

Measuring colour in a world of light



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Measuring colour in a world of light

ADMESY

Admesy's 'Measuring colour in a world of light' is intended to provide basic knowledge to everyone who is interested in light and colour measurement. This guide explains the terminology of light supported by background information about measurements and equipment. Additionally, different models for light and colour communication and a number of application areas are explained.



The
power
of light

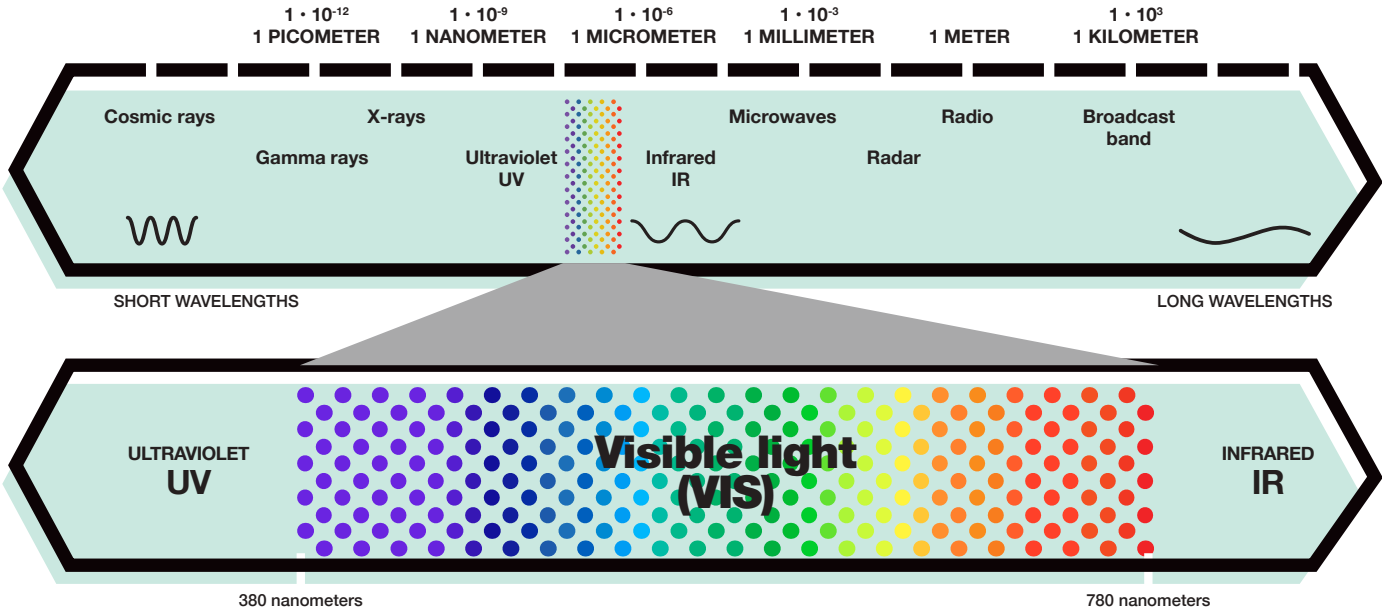
The power of light



2.1 WHAT IS LIGHT?

From a biological perspective light is energy that triggers the human eye and brain. The combination of light, eye and the brain provides sight. In physics light can be described according to two different theories: one theory defines light as particles and the second as waves. From the perspective of measurement equipment such as spectro[radio]meters which measure light in wavelengths, the second theory is the most applicable to explain light. For this reason, this guide focuses on wave theory.

Wave theory states that light can be understood as a form of energy in the electromagnetic spectrum. This spectrum encloses energy at different wavelengths of which only a small part ranging from roughly 380 to 780 nanometers is visible to the human eye. The ranges just below 380nm and just above 780nm are known as ultraviolet [UV] and infrared [IR] respectively. Although beyond the visual capabilities of the human eye, these wavelength ranges are also considered as light. The illustration shows the visual spectrum in perspective of the entire electromagnetic spectrum and its wavelength ranges.



THE ILLUSTRATION SHOWS THE VISUAL SPECTRUM IN PERSPECTIVE OF THE ENTIRE ELECTROMAGNETIC SPECTRUM AND ITS WAVELENGTH RANGES.

ULTRAVIOLET
UV
380NM
UV A-B-C

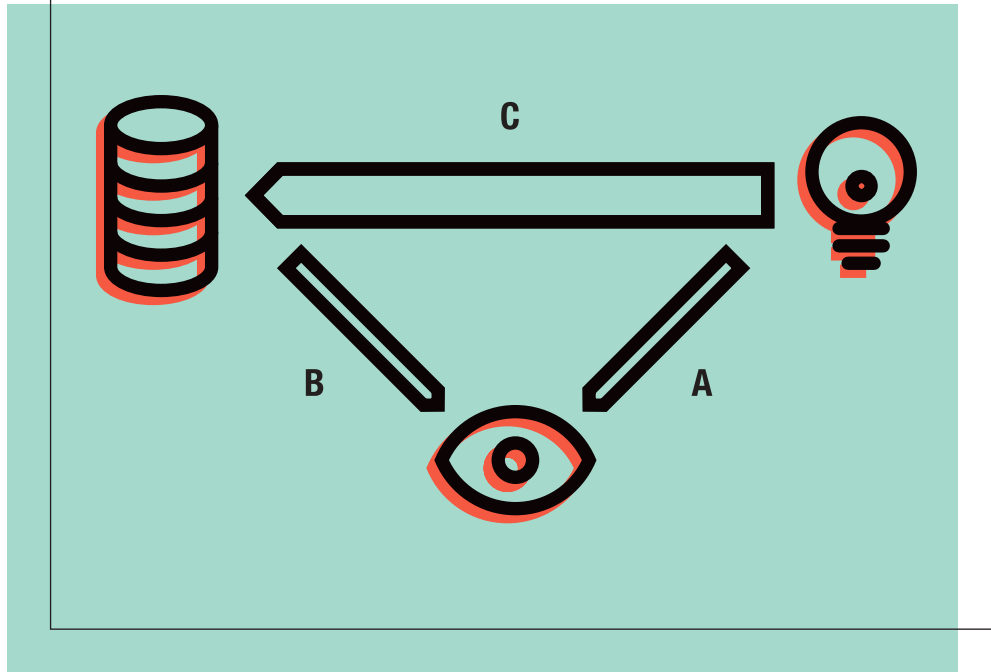


VISIBLE LIGHT
(VIS)
380NM-780NM
DISPLAY,
LIGHTING



INFRARED (IR)
780NM
THERMAL
RADIATION





LIGHT IS ONLY VISIBLE when looking either directly at a luminous object, for example a lamp, or when looking at illuminated objects that reflect light from a source. For example: in an entirely black room with a light source on one side and an object on the other as shown in the illustration. When looking into the light source, the eye detects light coming directly. This light from the source is visible [A]. Light from the light source reflecting on the object [B] reaching the eye is also visible. The reflecting light makes the object visible. When looking straight ahead no light is visible [C], although the light rays pass by: one would be staring at a black wall.

LIGHT

The power of light

2.2 MEASURING LIGHT

Light measurements can be carried out using various optical systems or geometries. For example, to measure the total power [flux] of a light source in all directions, in a certain direction or falling upon an area. The required optical configuration of a measurement setup depends on the unit of power which is measured. Three widely used optical configurations are integrating spheres, cosine correctors and lenses.

2.3 OPTICAL CONFIGURATIONS



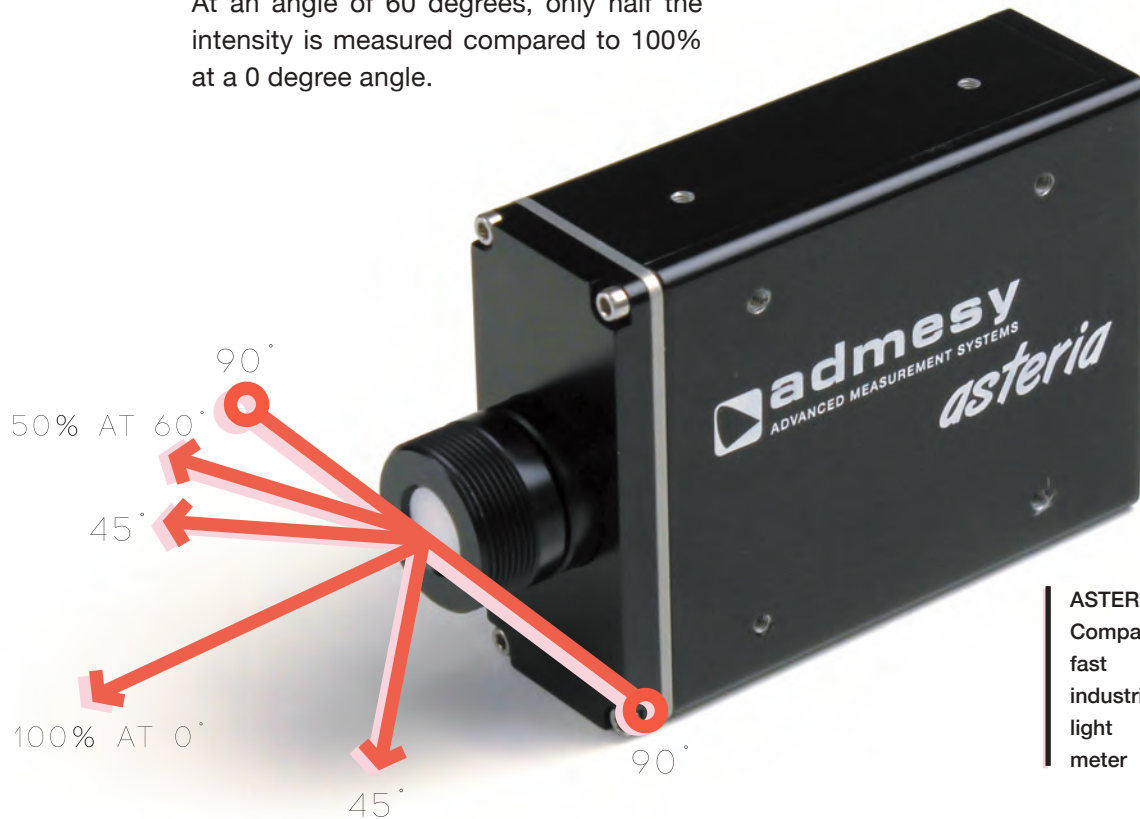
2.3.1 INTEGRATING SPHERE

An integrating sphere is a hollow spherical cavity covered with a highly reflective, diffuse white coating. The purpose of an integrating sphere is to make radiation in all directions diffuse by scattering and reflecting emitted light multiple times. Typically, spectroradiometers are connected to integrating spheres to measure the quantity and characteristics of the light source under test. Integrating spheres come in various sizes depending on the dimensions, construction and power output of a light source.

SPECTRORADIOMETERS
CAN BE
CONNECTED
TO INTEGRATING
SPHERES

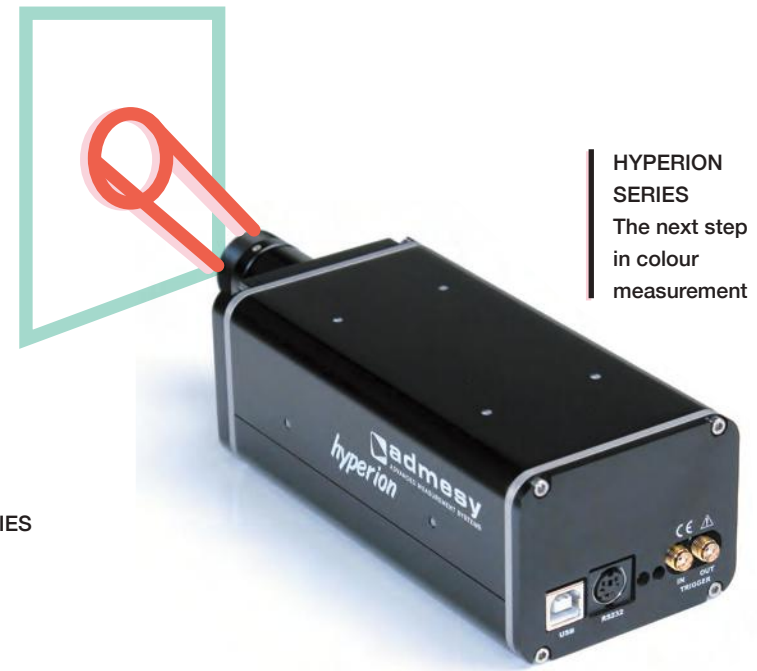
2.3.2 COSINE CORRECTOR

A cosine corrector is a diffuse surface used to capture light upon a surface over a 180 degree angle. The surface of cosine correctors respond according to Lambert's cosine law: the amount of light falling upon the cosine corrector is proportional to the cosine of the light beam's incident angle. At an angle of 60 degrees, only half the intensity is measured compared to 100% at a 0 degree angle.



