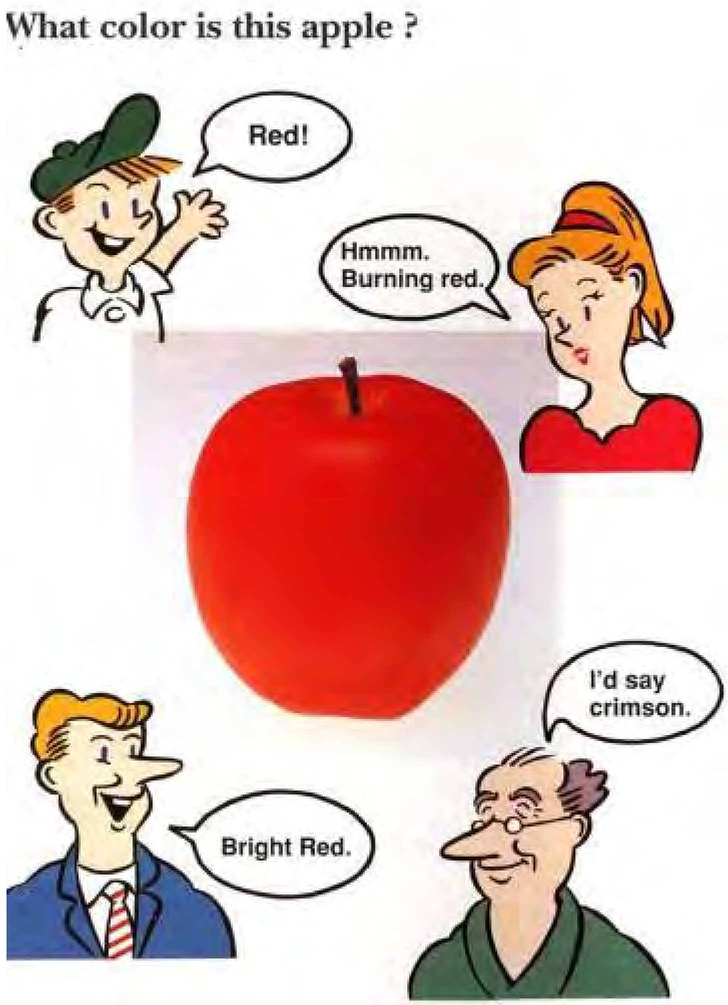
Fundamental of Colorimetry

Contents

1. Introduction

We need to measure and specify accurately colors.



1. Introduction

Inconsistent terminology in color appearance because our innate knowledge of color along with the imprecise use of color terms.

1. Introduction

Definitions of the perceptual attributes of color appearance, which define our perceptions of colored stimuli.

Sources for the definitions:

- The International Lighting Vocabulary published by the Commission Internationale de l'Éclairage, CIE.
- Two articles by Hunt, which provide descriptions of some of the work that led to the latest revision of the International Lighting Vocabulary.
- ASTM standard on appearance terminology.

1. Introduction

Color

The definition of the word color is quite difficult and usually includes circularity. According to The International Lighting Vocabulary color is:

"*Attribute of visual perception consisting of any combination of chromatic and achromatic content. This attribute can be described by chromatic color names such as yellow, orange, brown, red, pink, green, blue, purple, etc., or by achromatic color names such as white, gray, black, etc., and qualified by bright, dim, light, dark, etc., or by combinations of such names.*"

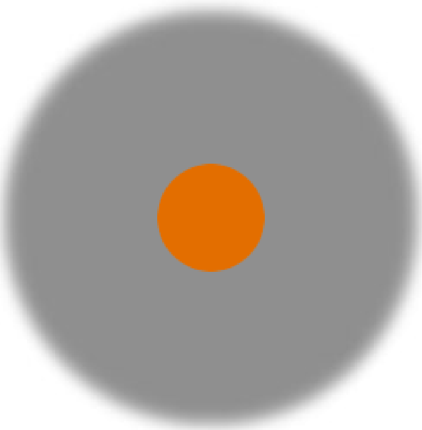
Note: "*Perceived color depends on the spectral distribution of the color stimulus, on the size, shape, structure, and surround of the stimulus area, on the state of adaptation of the observer's visual system, and on the observer's experience of the prevailing and similar situations of observations.*"

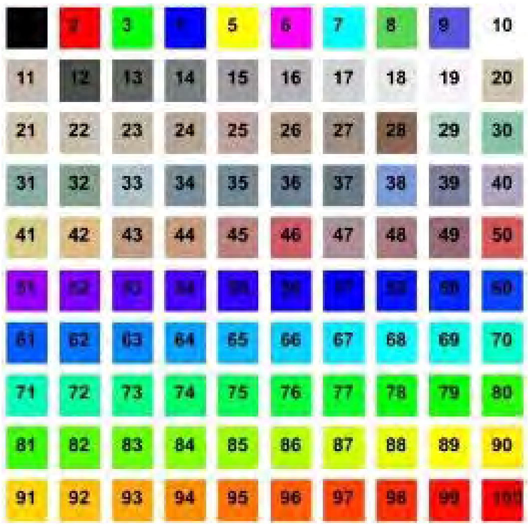
1. Introduction

Unrelated and related colors

- Unrelated Color: "*Color perceived to belong to an area or object seen in isolation from other colors.*"
- Related Color: "*Color perceived to belong to an area or object seen in relation to other colors.*"

The distinction between related and unrelated colors is critical for understanding color appearance.

