of Architectural Design, Form and Colour Studies, NTNU (Editor)

Bjørg Helene Andorsen is currently a Master student of Architecture at the Norwegian University of Science and Technology (NTNU) in Trondheim.

She participated in the "Lighting for Learning" workshop with A. Buckley from Helen Hamlyn Centre for Design, Royal College of Art, London, that took place at NTNU, Trondheim in 2014.

In the pilot project "Colours in Trondheim" in 2014 she excecuted the colour registration of selected streets of Trondheim (as acknowledged in the proceeding of Angelo, Kine; Booker, Alex: "Meeting New Challenges in Colour Tendencies in Norway", presented under AIC 2015 TOKYO "Color and Image").

Biography of Kine Angelo, Interior Architect and Assistant Professor, Department of Architectural Design, Form and Colour Studies, NTNU (Editor)

Kine Angelo trained as an interior architect at Bergen Academy of Art and Design and has twenty years of practice, specializing in colour design in architecture. She joined the Department of Building Design, Form and Colour at Faculty of Architecture and Fine Arts, NTNU in 2010. In her work she operates on the interface between research and application. As practitioner and researcher; she is giving lectures and workshops for educational institutions, organizations, companies and municipalities.

As a representative from NTNU she has been guest lecturer at several courses on all levels, mainly teaching colour in architecture, colour theory, visual *perception* and NCS. She is coordinating and teaching several master courses, and she is the responsible teacher for the master course Architectural Design with Light and Colour. She co-organized the Research Day - "Light and Colour" in 2011, the international PhD-course "Nordic Light and Colour" in 2012 and 2015, Light and Lighting workshop with Helen Hamlyn Centre for Design, Royal College of Art in London in 2013.

She has been a scientific researcher in the project Translucent Facade, initiated by the Norwegian Research Council, and in the Nordic SYN-TES project "Glazing", sponsored by Konstfack et. al. She is regularly featured in articles and magazines regarding colours in interiors and exteriors, and in 2012 she gave an oral presentation of the paper Colour shifts behind Modern Glazing, at the AIC conference in Taiwan.

In 2014 she co-organized the exhibition and international conference "Colour in the City", and initiated "Colours of Trondheim", a pilot project together with Trondheim Municipality which resulted in a public archive and guideline for façade colours in Trondheim. She was accepted for oral presentation in AIC Tokyo 2015 with the paper Meeting New Challenges in Colour Tendencies in Norway.

Kine Angelo is a board member of the Light & Colour Group at NTNU and Forum Farge (AIC Norway).

Biography of Barbara Szybinska Matusiak, Professor, Architect MSA, Ph.D., Head of Light & Colour Group at NTNU, Department of Architectural Design, Form and Colour Studies, NTNU (Editor)

Professor Barbara Szybinska Matusiak is trained as architect from the Technical University of Lodz, Poland. She has seven years architectural practice, mostly from Norwegian architectural offices; during this period she won several closed architectural competitions in Norway. She joined the Faculty of Architecture at NTNU in 1994 as a research fellow. Her doctoral project was devoted to daylighting in linear atrium buildings at high latitudes (finished 1998).

Since then she has been involved in many Norwegian and international scientific projects dealing with daylighting and artificial lighting in architecture, e.g. project manager of the "Visual environment in apartment buildings", project leader for the bilateral Polish-Norwegian scientific project STEP, partner of the "Translucent façade" project and member of the SYN-TES, the Nordic network. Currently she is the head of two projects: "DayLighting" and "HOME, holistic monitoring of building environment".

She is also strongly involved in the activities of the international organizations: CIE, AIC and IEA and is the member of the CEN international group working on the proposal of a new European standard for daylighting in buildings.

She designed the artificial sky and artificial sun for the daylight laboratory (constructed 2000-2002, redeveloped in 2015) and the newest version of the full-scale room laboratory ROMLAB (finished 2006).

Her teaching activities (master courses) are devoted to daylight, artificial light and colour in architecture. She is the supervisor for 4 PhD-candidates at the Faculty of architecture and is organizing the international PhD-course: Nordic light and colours. She has been opponent for many PhD-projects and reviewer for international scientific journals and conferences.

She has established Light & Colour Group at the Faculty of Architecture at NTNU in 2011 and has been guiding the group since then.

www.ntnu.edu/bff/lightandcolour

Biography of Claudia Moscoso, Ph.D. Candidate, Department of Architectural Design, Form and Colour Studies, NTNU (Editor)

Claudia Moscoso is trained as an architect by the Ricardo Palma University in Lima, Peru; where she obtained the title of Professional Architect.

She is a member of the Architects Association of Peru. She has wide professional experience in the development and management of architectural projects, being responsible of small and large scale projects in her home country and in the US.

She is currently a PhD Candidate at the Norwegian University of Science and Technology (NTNU) in Trondheim. Her doctoral research use advanced visual equipment to focus on the impact of daylight on the aesthetic perception of architecture.

Moscoso has published papers in international scientific journals, and articles in popular magazines related to light and light design. She has also given several oral presentations in institutions, colleges and universities both at national and international level.

Her research interests are daylighting, daylight in architecture, light and colour in architecture, stereoscopic imaging, and light and environmental aesthetics.

She is now an active member of the Light and Colour Group at NTNU.

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