2.3.3 LENS

Lenses on measurement devices are used to look at a target area. The covered area captured by the lens depends on the distance and acceptance angle of the lens. Generally, lens optics are used to measure homogeneous surfaces, like the backlights of displays.



HYPERION SERIES
The next step in colour measurement

ASTERIA SERIES
Compact, fast industrial light meter

2.4 MEASUREMENT PRINCIPLES

Besides the optical configuration, the measurement principle used is also important in light measurement. Radiometric, spectroradiometric and photometric are three major principles which express the power [flux] of a light source in a specific quantity. Depending on the measurement principle used the power is expressed either in an absolute quantity [radiometric], per wavelength [spectroradiometric] or according to the response of the human eye [photometric]. These measurement principles are measured by means of radiometers, spectroradiometers or spectrophotometers respectively. The table provides an overview of these measurement principles and the optical configurations used to obtain specific light quantities.

THE SPECTRORADIOMETRIC PRINCIPLE provides all radiometric quantities per nanometer and is measured by means of a spectroradiometer. Radiant power for example is expressed in Watts, thus its spectroradiometric equivalent in Watt per nanometer.

SPECTRORADIOMETRIC

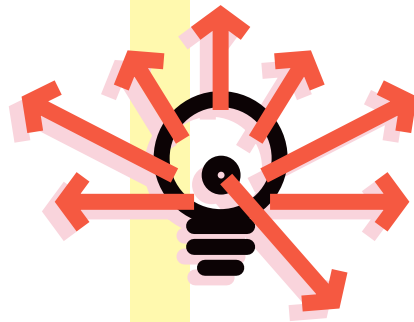
GEOMETRY

MEASUREMENT PRINCIPLES

OPTICAL CONFIGURATION	RADIOMETRIC	SPECTRORADIOMETRIC	PHOTOMETRIC
POWER OR FLUX	INTEGRATING SPHERE WATT W	RADIANT POWER WATT PER NANOMETER W/nm	LUMINOUS POWER LUMEN lm
POWER/AREA	COSINE CORRECTOR INTEGRATING SPHERE	IRRADIANCE WATT PER SQUARE METER W/m^2	SPECTRAL IRRADIANCE WATT PER SQUARE METER PER NANOMETER $W/m^2/nm$
POWER/SOLID ANGLE	COSINE CORRECTOR INTEGRATING SPHERE	RADIANT INTENSITY WATT PER STERADIAN W/sr	SPECTRAL RADIANT INTENSITY WATT PER STERADIAN PER NANOMETER $W/sr/nm$
POWER/AREA/SOLID ANGLE	COLLIMATING LENS	RADIANCE WATT PER SQUARE METER PER STERADIAN $W/m^2/sr$	SPECTRAL RADIANCE WATT PER SQUARE METER PER STERADIAN PER NANOMETER $W/m^2/sr/nm$
			LUMINANCE CANDELA PER SQUARE METER $lm/m^2/sr = cd/m^2 = nit$

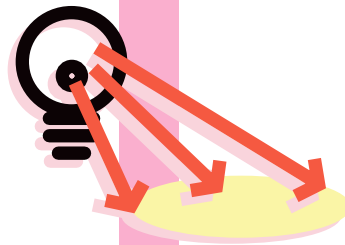
2.4.1 RADIOMETRIC

The first principle [radiant power or radiant flux] refers to the total power emitted by a source in all directions. Radiant power measurements are common during the development and production of lighting. The unit of radiant power is the Watt: **W**



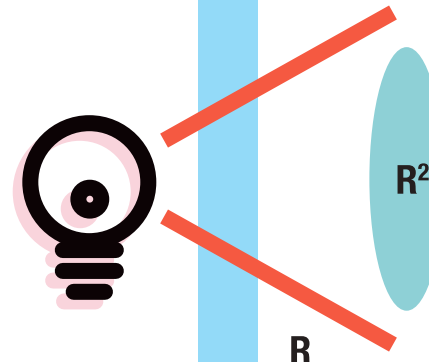
RADIANT
POWER

Irradiance is the amount of radiant power incident on a surface and it is expressed in Watts per unit area: **W/m²**



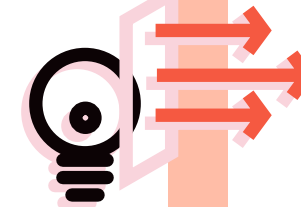
IRRADIANCE

The radiant intensity of a source is a directional quantity which defines the total amount of power that is emitted per solid angle. Hence, radiant intensity is expressed in Watts per solid angle: **W/sr**



RADIANT
INTENSITY

The fourth principle is radiance which is the radiant intensity per unit projected area. It defines the total amount of power per solid angle that is emitted from an area and is expressed in Watts per unit area per solid angle: **W/m²/sr**



RADIANCE

The power of light

2.4.2 PHOTOMETRIC

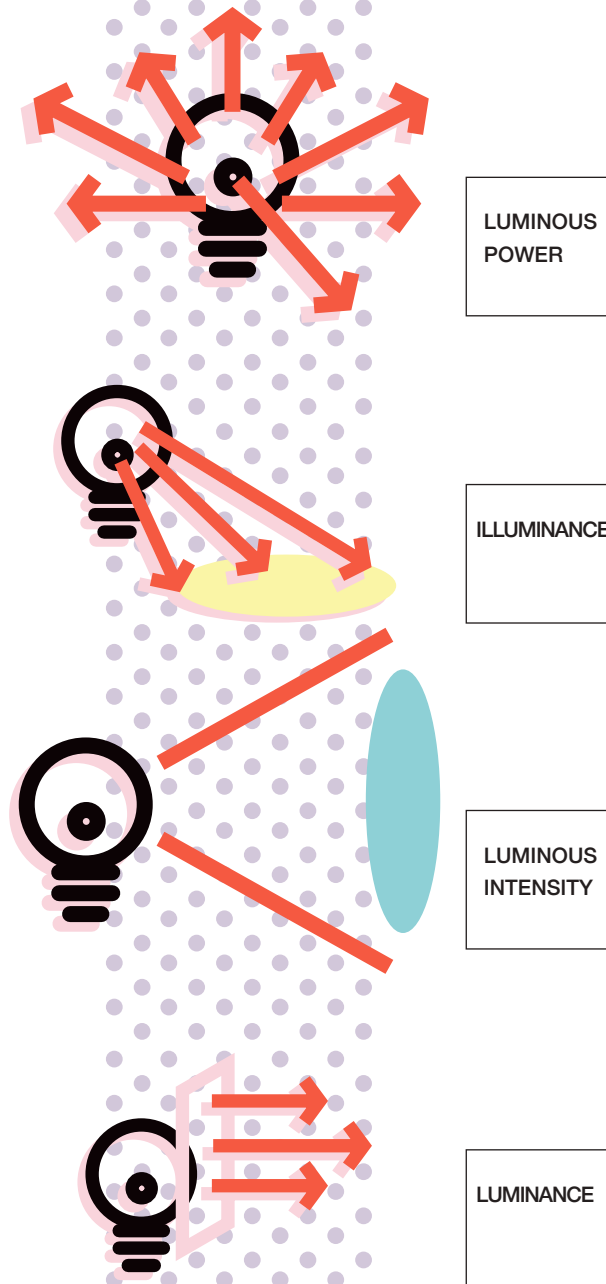
In contrast to radiometry and spectroradiometry, the photometric principle measures light according to the response of the average human eye. This response is known as the luminosity function V_λ .

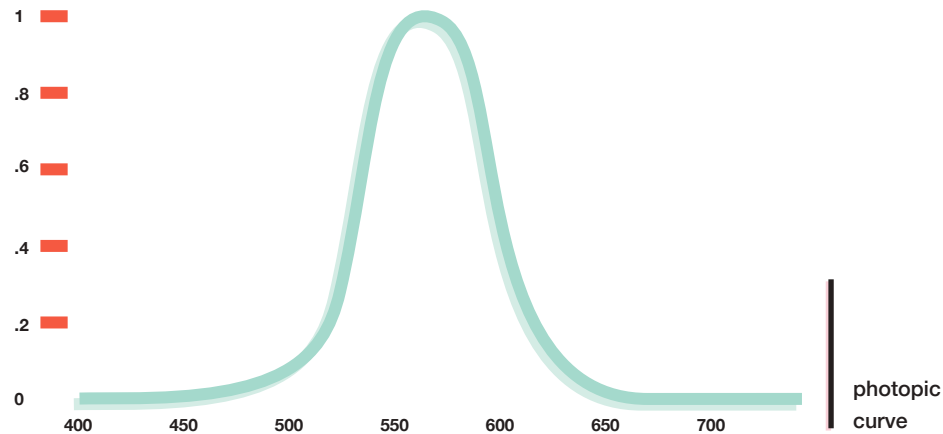
The photometric equivalent of radiant power is luminous power, expressed in Lumens: **lm**. Luminous power is typically measured using an integrating sphere, alike its [spectro]radiometric equivalent.

Light measurement devices equipped with cosine correctors are used to measure illuminance. Values correspond to the amount of lumen per square meter: **lm/m²**, also known as lux.

The photometric equivalent of radiant intensity is the luminous intensity which is expressed in candela: **cd**. This unit is typically used to quantify the brightness of directional light sources such as spot lights.

Luminance is used to specify the brightness of homogeneous surfaces like displays and it is usually expressed in candela per square meter: **cd/m²** which is equivalent to the currently less used unit nit.

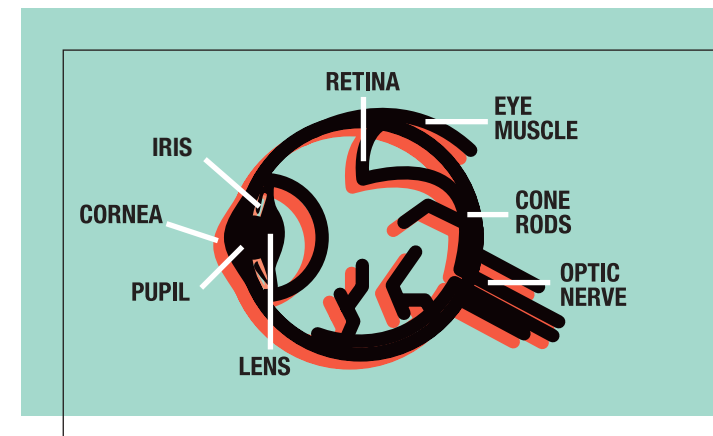




Under normal lighting conditions, for example during daytime, photopic vision dominates. Photopic vision is based on three types of cones which are sensitive to long, middle and short wavelength ranges which typically appear red, green and blue respectively to the human eye. In terms of light sensitivity cones are limited. Vision above 3 cd/m² is based on photopic vision which allows for good colour discrimination. In 1924 the Commission Internationale de l'Eclairage [CIE] defined a general photopic spectral sensitivity function of the average human eye based on a number of experiments. This photopic sensitivity is based on the mid-range of the visual spectrum known as the V_λ or $\bar{y}(\lambda)$ and the basic principle of the response of light meters. The function graph above shows the human eye is not equally sensitive to light over the entire visual spectrum: the peak sensitivity is concentrated around 555nm.

THE HUMAN EYE : sensing light in contrast to objective measurement equipment, humans are biased when it comes to see light and colour. The human eye cannot distinguish individual wavelengths but is sensitive towards different parts of the spectrum covering multiple wavelengths. This response forms the basis of the photometric principle. Eyes contain rods and cones which make it possible to see under different luminance levels and distinguish colours respectively.