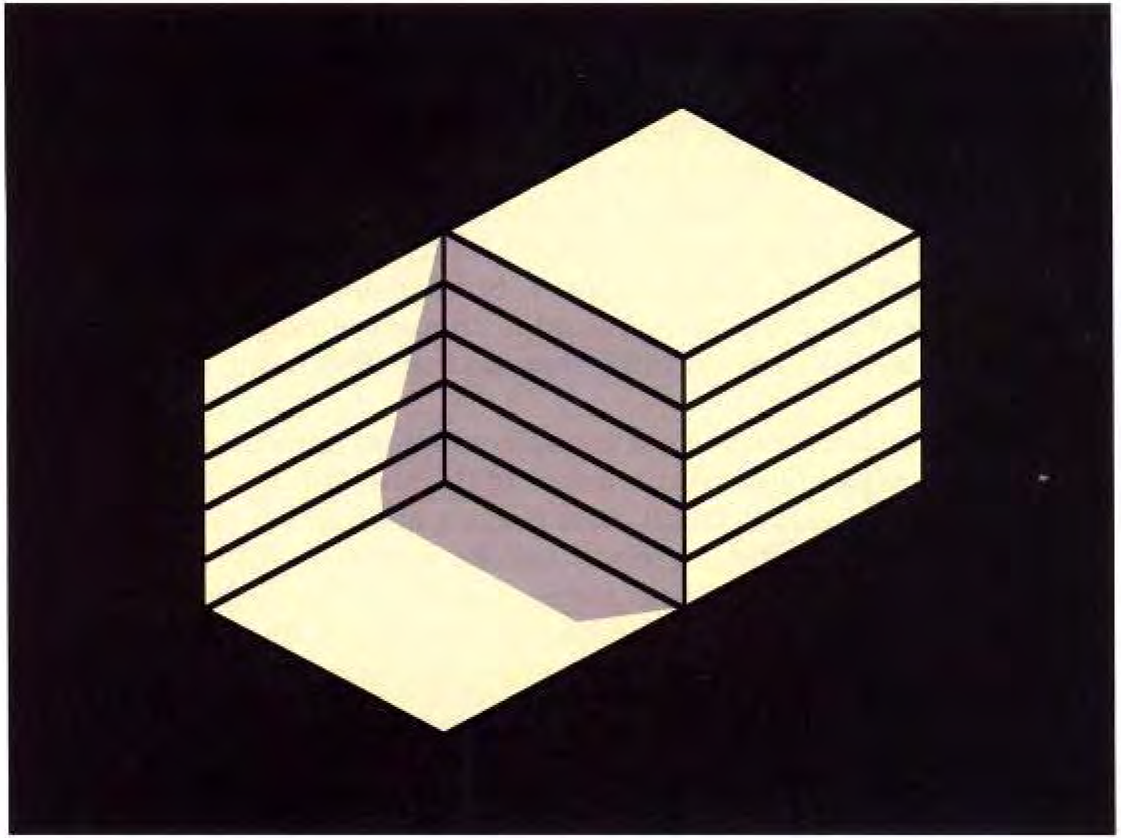




1. Introduction

Modes of viewing

The color appearance of object is based on cognitive information about the illumination and could not be reversed once the illumination is known. Knowledge of the object produced a color perception, even when it is not present.



1. Introduction

Modes of viewing

The five modes of viewing defined in the OSA chapter are:

1. **Illuminant**
   Color perceived as belonging to a source of light. It is an 'object mode'.
2. **Illumination**
   Color attributed to properties of the prevailing illumination rather than to objects. It is a 'non-object' mode and is mediated by the presence of illuminated objects that reflect light and cast shadows.
3. **Surface**
   Color perceived as belonging to a surface. It is an 'object mode'.
4. **Volume**
   Color perceived as belonging to the bulk of a more or less uniform and transparent substance. It is an 'object mode' and requires transparency.
5. **Film or aperture mode**
   Color perceived in an aperture with no connection to an object. It is a 'non-object' mode.

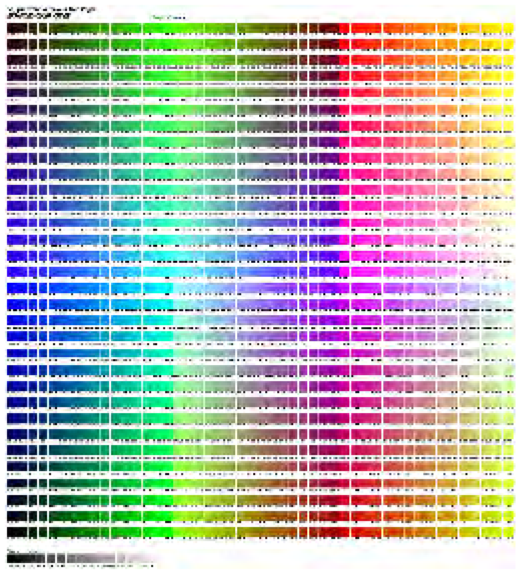
1. Introduction

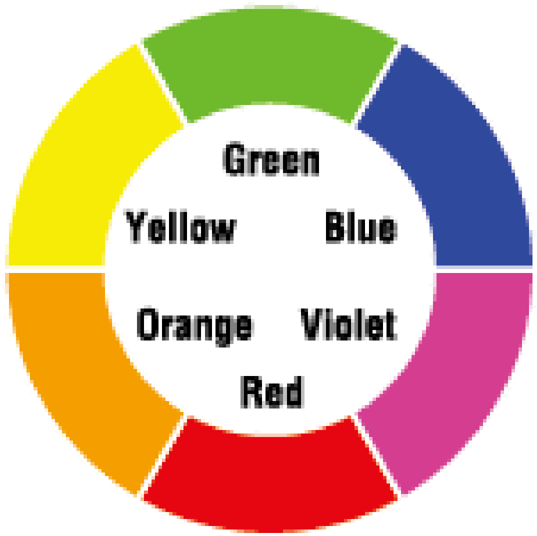
Hue

Hue: "*Attribute of a visual sensation according to which an area appears to be similar to one of the perceived colors: red, yellow, green, and blue, or to a combination of two of them.*"

Achromatic Color: "*Perceived color devoid of hue.*"

Chromatic Color: "*Perceived color possessing a hue.*"

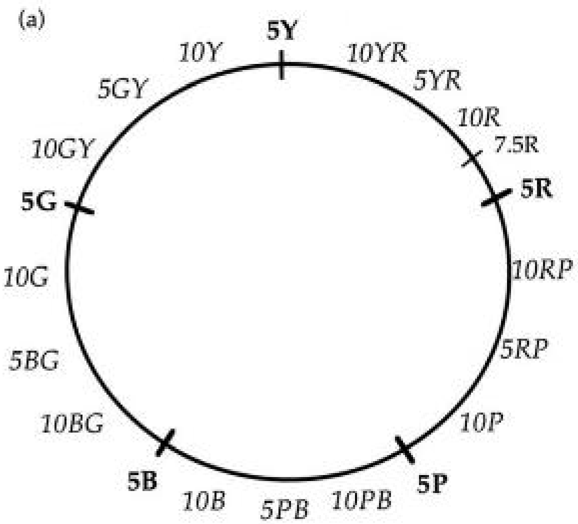


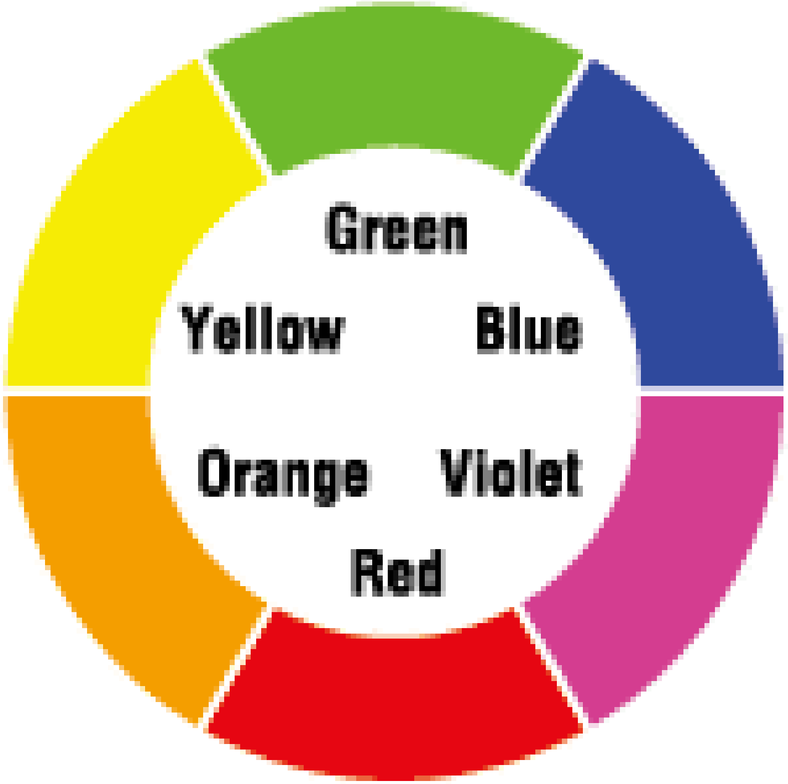


1. Introduction

Hue

All of the hues can be described using the terms red, yellow, green, blue, or combinations of them as predicted by Hering's opponent theory of color vision.





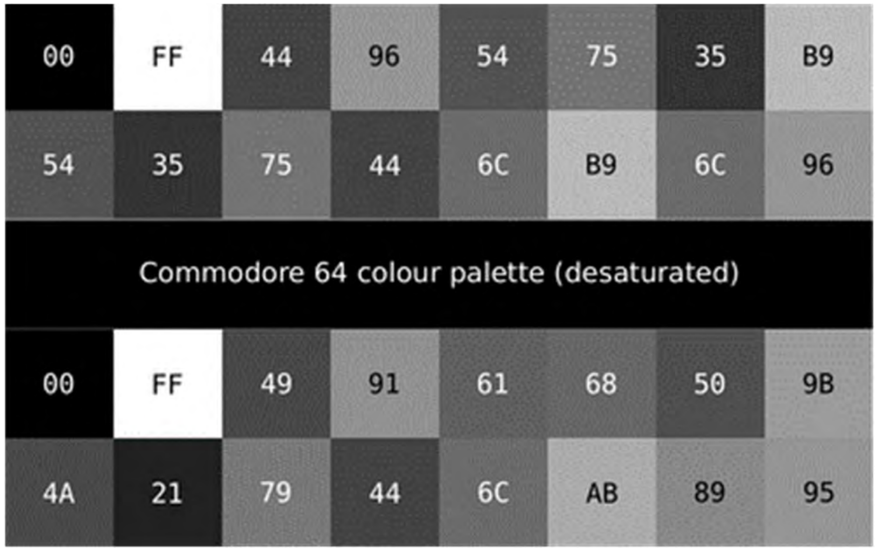
1. Introduction

Brightness and lightness

Brightness: "*Attribute of a visual sensation according to which an area appears to emit more or less light.*"