THE HUMAN EYE



Scotopic

Mesopic

Rod based vision

$1 \cdot 10^{-6}$

$1 \cdot 10^{-5}$

$1 \cdot 10^{-4}$

$1 \cdot 10^{-3}$

$1 \cdot 10^{-2}$

0.1

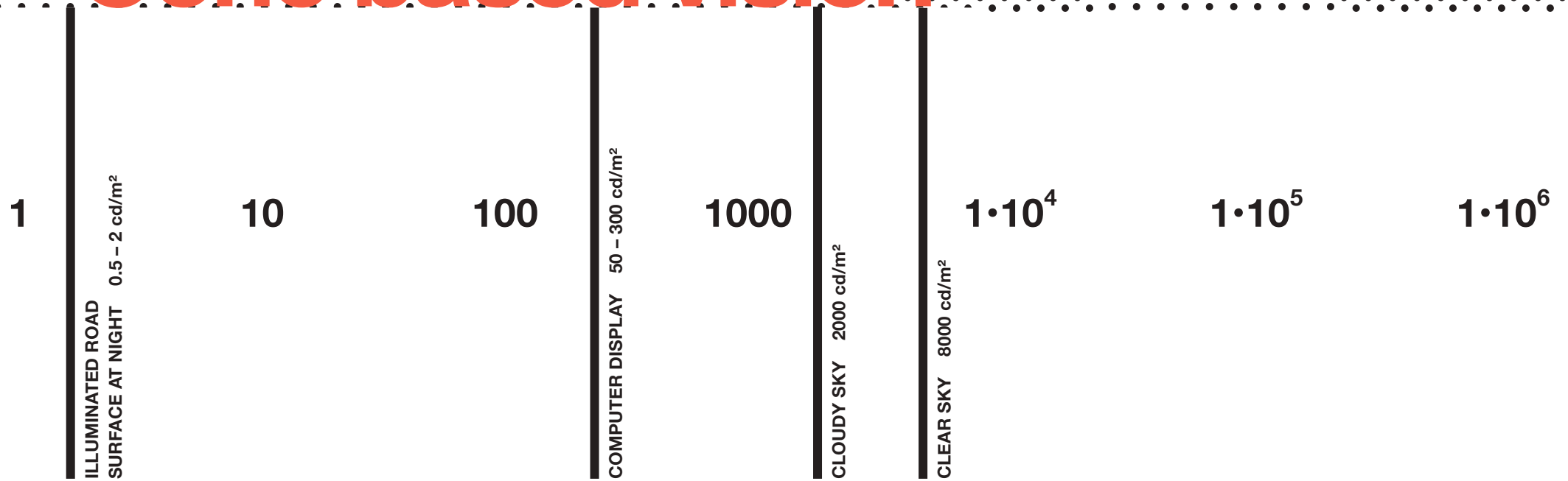
Human eye
luminance
level range and
types of vision:
cd/m²

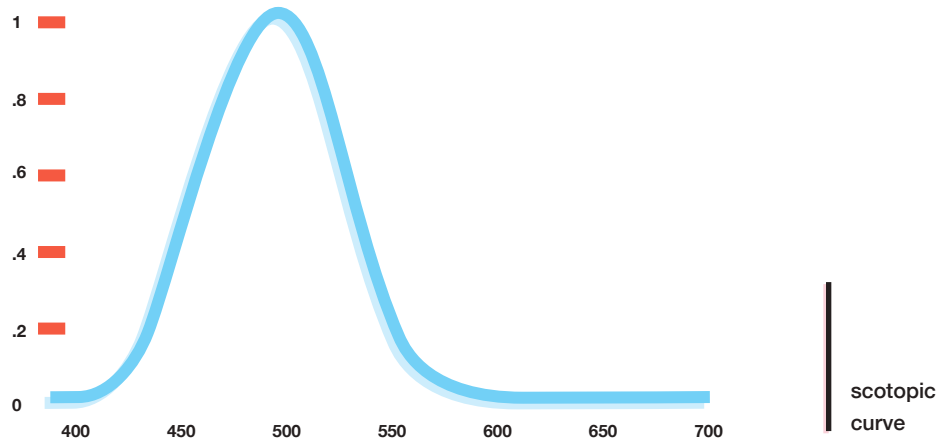
EXAMPLES

STARLIGHT $3 \cdot 10^{-4}$ cd/m²

Photopic

Cone based vision



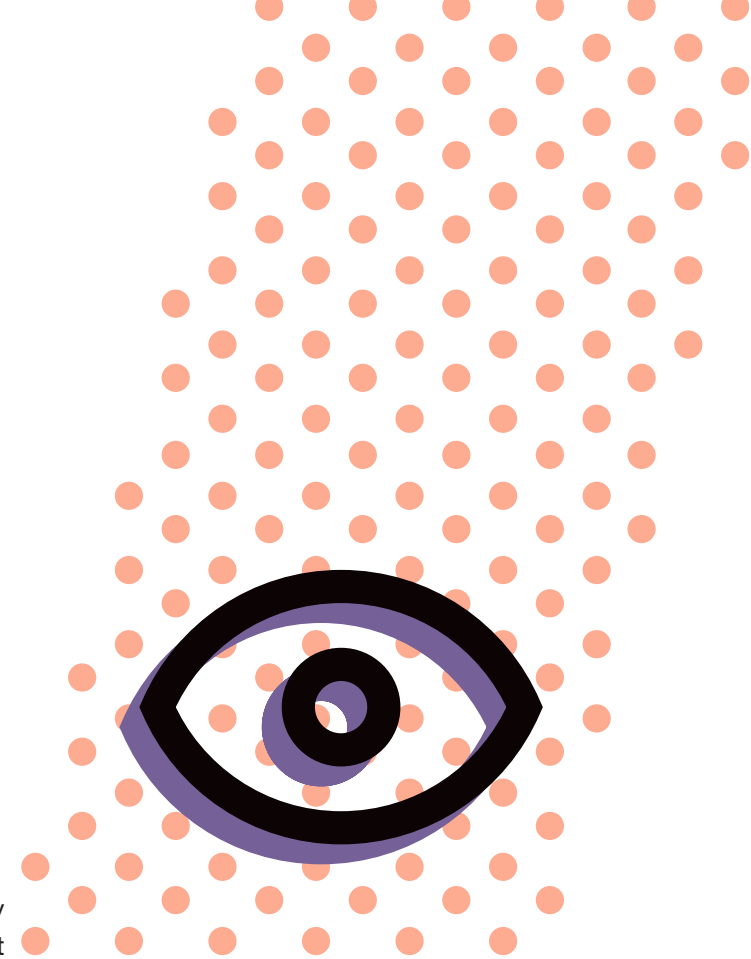


The power of light

Night vision

Rods are more sensitive to light compared to cones, but are not sensitive to different colours as there is only one type of rod. For this reason human vision loses the ability to discriminate between colours under low light conditions. Rods however, are extremely effective under low light conditions below 0.001 cd/m². This type of vision is known as scotopic vision which has been defined by the CIE in 1951 as the relative sensitivity of scotopic vision: V'_{λ} . The highest sensitivity of scotopic vision is found at a wavelength of approximately 507nm. This shift in peak sensitivity when adapting between photopic and scotopic vision is known as the Purkinje effect. Light levels between scotopic and photopic vision are mediated by a combination of rods and cones which is known as mesopic vision.

Generally the photometric quantities of light sources are measured as one usually functions under normal lighting conditions. Scotopic quantities of light sources may be given by a S/P ratio: the ratio between the scotopic and photopic values of a light source. Once the light source's output is known for both photopic and scotopic conditions, the scotopic output of a light source can be calculated when measuring its photopic value.



RODS ARE EXTREMELY EFFECTIVE UNDER LOW LIGHT CONDITIONS BELOW 0.001 cd/m².

Measurement equipment

ADMESY

3.1 INTRODUCTION

Knowing the basics of light in perspective of physics and human perception is important to understand different types of light measurement equipment. Quantifying light is done in absolute quantities in perspective of physics and quantities based on the response of the human eye. As light is typically expressed in wavelengths in the application areas Admesy supports, this guide explains the light measurement equipment in perspective of wave theory.

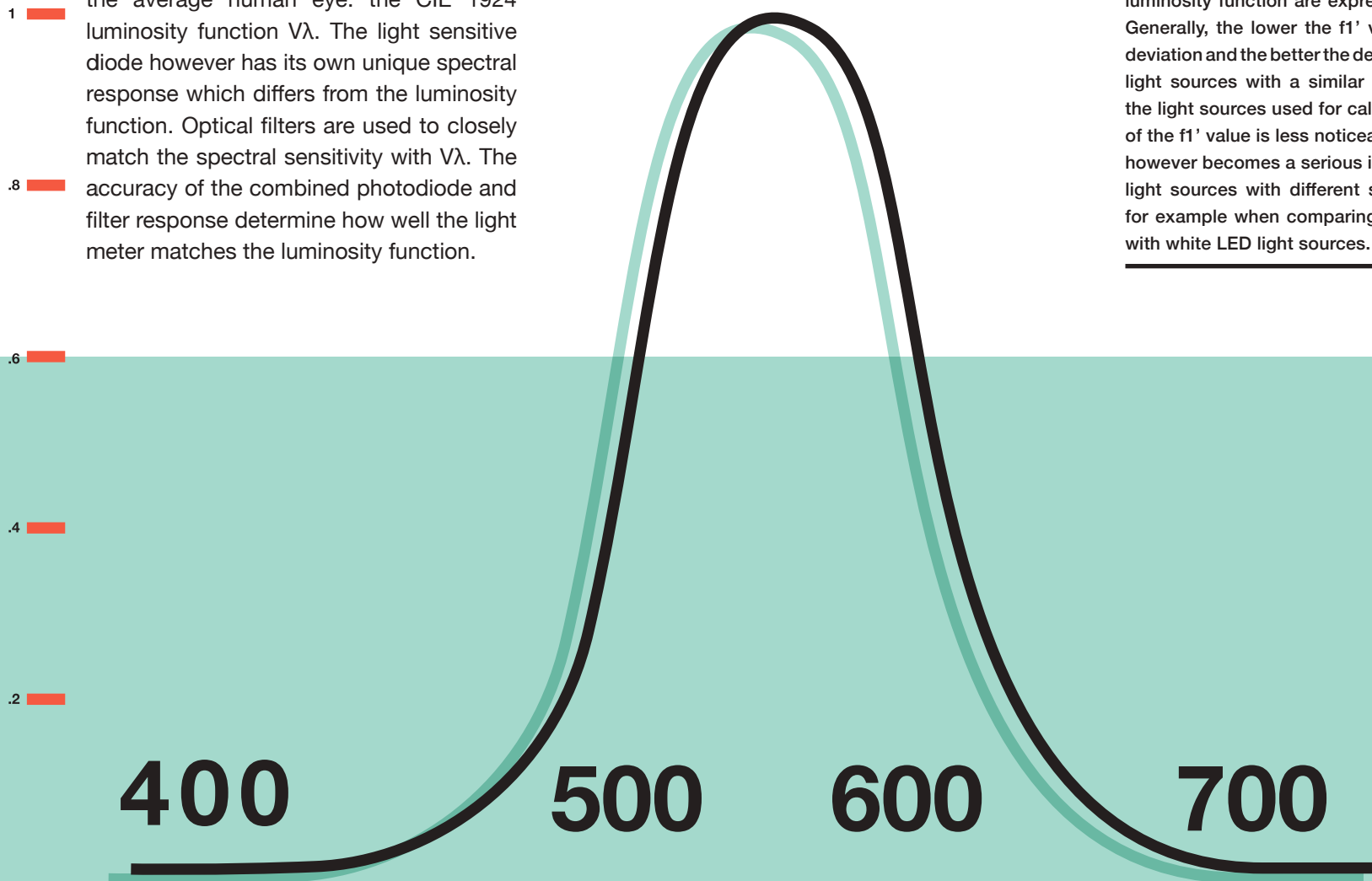
Measurement equipment

3.2 LIGHT METER

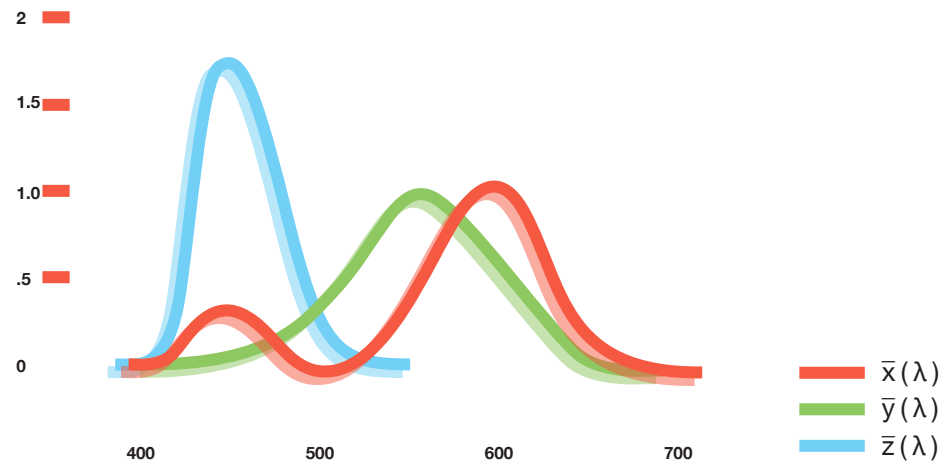
Light meters or photometers are radiometers equipped with a photodiode and filter which responds according to the average human eye: the CIE 1924 luminosity function V_λ . The light sensitive diode however has its own unique spectral response which differs from the luminosity function. Optical filters are used to closely match the spectral sensitivity with V_λ . The accuracy of the combined photodiode and filter response determine how well the light meter matches the luminosity function.

DEVIATIONS BETWEEN the light meter and luminosity function are expressed in the f_1' value. Generally, the lower the f_1' value, the smaller the deviation and the better the device. When measuring light sources with a similar spectral response as the light sources used for calibration, the influence of the f_1' value is less noticeable. A larger f_1' value however becomes a serious issue when measuring light sources with different spectral distributions, for example when comparing incandescent lamps with white LED light sources.