Lightness: "*The brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting.*"

$$\text{Lightness}=\frac{\text{Brightness}}{\text{Brightness (White)}}$$



Note: "*Only related colors exhibit lightness.*"

1. Introduction

Colorfulness and chroma

Colorfulness: "*Attribute of a visual sensation according to which the perceived color of an area appears to be more or less chromatic.*"

Note: "*For a color stimulus of a given chromaticity and, in the case of related colors, of a given luminance factor, this attribute usually increases as the luminance is raised, except when the brightness is very high.*"

Chroma: "*Colorfulness of an area judged as a proportion of the brightness of a similarly illuminated area that appears white or highly transmitting.*"

$$\text{Chroma}=\frac{\text{Colorfulness}}{\text{Brightness (White)}}$$

Note: "*For given viewing conditions and at luminance levels within the range of photopic vision, a color stimulus perceived as a related color, of a given chromaticity, and from a surface having a given luminance factor, exhibits approximately constant chroma for all levels of luminance except when the brightness is very high. In the same circumstances, at a given level of illuminance, if the luminance factor increases, the chroma usually increases.*"

1. Introduction

1. Introduction

Saturation

Saturation: "*Colorfulness of an area judged in proportion to its brightness.*"

$$\text{Saturation} = \frac{\text{Colorfulness}}{\text{Brightness}}$$

Note: "*For given viewing conditions and at luminance levels within the range of photopic vision, a color stimulus of a given chromaticity exhibits approximately constant saturation for all luminance levels, except when brightness is very high.*"

1. Introduction

Saturation

1. Introduction

The perceptual color terms hue, brightness, lightness, colorfulness, chroma, and saturation are applied differently to related and unrelated colors.

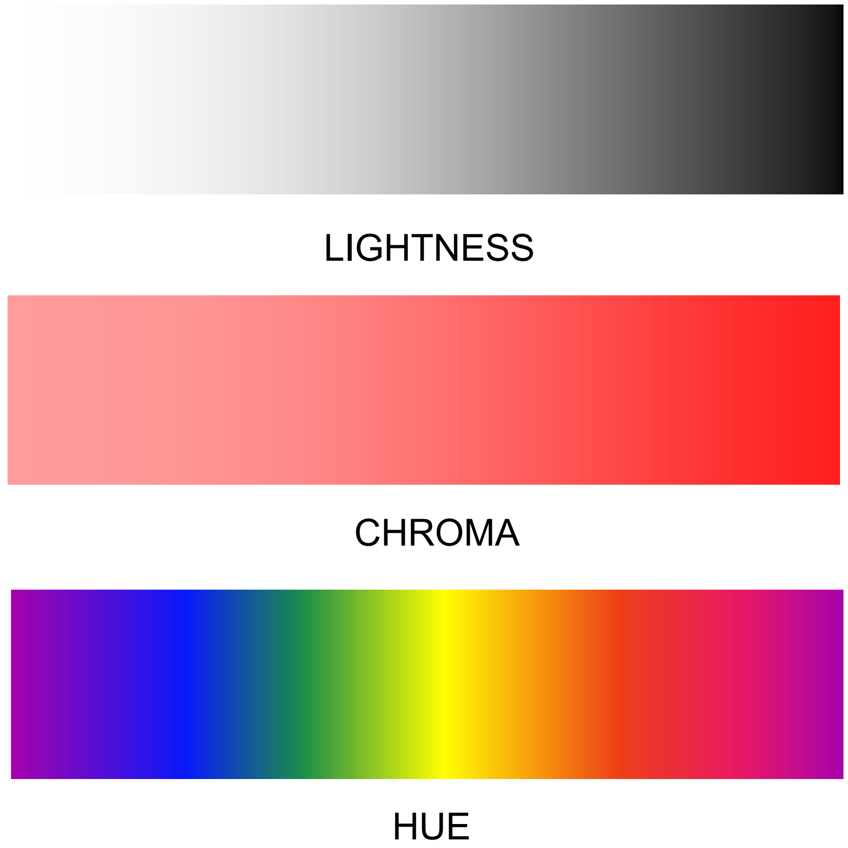
Unrelated colors only exhibit the perceptual attributes of hue, brightness, colorfulness, and saturation. The attributes that require judgment relative to a similarly illuminated white object cannot be perceived with unrelated colors.

Related colors exhibit all of the perceptual attributes of hue, brightness, lightness, colorfulness, chroma, and saturation.

1. Introduction

Five perceptual dimensions are required for a complete specification of color appearance:

- Brightness
- Lightness
- Colorfulness
- Chroma
- Hue



Saturation is redundant since it is known if the five attributes are known.

For related colors: lightness, chroma, and hue.

1. Introduction

Modes of viewing

Attribute	Illuminant (glow)	Illumination (fills space)	Surface (object)	Volume (object)	Film (aperture)
Brightness	*	*			*
Lightness			*	*	(*)
Colorfulness	*	*			*
Chroma			*	*	(*)
Hue	*	*	*	*	*

Table summarizes the color appearance attributes that are most commonly associated with each mode of viewing. Those in parenthesis are possible, although less likely.

1. Introduction

Basic colorimetry

Wyszecki's description of basic colorimetry is as follows:

'Colorimetry, in its strict sense, is a tool used to making a prediction on whether two lights (visual stimuli) of different spectral power distributions will match in colour for certain given conditions of observation. The prediction is made by determining the tristimulus values of the two visual stimuli. If the tristimulus values of a stimulus are identical to those of the other stimulus, a colour match will be observed by an average observer with normal colour vision.'

Basic colorimetry:

- CIE systems.
- Specify stimuli in terms of their sensory potential for an average human observer.
- Foundation for color appearance models.