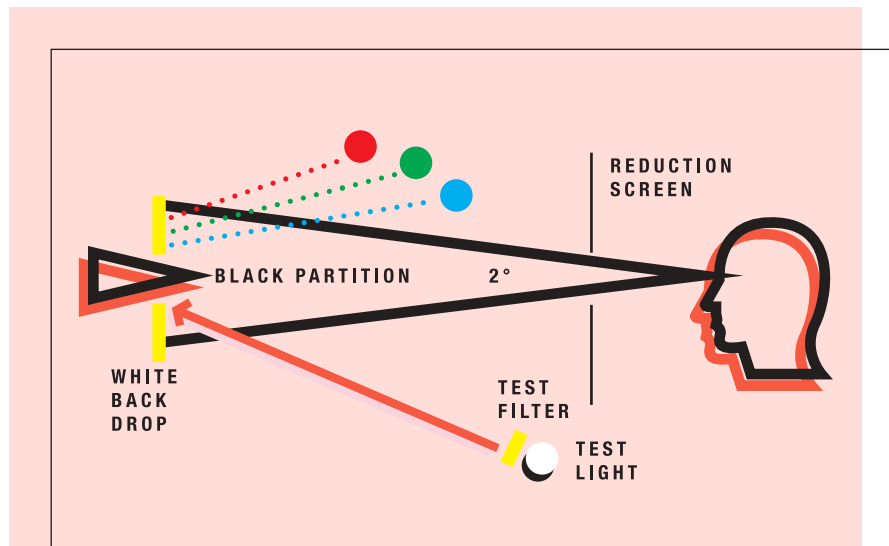
f_1' VALUE



3.3 TRI-STIMULUS COLORIMETER



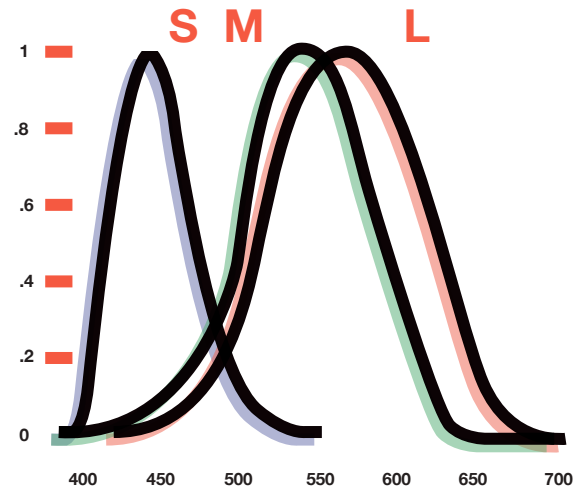
Tri-stimulus colorimeters are similar to a light meter as they also cover the luminosity function $V\lambda$. Besides this $\bar{y}(\lambda)$ function, colorimeters also cover additional $\bar{x}(\lambda)$ and $\bar{z}(\lambda)$ functions which represent additional sensitivity in the red and blue spectral areas respectively and have in total three types of sensors. All three functions have been defined by the CIE in 1931 based on the 2° Standard Observer. Experiments were carried out to determine the average human eye response for red, green and blue which led to the CIE tri-stimulus values X, Y and Z.



THE MODEL OF the 2° Standard Observer was the result of experiments by Wright and Guild, carried out with a select group of people checking and matching a number of colours against colours produced using tuneable light sources. At that time, it was generally assumed that all cones were located within the eye's fovea with a field of view of 2 degrees. For that reason, the experiments were carried out by looking through a small aperture which corresponded to a viewing angle of 2 degrees, hence the name. Both the results from this experiment and earlier findings from CIE 1924 [V λ] were used to define tri-stimulus $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ functions.

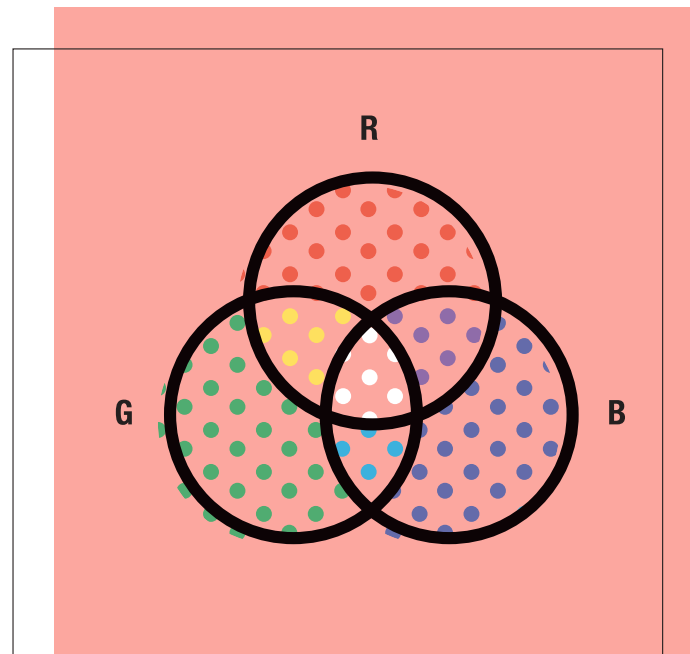
In the 1960's, these experiments have been repeated with a 10 degree viewing angle resulting in different values. Corresponding to the experiment conditions, this is known as the 10 degree standard observer.

2° STANDARD OBSERVER

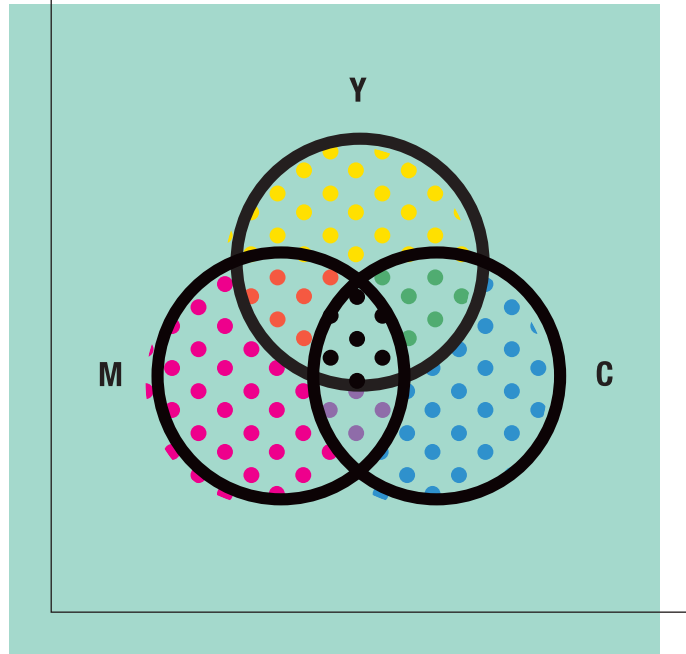


ACTUAL
RESPONSE
OF THE THREE CONE
TYPES
FOR SHORT [S],
MEDIUM [M]
AND LONG [L]
WAVELENGTHS
OF THE AVERAGE
HUMAN EYE.

Although the true response of the human eye for short, mid and long wavelengths [shown above] differs slightly from the $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ functions, the 1931 model is still acknowledged and used as a standard. Despite the differences in response, the $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ functions are based on the three component theory of human colour vision. A theory that states humans see multiple colours by mixing the responses of the three different cone types. Each cone type in the human eye responds to certain regions in the visible spectrum with peak responses in either the red, green or blue part of the visual spectrum. Different colours are then distinguished by triggering all three cone types in different proportions. The colour range also includes white light as an additive mixture of all three primary colours. Adding the different primaries red, green and blue to create colours is known as additive mixing and is applicable to luminous objects like displays or light sources. The mixed colours of two primaries are called secondaries, and they are yellow, cyan and magenta.



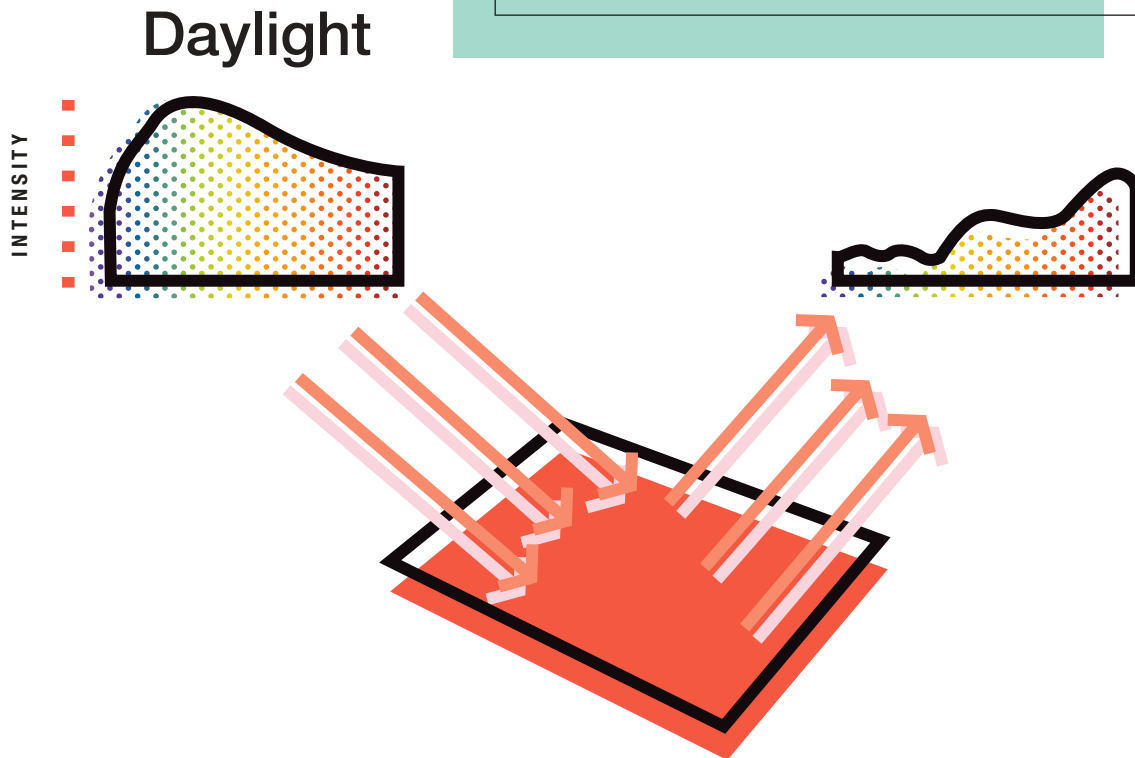
ADDITIVE MIXING



SUBTRACTIVE COLOUR MIXING

typically applies to illuminated objects that reflect light. Depending on the colour and properties of an object, particular wavelengths of the incoming light are absorbed, i.e. subtracted from the light, [or transmitted in case of translucent objects] and a part is reflected. For example, red objects reflect a lot of longer wavelengths [red] and absorb most of the shorter wavelengths [blue and green] when illuminated by broad band [white] light sources. As the reflected light contains mostly longer wavelengths, the red cones are triggered more and blue and green less which results in the object being experienced as red. The concept of subtractive mixing is applied in industries related to dyes, ink and pigments and use the secondaries of additive mixing as primaries.