1. Introduction

System of photometry

Spectral weighting function that could be used to describe the perception of brightness matches.

Direct comparison method: repeated for all the visible spectrum ($\Delta\lambda$=5 or 10 nm).

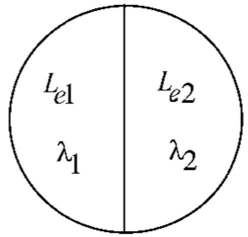
The value of K is called the luminous efficacy of radiation. The maximum value, K_m, of $K(\lambda)$, is called the maximum luminous efficacy.

The ratio of $K(\lambda)$ to K_m is called the **spectral luminous efficiency**, ***V*(λ).**

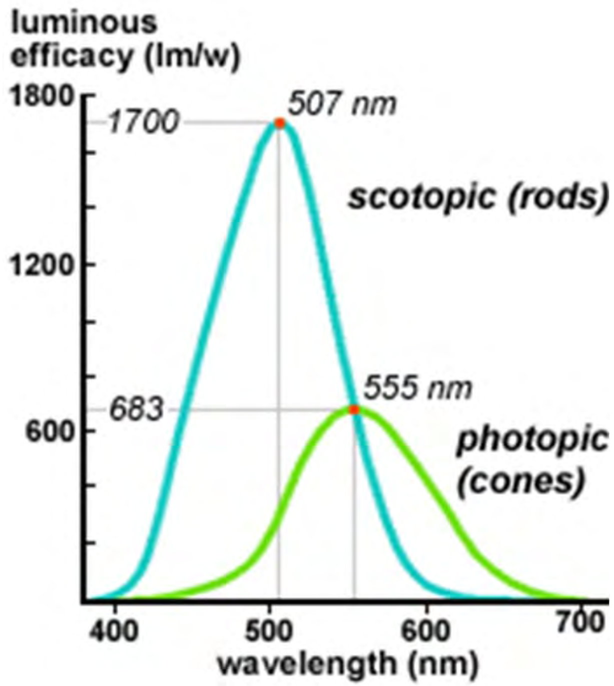
CIE spectralluminous efficiency function $V(\lambda)$ for photopic vision (1924): photopic vision.

The first step toward a system of colorimetry.

The $V(\lambda)$ function is used as a spectral weighting function to convert radiometric quantities into photometric quantities via spectral integration.



$$L_{e1} = K L_{e2}$$



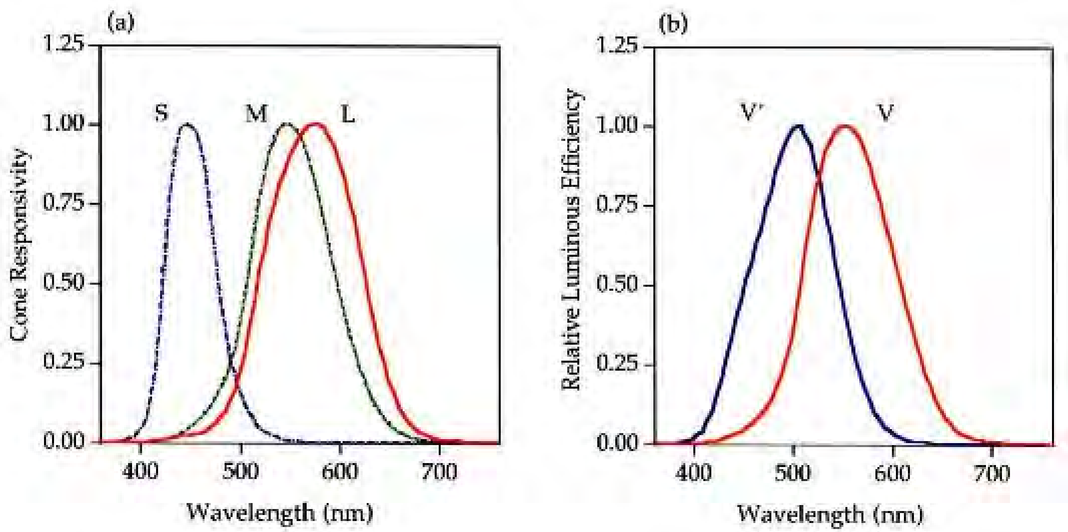
1. Introduction

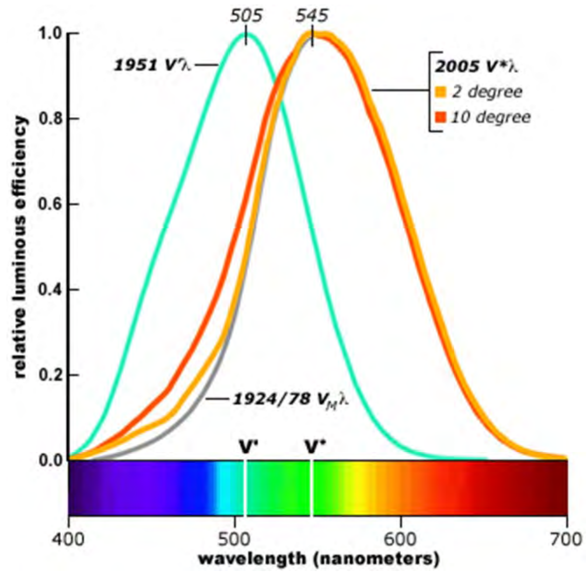
System of photometry

The *V*(λ) function is not one of the cone responsivities. Corresponds to a weighted sum of the three cone responsivity functions.

There is also a luminous efficiency function for scotopic vision (rods) known as the *V'*(λ) function: Purkinje shift.