SUBTRACTIVE MIXING

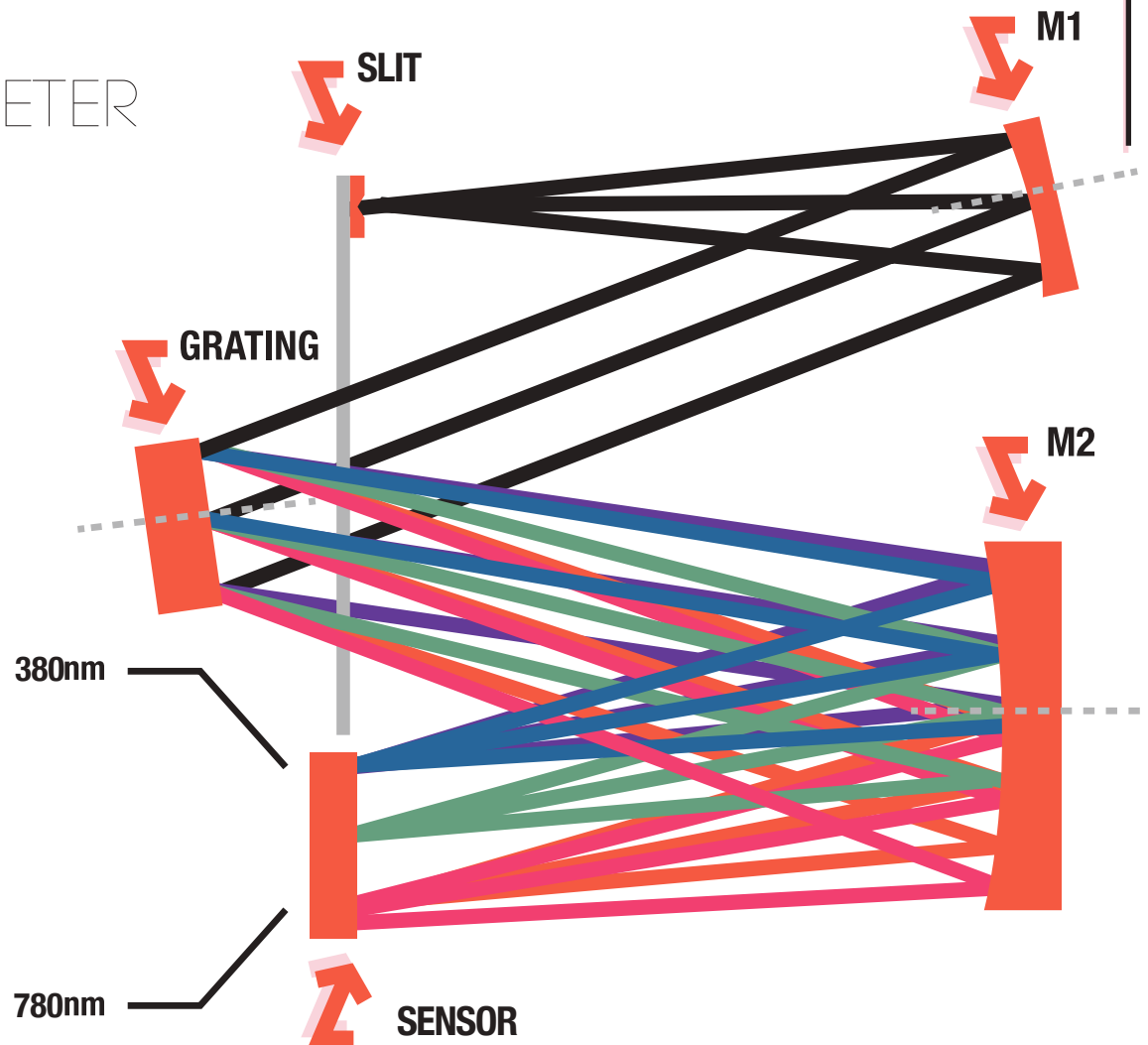


EXAMPLE
OF RED
OBJECT
ILLUMINATED
BY DAYLIGHT
AND
PROPORTIONS OF
WAVELENGTHS
BEING
REFLECTED.

Measurement equipment

3.4 SPECTROMETER

Spectroradiometers, sometimes simply called spectrometers, are based on the principle of refracting light. Spectroradiometers allow the intensity of light per wavelength to be measured, which can then be visualized as a spectral distribution. Each type of light source has its own spectral distribution showing the proportions between individual wavelengths. Spectral distributions are useful for the determination of qualitative aspects of light such as colour and colour rendering capabilities. In addition to the visual spectrum covered by spectrophotometers, spectroradiometers can also be configured to measure UV and IR light.



THE ILLUSTRATION BELOW SHOWS THE BASIC PRINCIPLE AND COMPONENTS OF A SPECTROPHOTOMETER'S OPTICAL BENCH AS APPLIED IN ADMESY'S RHEA SPECTRORADIOMETER SERIES FOR THE VIS RANGE.



LIGHT JOURNEY THROUGH THE SPECTROMETER

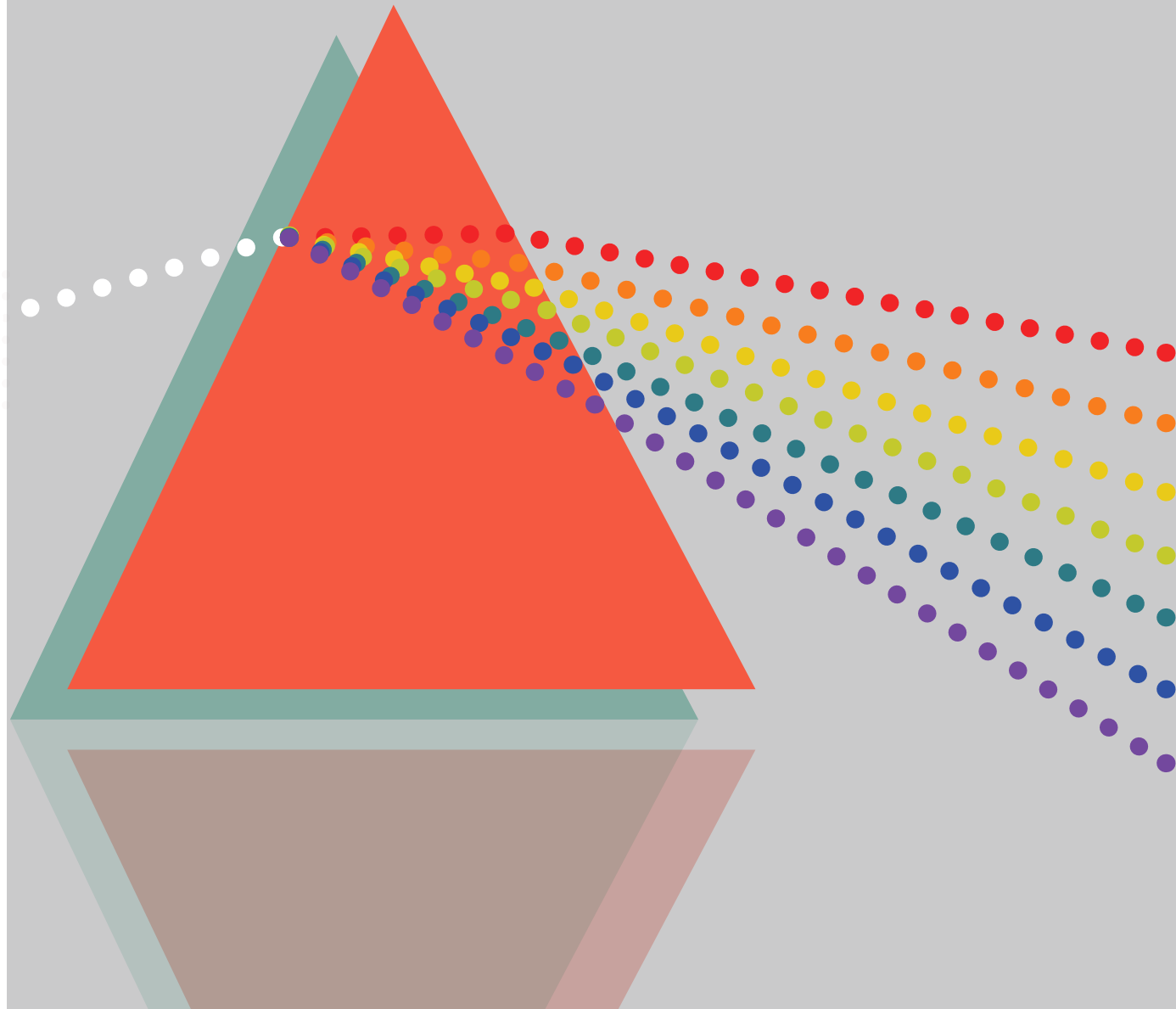
After passing through an optical configuration, such as a lens, the light enters the spectrometer through the slit. The dimensions of this slit regulate the amount of light entering the optical bench and this affects the optical resolution of a spectroradiometer. A concave mirror [M1] reflects the divergent incoming beam into a collimating beam towards the grating where dispersion of the light takes place. Admesy's Rhea uses a reflective grating: the collimated light beam is dispersed into different wavelengths upon reflecting on the grating. Different wavelengths reflect on the grating under different angles, creating multiple divergent beams. A second concave mirror [M2] reflects and focuses the different separated wavelengths towards the detector. The optical bench of a spectrometer is designed in such a way that particular wavelengths are focused on specific pixels of the sensor. By verifying wavelengths and assigning pixels to specific wavelengths the device is wavelength calibrated: signals picked up by a pixel are linked to a specific wavelength and this results in a device known as a spectrometer. A second calibration step is necessary as not every pixel responds the same way to the true intensity of a wavelength. For this reason, it is important to determine the correct proportions for each pixel. This second calibration step is achieved by calibrating against [calibration] light sources such as a NIST traceable lamp. Such light sources come with datasheets on their spectral distribution in absolute values. Once the results from the spectrometer are matched towards the known results of a standard light source, the device is entirely calibrated and ready for absolute and accurate measurements. After this calibration step, the device is known as a spectroradiometer. Besides the radiometric quantities, a spectroradiometer can also measure colorimetric and photometric quantities very accurately if it covers the VIS range. Spectroradiometers that cover the 380-780nm VIS range only, are also known as spectrophotometers. By using software to process the spectral data, precise values for the tri-stimulus values and other functions like the PAR can be derived. A major advantage of measuring these values using a spectrophotometer is the fact that measurement errors are lower compared to tri-stimulus colorimeters or light meters. Although a spectrophotometer is more precise in displaying these values, it typically takes more time to complete a measurement using a spectrophotometer compared to a colorimeter at a given luminance level.



Measurement equipment

HISTORY OF SPECTROMETRY

The history of spectrometers goes back into the 17th century when Sir Isaac Newton demonstrated and researched the composition of white light. By means of a prism he demonstrated that incoming light can be dispersed into different wavelengths. Each wavelength bends at a different angle when passing through materials of different optical densities. Longer wavelengths, corresponding to red light, tend to bend less than short wavelengths [blue light] in a prism. The same principle occurs in a rainbow: when sunlight [which typically covers the entire visual spectrum] is dispersed in a raindrop, one can see the different wavelengths from red, orange, yellow to green, blue and ending with violet in the sky.



Each wavelength bends at a different angle when passing through materials with different optical densities.

The colour of light

ADMESY

4.1 HOW DO WE DESCRIBE THE COLOUR OF LIGHT?

One of the major shortcomings of the human eye is the fact that it cannot sense light objectively. Its automatic adaption to different light levels makes it impossible to quantify absolute luminance levels. The same problem occurs when quantifying an important characteristic of light: colour.

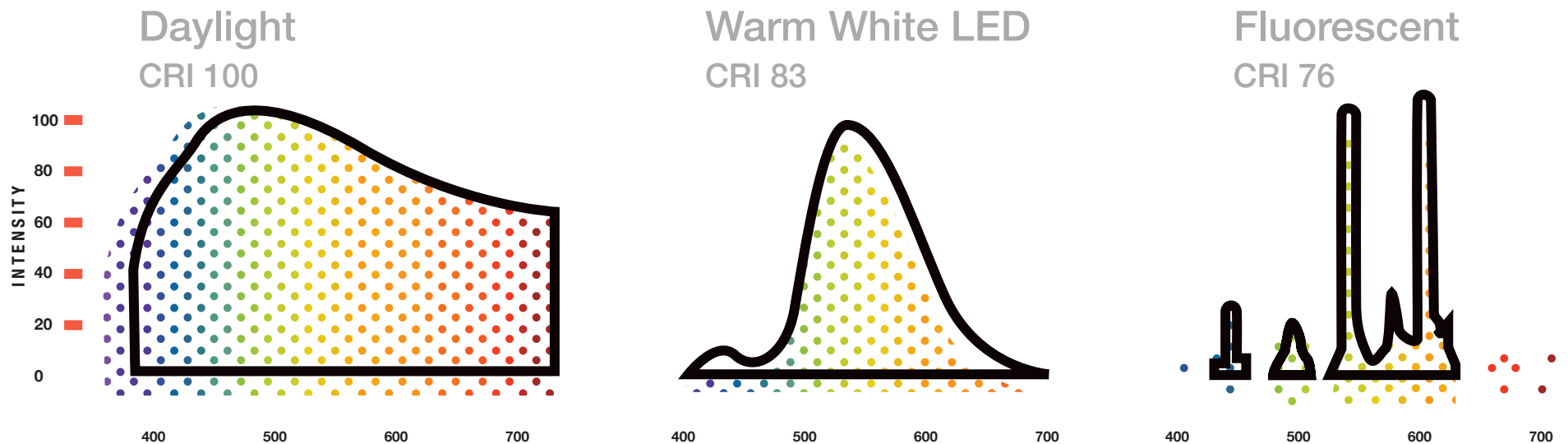


The colour of light

Triggering the three cone types in different proportions allow people to see millions of different colours. How these colours are actually perceived differs from person to person as everyone's eyes demonstrate a different physical response. The surrounding conditions play an important role too: for example, the spectrum of daylight at sunrise, noon or sunset is completely different. A green leaf appears to have different colours over the course of a day. Still, people will experience the colour to be the same as the human brain automatically compensates for the influence of the light source by 'knowing' what colour the object should be. Size, texture, the presence of other colours and cultural background can all influence how people perceive a colour. This shows that keeping the conditions constant is very important for accurate colour assessment. Next to the biased and influenced human vision of colour perception, communicating perceived colours is limited to one's vocabulary and often relates only to what is objectively known as hue. A general way of understandable colour communication is based on three parameters: hue, chroma and value. Hue refers to what people generally talk about as colour and describes whether something is blue, red, yellow etc. Chroma describes the vividness or saturation of a colour. Value or lightness expresses an object's brightness compared to a perfect white reference.

DIFFERENCES IN COLOUR AND REPRODUCTION

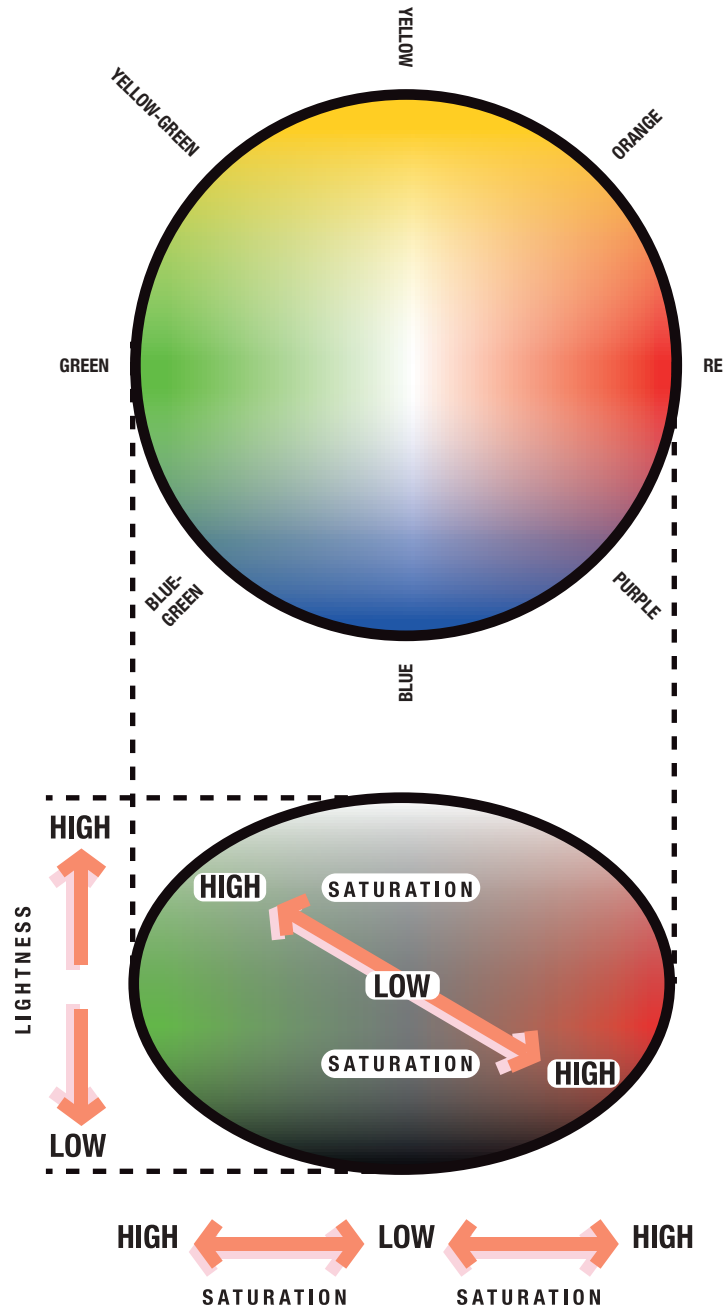
Keeping the conditions constant when assessing colours is important as colours may appear differently under different types of lighting. Even two light sources that appear to have the same colour as they trigger the cones in the eye in a similar way may result in objects being perceived differently. As white light sources can have different spectral distributions, the mixture of wavelengths reflected by an object may be different, which influences the perceived colour. This effect is known as metamerism. For the accurate reproduction and assessment of colours, light sources with good colour rendering capabilities are necessary. A long term standard used to express the rendering capabilities of a light source is known as the CRI: the colour rendering index, Ra, which can have a value of up to 100. Light sources with a continuous spectrum, enclosing all wavelengths of the visible spectrum, typically have perfect rendering capabilities resulting in high Ra value. For example, daylight has a Ra value of 100. Light sources with discontinuous spectrums lacking parts of the visible spectrum logically result in lower Ra values. Still, different types of light sources, both continuous and discontinuous, can appear white to the human eye like the examples below.



The colour of light

4.2 COLOUR WHEEL

The three parameters hue [colour], lightness and saturation [vividness or purity] cover all colours and also form the basis of graphical colour spaces such as colour wheels. In colour wheels the hues are located along the outer boundaries of the circle with opponent colours on opposite sides: according to the opponent colour theory, which states a colour cannot be both red and green or blue and yellow. Mixtures between two non-opponent colours however are possible. Around the center of the colour wheel the unsaturated colours are located with grey as center point.

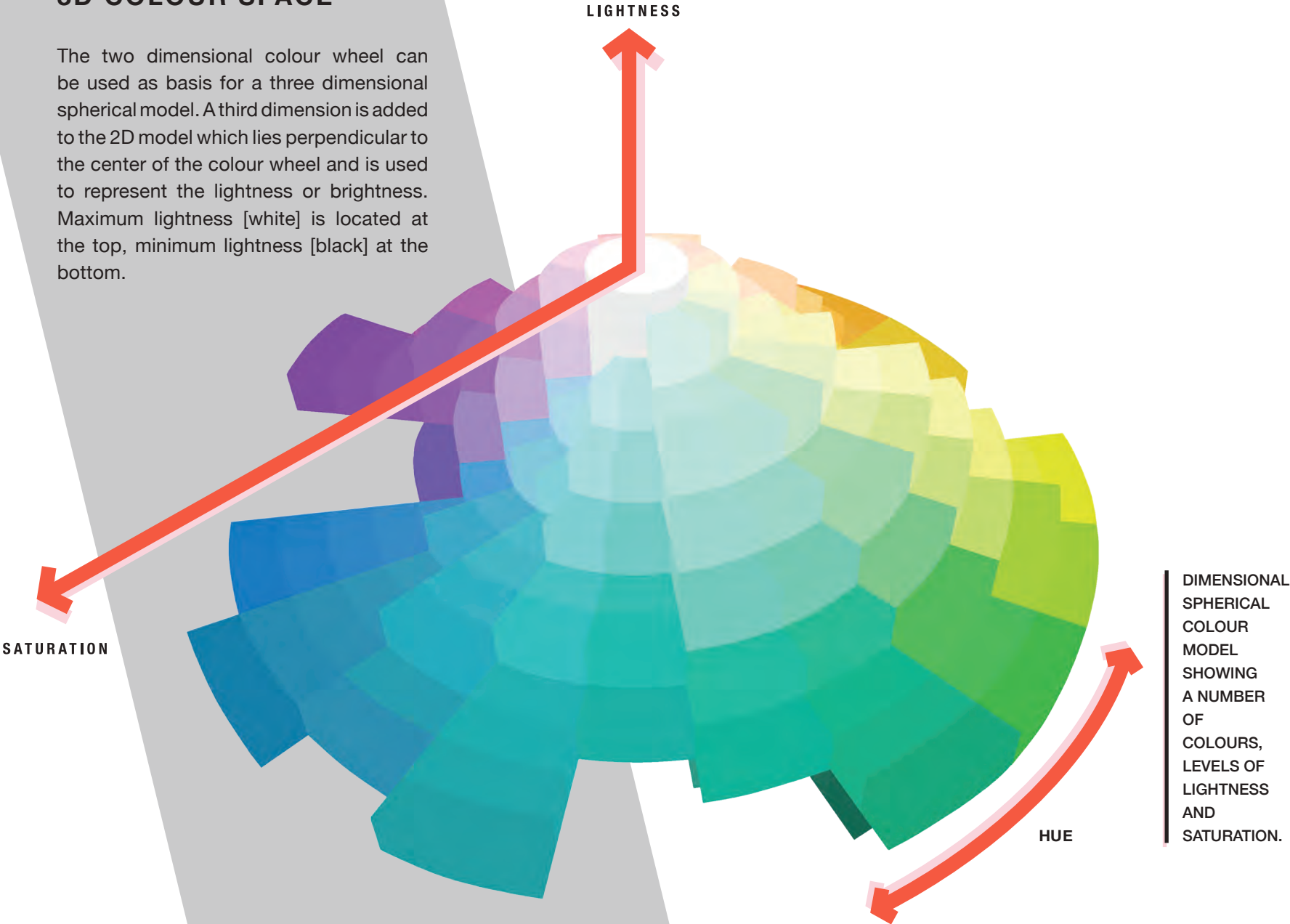


Although it shows all visible colours, the outer boundary is not the same as the visual spectrum of different wavelengths starting at ultraviolet towards [near] infrared. The colour wheel also includes mixed purple colours which do not exist as an individual wavelength in our visual spectrum.

CHANGES IN LIGHTNESS AND SATURATION FOR RED AND GREEN.

3D COLOUR SPACE

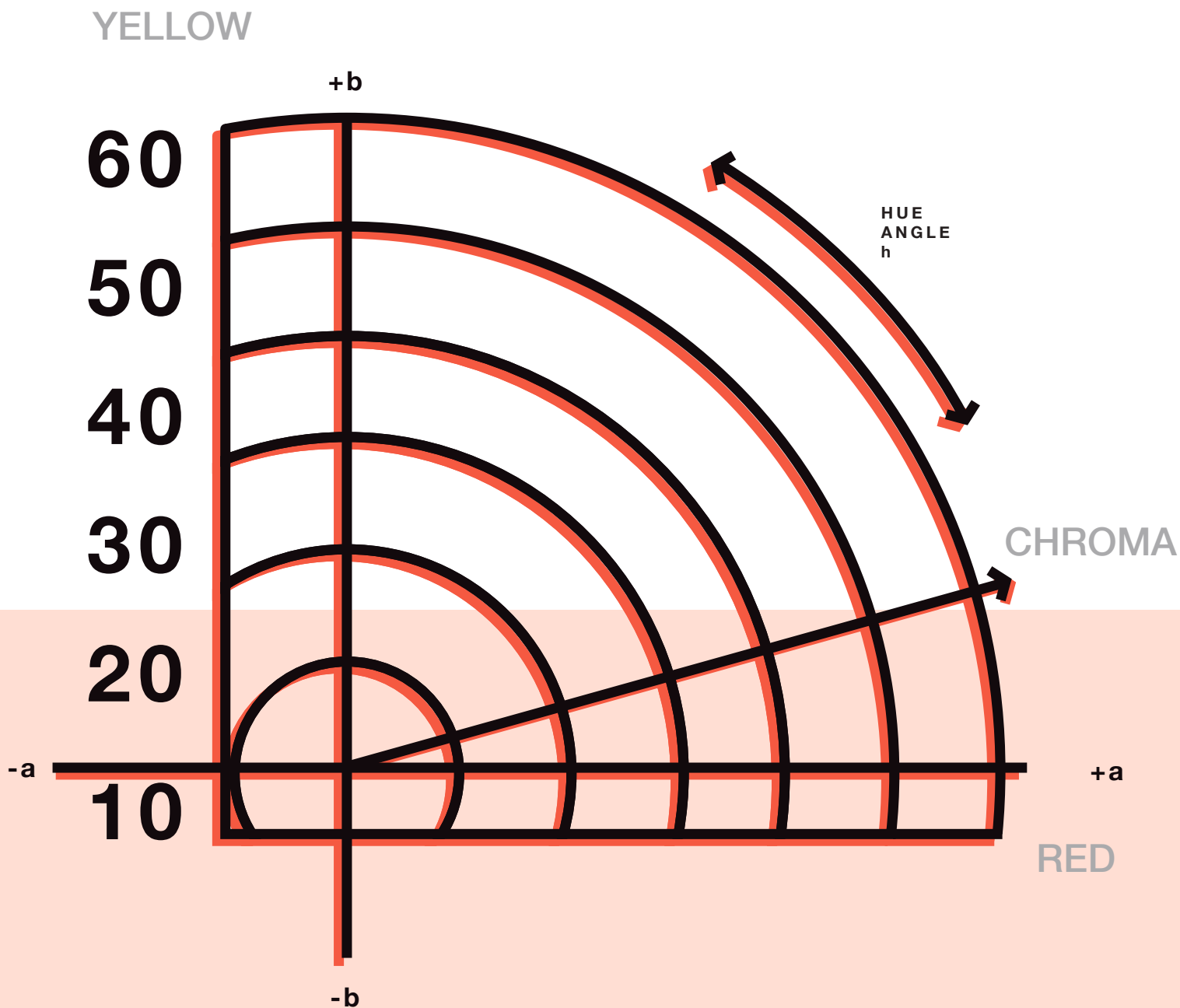
The two dimensional colour wheel can be used as basis for a three dimensional spherical model. A third dimension is added to the 2D model which lies perpendicular to the center of the colour wheel and is used to represent the lightness or brightness. Maximum lightness [white] is located at the top, minimum lightness [black] at the bottom.



The colour of light

4.3 $L^*C^*h^*$ AND $L^*a^*b^*$ COLOUR SPACES

An example of a spherical colour opponent model is the $L^*C^*h^*$ colour space. It is based on a circular colour scale, similar to a colour wheel, with polar coordinates which define the chroma [saturation] and hue. The starting point of colour notation using this colour scale is a line drawn from the unsaturated center towards fully saturated red. Following this line from the center [zero saturation] towards the outer shell [maximum saturation], chroma [**C**] increases. Hue [**h**] is defined as an angle starting from red at 0 degrees towards yellow at 90 degrees. Green and blue are located at 180 and 270 degrees respectively. The lightness axis **L** is perpendicular to the colour circle and has a value between 0 and 100: the higher the value of **L**, the lighter the colour.