CIE 1988 spectralluminous efficiency function, $V_M(\lambda)$.

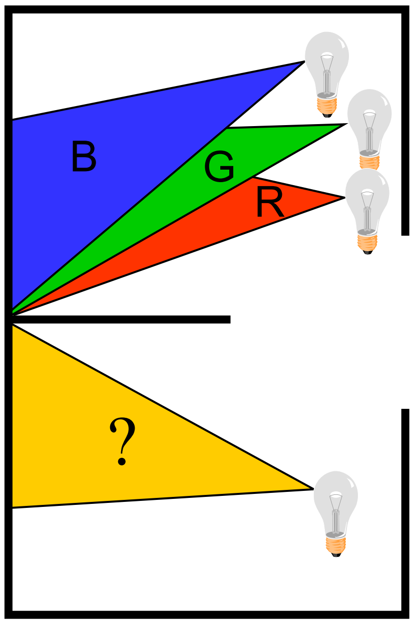


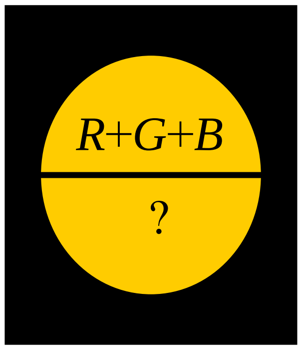


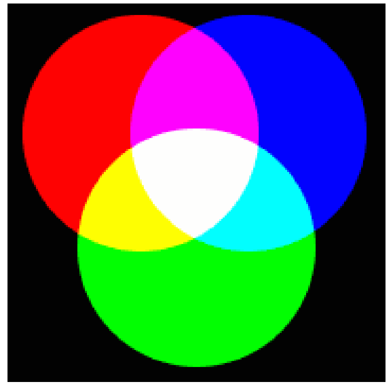
2. Color spaces

System of colorimetry

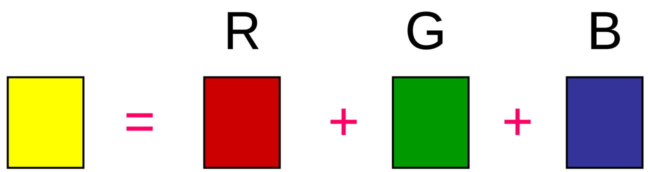
Based on the principles of trichromacy and Grassmann's laws of additive color mixture. 3 primary colors.







Tristimulus values: normalized quantities of each one of the primaries.



Specify when two metameric stimuli match in color for an average observer.

2. Color spaces

System of colorimetry

Grassmann's laws
We represent a color by (Q) and if two color match, the matching by:

(Q1)=(Q2)

Proportionality:
Color matching holds when the intensities (SPDs) of all the components are multiplied by a constant α.

If (Q1)=(Q2) then α(Q1)=α(Q2)

Additivity:
Color matching holds for stimuli obtained by adding color-matched stimuli.

If (Q1)=(Q2) and (Q3)=(Q4) then
(Q1)+(Q3)=(Q2)+(Q4)

2. Color spaces

System of colorimetry

Additive color matchings using primary stimuli

Consider a set of primary stimuli (R), (G) and (B). In general, a color stimulus can be matched by amounts R, G and B (tristimulus values) of (R), (G) and (B). Mathematically:

$$(Q)=R(R)+G(G)+B(B)$$

The colorimetric values R, G and B are relative values of luminance, in such a way that R=G=B for a match of specified standard stimulus (spectral equienergetic white). That is:

$$R=P_R/L_R,\ G=P_G/L_G \text{ and } B=P_B/L_B$$

Where P_R, P_G and P_B are the luminances of (R), (G) and (B) in the matching and L_R, L_G and L_B are called luminous units.

2. Color spaces

System of colorimetry

Extension of tristimulus values for any given stimulus defined by a spectral power distribution.

- Obtain tristimulus values for matches to spectral colors (color matching functions).

$$(q_\lambda) = r_\lambda(R) + g_\lambda(G) + b_\lambda(B)$$

- Grassmann's laws of additivity and proportionality.

$$(\mathrm{P}) = \sum_\lambda (\mathrm{P}_\lambda) = \sum_\lambda \mathrm{P}_\lambda(\mathrm{q}_\lambda)$$

$$(\mathrm{P}) = \sum_\lambda \mathrm{P}_\lambda(\mathrm{r}_\lambda(\mathrm{R}) + \mathrm{g}_\lambda(\mathrm{G}) + \mathrm{b}_\lambda(\mathrm{B})) = \sum_\lambda \mathrm{P}_\lambda \mathrm{r}_\lambda(\mathrm{R}) + \sum_\lambda \mathrm{P}_\lambda \mathrm{g}_\lambda(\mathrm{G}) + \sum_\lambda \mathrm{P}_\lambda \mathrm{b}_\lambda(\mathrm{B})$$

On the other hand: (P)=R(R)+G(G)+B(B)

$$\mathrm{R} = \sum_\lambda \mathrm{P}_\lambda \mathrm{r}_\lambda \qquad \mathrm{G} = \sum_\lambda \mathrm{P}_\lambda \mathrm{g}_\lambda \qquad \mathrm{B} = \sum_\lambda \mathrm{P}_\lambda \mathrm{b}_\lambda$$