The L*a*b* colour space uses the same spherical space as the L*C*h* space, with the parameter **L** for brightness. Instead of polar coordinates, hue and saturation are defined by a Cartesian coordinate system: the **a*** value defines the location along the green-red axis. Negative values for **a*** indicate a green colour, positive values red. Values for **b*** can be positive [yellow] or negative [blue]. The advantage of colour notations like L*C*h* and L*a*b* is that values are relatively easy to interpret as the colour they represent: a high value for lightness refers to a light colour, the value for chroma defines the level of saturation and the angle directly corresponds to the colour itself.

Both L*a*b* and L*C*h* colour spaces are used to compare colours and identify differences between colours. Differences expressed as Δ [delta] can be determined for each single parameter like ΔL^* , Δa^* or Δb^* , but also as colour difference as a single value. The total colour difference ΔE^* can be calculated according to the following formula:

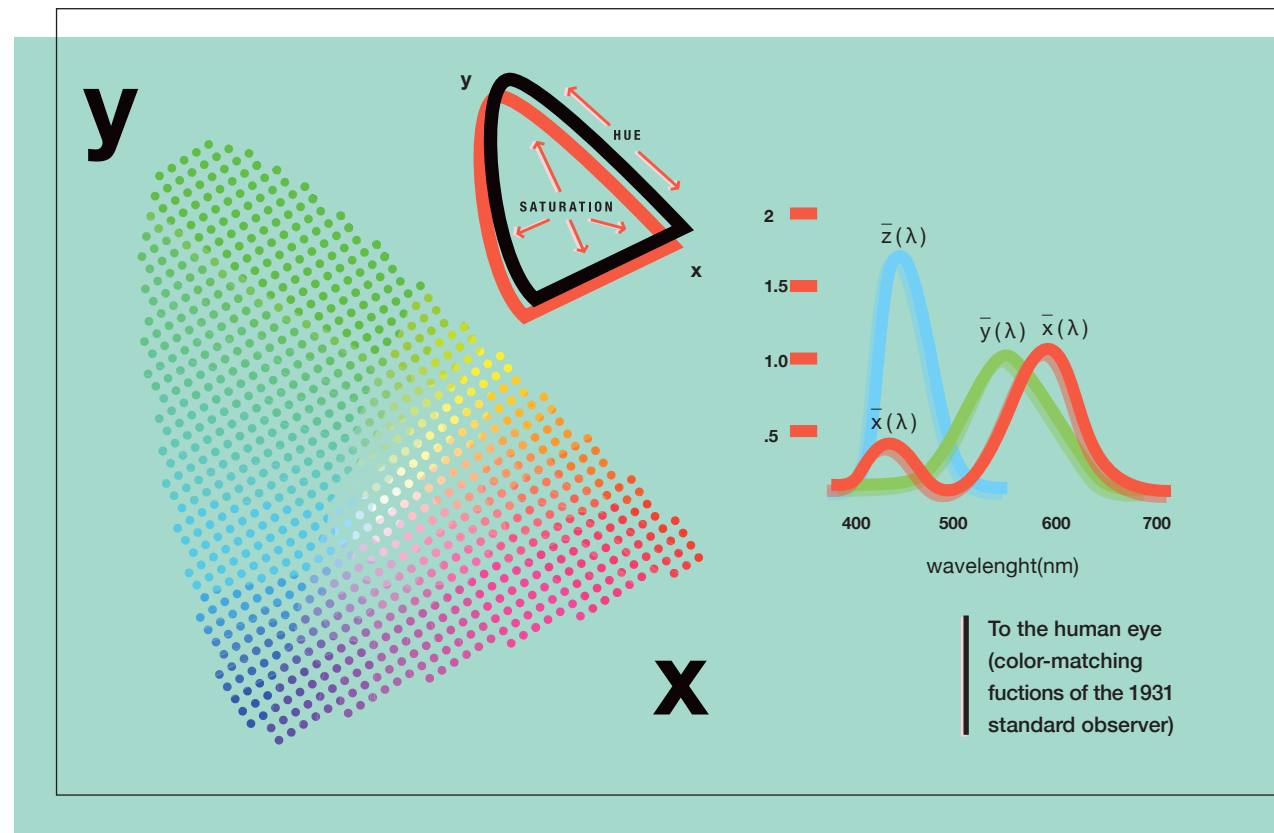
$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

From these formulas, the difference in hue ΔH^* can be calculated as a separate value. Note that the hue difference is not calculated as a difference in metric hue-angle as the L*C*h* colour space would suggest, but as a metric hue difference.

$$\Delta H^* = \sqrt{(\Delta E^*_{ab})^2 - (\Delta L^*)^2 - (\Delta C^*)^2} = \sqrt{(\Delta a^*)^2 + (\Delta b^*)^2 - (\Delta C^*)^2}$$

4.4 CIE 1931

A colour space still widely used today is the CIE 1931 chromaticity diagram that translates the X, Y and Z values into Yxy. In contrast to the spherical colour spaces, the third dimension [lightness, Y] is not directly plotted into the graph and which results in a two dimensional colour space. Hue and saturation are shown by means of coordinates x and y.



An important characteristic of the CIE 1931 colour space is that it is based on the response of the human eye. The least saturated colours are located near the center white point. The outer locus is scaled by wavelengths of the visual part of the spectrum: meaning fully saturated colours on this locus can be made by a single wavelength emitting source. The straight line at the lower end of the colour space connecting the blue and red ends of the locus directly, contain shades of blueish-purple towards reddish-purple and red. Colours along this 'line of purples' cannot be made by a single wavelength and are always a combination of multiple wavelengths.

Values for x and y are calculated according to the following formulas:

$$x = X / (X + Y + Z)$$

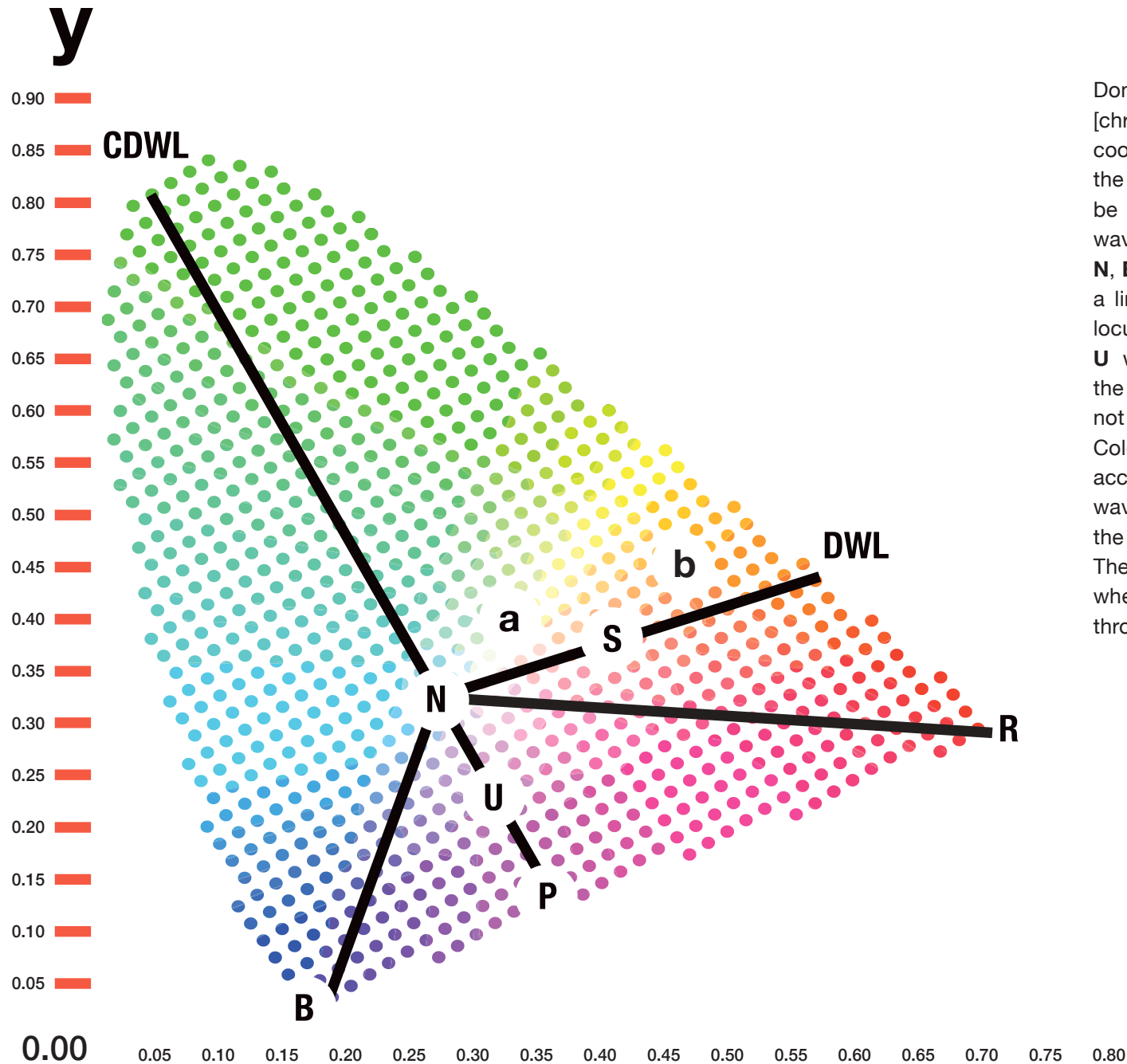
$$y = Y / (X + Y + Z)$$

DOMINANT WAVELENGTH & PURITY

In the CIE 1931 colour space the level of saturation is known as purity: the more the colour point is located towards the locus, the higher its purity. A line drawn from illuminant or white point **N** through the coordinates of sample colour **S**, crosses the locus at a certain point. The location of white point **N** can vary depending on the application. At the intersection of the line from **N** through **S** with the locus defines the dominant wavelength **DWL**: the wavelength that corresponds with the fully saturated colour of the sample.

PURITY IS CALCULATED ACCORDING TO THE FOLLOWING FORMULA BASED ON THE LOCATION OF THE SAMPLE'S COLOUR POINT ON THE LINE.

$$\text{PURITY} = \frac{(a)}{(a + b)}$$



Dominant wavelength [hue] and purity [chroma] are known as the Helmholtz coordinates. For particular colours within the Yxy colour space, these values cannot be calculated as they lack a dominant wavelength: all colours within the triangle **N**, **B** and **R** cannot be defined by drawing a line from the center towards the outer locus. A line from **N** through sample colour **U** would intersect the colour space at the blue-red line at point **P** - which does not correspond to a single wavelength. Colours within this area can be expressed according to their complimentary dominant wavelength [**CDWL**] which is located at the opposite side of the illuminant point. The **CDWL** can be found at the location where the line drawn from sample point **U** through **N** intersects with the outer locus.

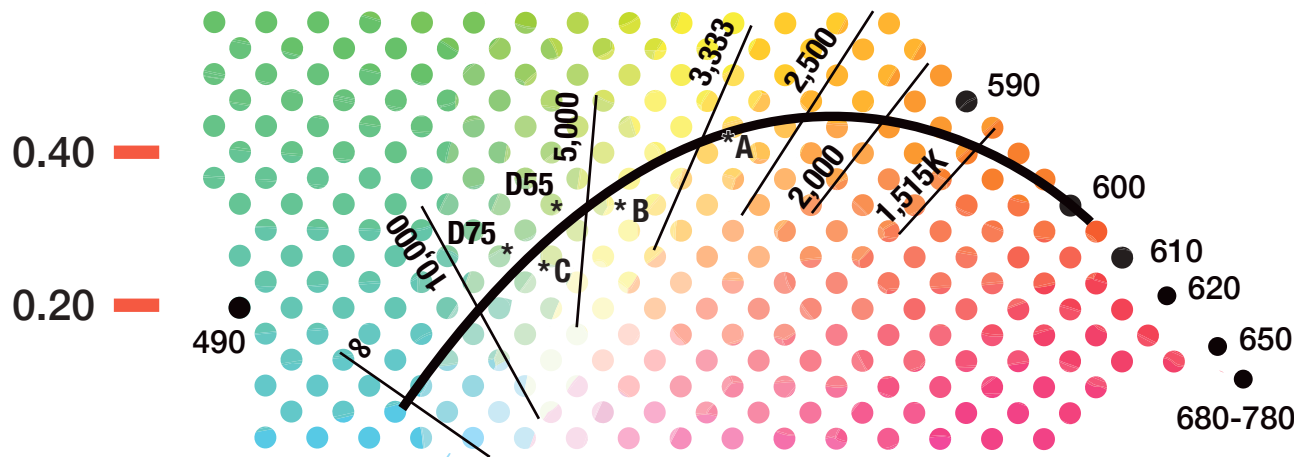
X

The colour of light



COLOUR TEMPERATURE

Colour temperature is defined along a second locus positioned in the colour space. This black body locus is often used in lighting measurement to express different shades of white light by its colour temperature [CT] expressed in Kelvin [K]. Colour temperature is based on Planck's Law which describes the changing colour of a heated black body radiator over a certain temperature range. When heating a [theoretical] black body radiator, it starts emitting 'warm' orange light at approximately 1700K. When increasing the temperature, the colour shifts more towards yellowish-white and then towards blueish-white. Thus, high colour temperatures correspond to cool colours, whereas low colour temperatures correspond to warm colours. In reality, light sources rarely match the exact colour point on the black body locus, like the standard illuminants shown in the graph below. For such light sources that only closely match the black body locus the term correlated colour temperature [CCT] is used. Iso-temperature lines intersecting the black body locus define boundaries for similar colour temperatures. Colours of light sources on one iso-temperature line all have the same CCT but may vary in colour point: If light sources share the same CCT, it does not necessarily mean they have the same colour point.