2. Color spaces

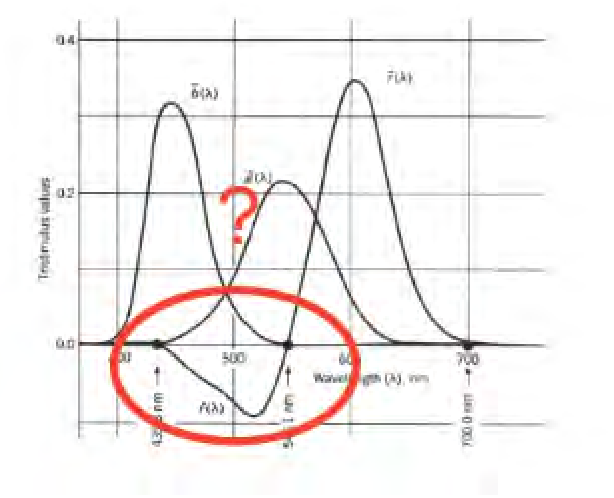
System of colorimetry: color matching functions

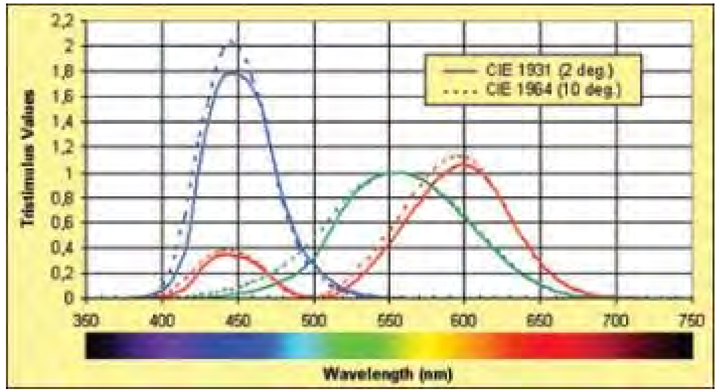
Color matching functions for individual observers, all with normal color vision, can be significantly different.

Establish a standardized system of colorimetry, the CIE adopted an average of the data reported by Guild (1931) obtained for seven observers and Wright (1928-1929) from ten observers.

William David Wright
1908-1998

John Guild
1889-1979





2. Color spaces

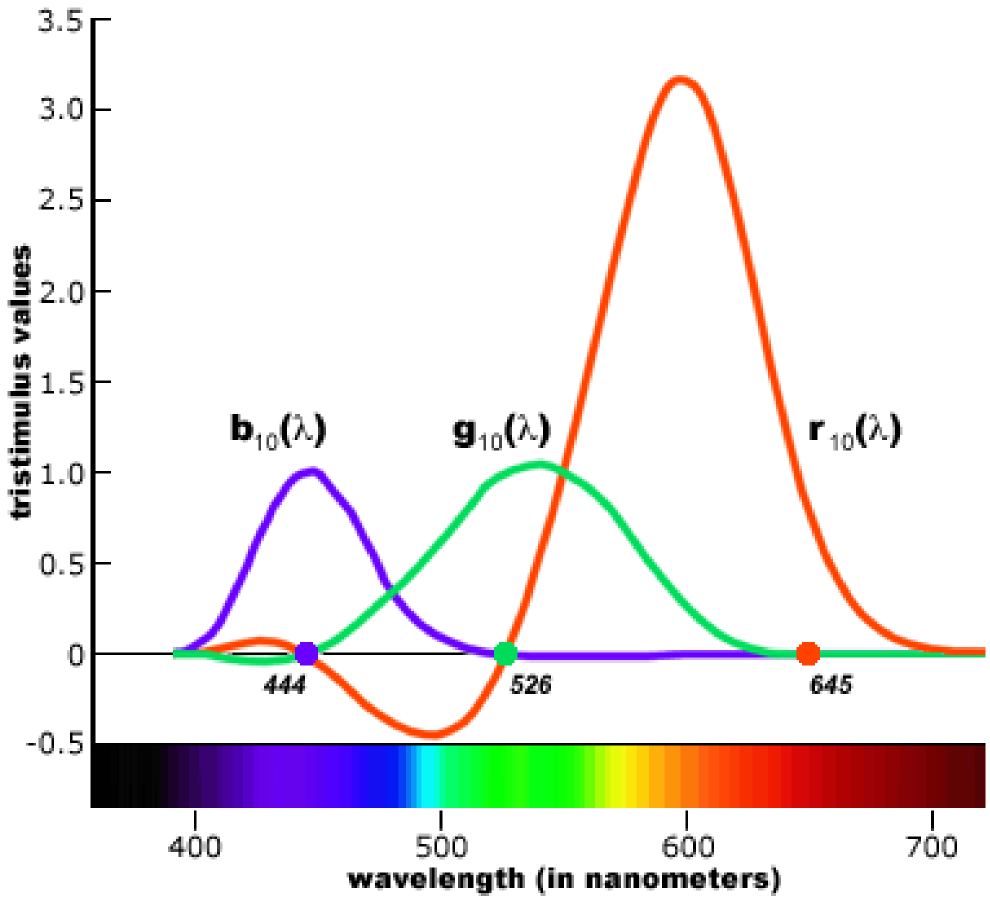
Color matching functions

Quantification of the human visual response by the absorption of energy in the cone photoreceptors.

Psychophysics: color matching, by spectral responsivities of the three cone types.

Metamerism: only the three signals from the cones need be equal for a color match, it is not necessary for the spectral power distributions of the two stimuli to be equal.

The CIE, in establishing the 1931 system of colorimetry, predates the knowledge of the cone spectral responsivities.



2. Color spaces

CIE 1931 RGB color specification system

In 1931 the CIE adopted the primary stimuli: (R), (G) and (B) are monochromatic lights of wavelength 700.0 , 546.1 and 435.8 nm respectively.