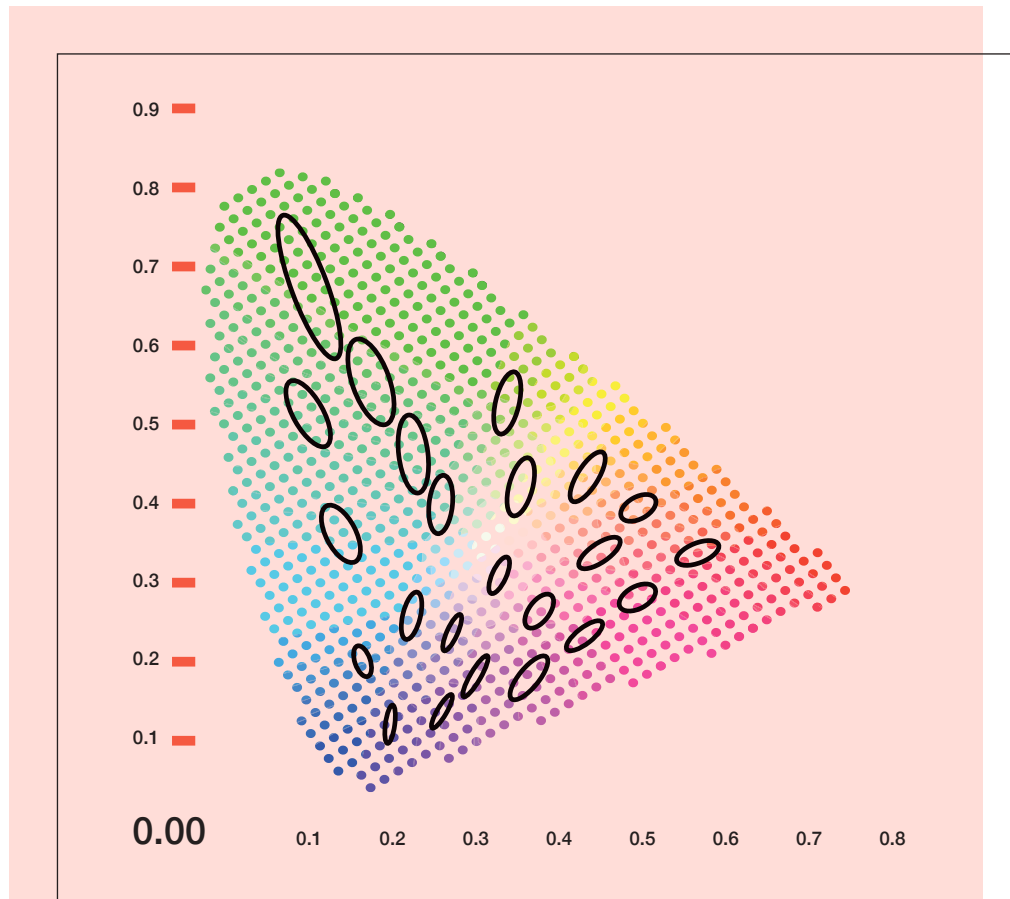


EXAMPLES

CANDLE	1900K
INCANDESCENT BULB	2700-3000K
MOONLIGHT	4100K
XENON/LED CAR HEADLIGHT	4300-8000K
SUNLIGHT	5000-5800K
DAYLIGHT	5800-8500K

COLOUR DEVIATIONS: MACADAM ELLIPSES

Small deviations in colour are not only important to the colours on or around the black body locus, but in the entire colour space. In the 1940's MacAdam conducted an experiment to determine which areas of colours are perceived the same by the human eye. For a number of sample colours, participants were asked to reproduce the same colour as accurately as possible. Analysis of these experiments showed colours which were perceived to be similar to the sample colour were located in ellipses in the 1931 chromaticity diagram. The different sizes and orientations of these ellipses, as well as their elliptical [rather than circular] shape around a sample colour proved that equal distances in the colour space do not correspond to equally perceived colour differences. In other words: the CIE 1931 chromaticity diagram appeared to be non-uniform.



EXAMPLES
OF
MACADAM
ELLIPSES
IN
THE
1931
CHROMATICITY
DIAGRAM.

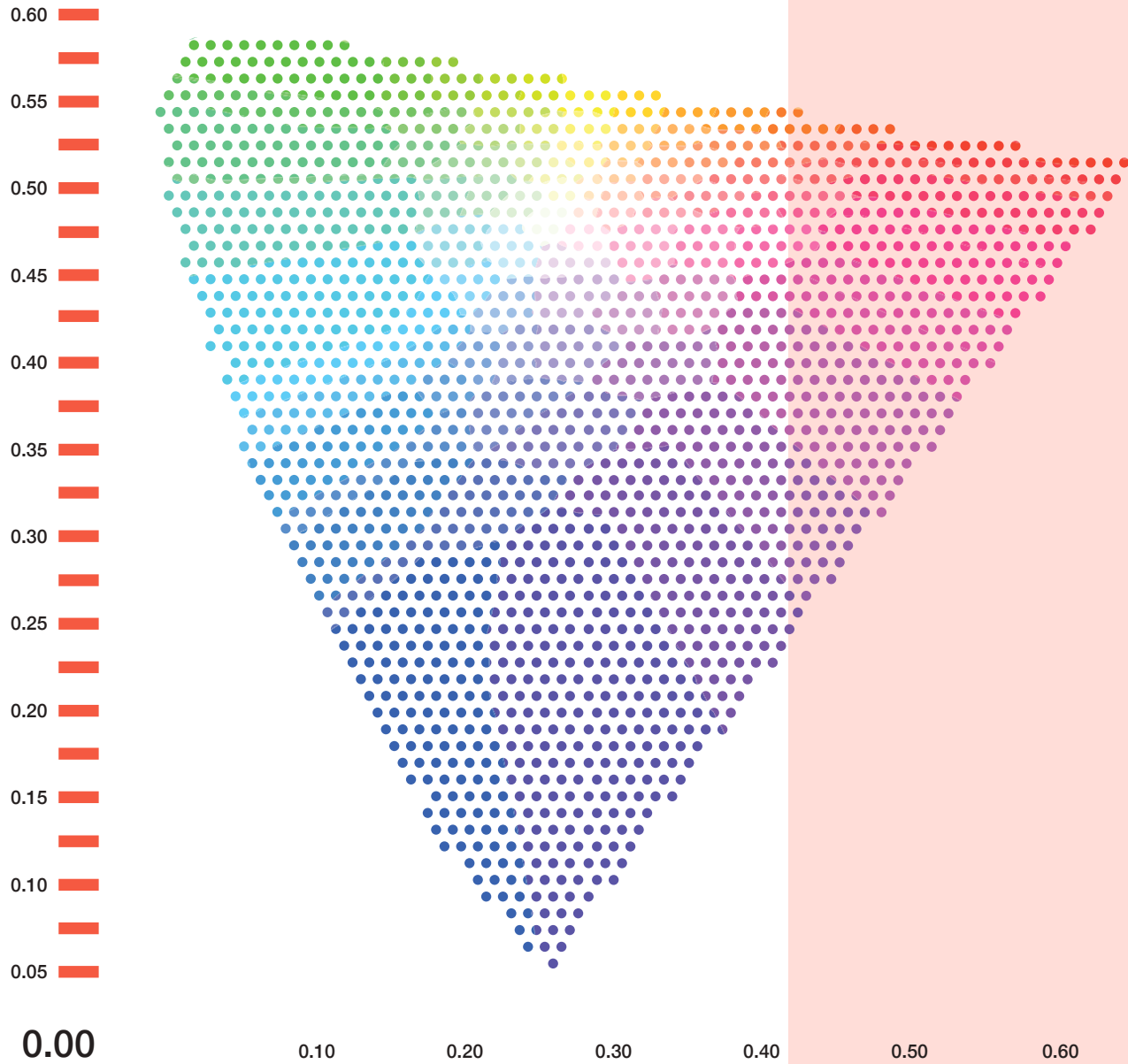
4.5 CIE 1960 & 1976

Although the 1931 colour space was based on the average human eye, its non-uniformity was considered a major disadvantage. To overcome its non-uniformity, an updated colour space was developed by the CIE in 1960 known as the Uniform Chromaticity Scale UCS. This new model was to be replaced quite quickly by its 1976 successor - the CIE $L^*u^*v^*$ and simultaneously the $L^*a^*b^*$ model. Instead of x and y , the 1960 UCS uses u and v as coordinates. To discriminate the differences between the 1960 and 1976 colour space, the 1976 uses u' and v' . Alike the 1931 and 1960 models these coordinates are based on CIE XYZ, but calculated in a slightly different way. CIE 1976 $u'v'$ calculation formulas:

$$u' = 4X / (X + 15Y + 3Z)$$

$$v' = 9Y / (X + 15Y + 3Z)$$

v'



The 1976 colour space is shaped in a similar way to its 1960 and 1931 predecessors with a spectral locus and purple line. Saturated colours are located along the spectral locus but colours and white point coordinates have moved according to the enhanced uniformity of the diagram. Despite the influence of the work by MacAdam, the improved colour space is not yet perfect. Creating and developing new and more accurate colour spaces that match the human eye is a continuous process in which the CIE plays an important role. Even though these developments allow for more accurate definitions in colour deviation, the older colour spaces such as CIE 1931 are still widely used in colour measurement.

u'

Application areas

ADMESY

Measuring and monitoring light and colour objectively and accurately is important to various industries and applications. Each industry has its own needs and challenges when it comes to measuring light and colour in, for example, R&D or production. Four important application areas Admesy supports include OEM spectrometry, display, lighting and analysis applications.

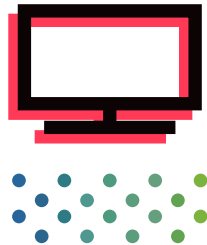
Application areas

5.1 OEM SPECTROMETRY



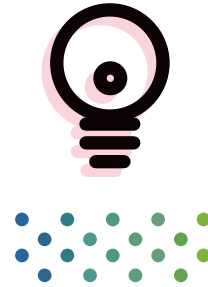
Besides stand-alone applications or the direct integration into production lines, Admesy's Rhea series spectrometers offer tailored spectral measurement engines fitted perfectly for OEM integration. Their configurational flexibility allows for any OEM integration where high-end measurements and accuracy are key.

5.2 DISPLAY



Both large displays and mobile display systems like LCD, LED and OLED may encounter variations in colour, luminance and flicker as a result of variation in production processes. Filtering or adjusting these optical characteristics early, during research and development, and later in production lines saves time, increases yield and customer satisfaction. To ensure the end product quality is at a high standard, displays are typically tested at several stages during the development and production process. Typical display tests include colour analysis to ensure uniformity of colour reproduction of displays, testing and adjusting flicker, white point adjustment and response time testing.

5.3 LIGHTING



LED and Solid state lighting [SSL] is often referred to as the light of the future: combining low energy consumption, efficient technology and long product life times. An inherent challenge to the production process of LEDs and Solid State Lighting products are driver related variations in their optical characteristics such as brightness, colour and flicker, even within the same production batches. In order to ensure a high-end lighting product, it is necessary to measure these optical characteristics during the development of LEDs and perform a 100% inspection during the production process. Typical LED and SSL measurements include the spectral power distribution, radiant power, irradiance, illuminance and flicker measurements.

5.4 ANALYSIS SOLUTIONS



Spectrometers can also be used as an analysis tool to measure the fluorescence or light absorption of translucent materials. For example, spectroscopy is carried out on optical foils or liquids in cuvettes to determine colour characteristics or to observe reactions by measuring the spectral throughput. Fluorescent effects or small deviations in colour or density can be analysed quickly by placing the product between a stabilized light source and a spectrometer. Other methods like reflective analysis can be used to measure the reflection of surfaces.



Colofon

‘Measuring Colour in a world of light’

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