The basic stimulus is the white color stimulus of the equi-energy spectrum. The amount of the primary stimuli (R), (G) and (B) required to match the basic stimulus are in the ratio 1.0000:4.5907:0.0601 when expressed in photometric units.

2. Color spaces

CIE 1931 RGB color specification system

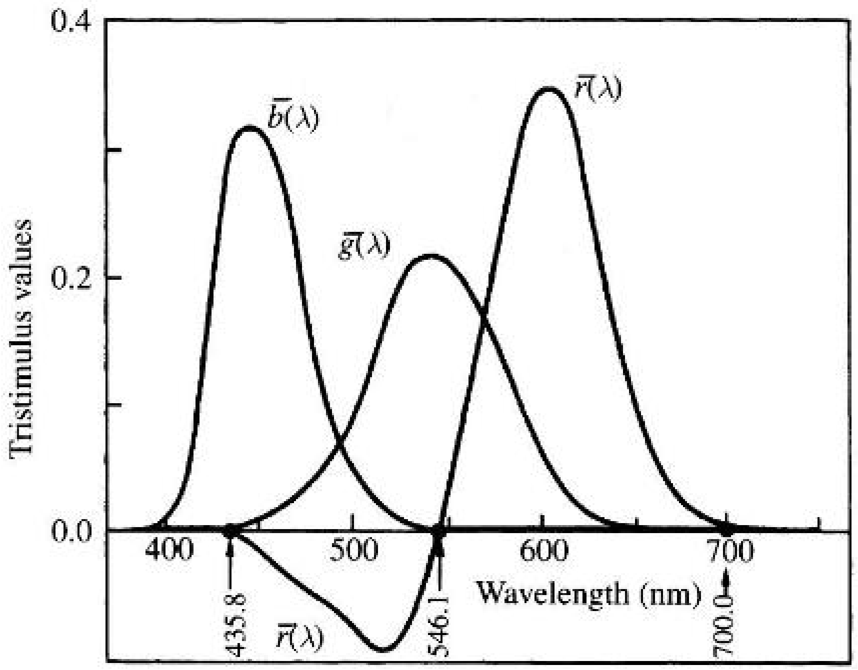
Why negative values of the color-matching functions?

For certain monochromatic lights is impossible to obtain a match with the additive mixing of amounts of the primary stimuli. But it is possible a match in this way:

$$(F_\lambda) + R(R) = G(G) + B(B)$$

That is:

$$(F_\lambda) = -R(R) + G(G) + B(B)$$

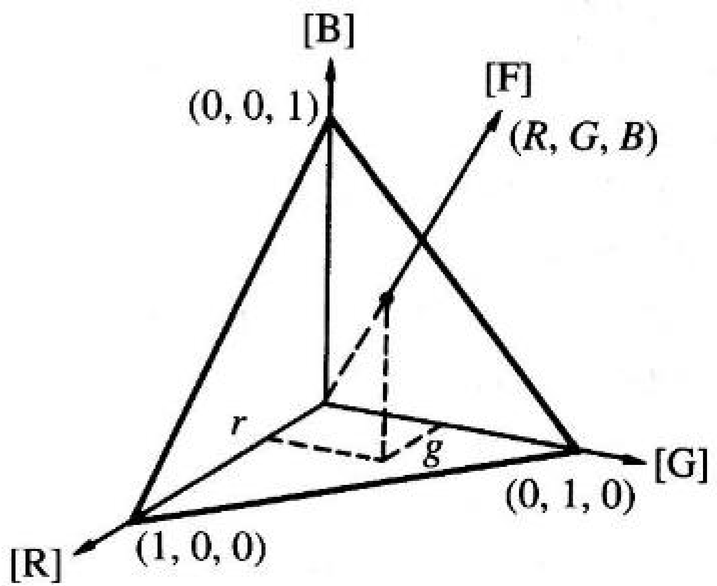


2. Color spaces

CIE 1931 RGB color specification system

A three-dimensional space can be defined in which any color (F) can be specified by its corresponding tristimulus values. This space is named color space, where the color (F) is specify by the vector components (R,G,B)

$$(F) = R(R) + G(G) + B(B)$$

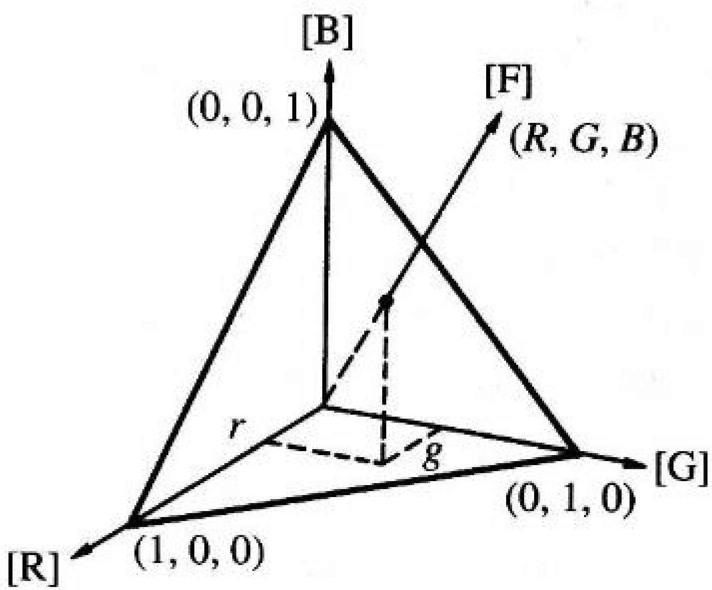


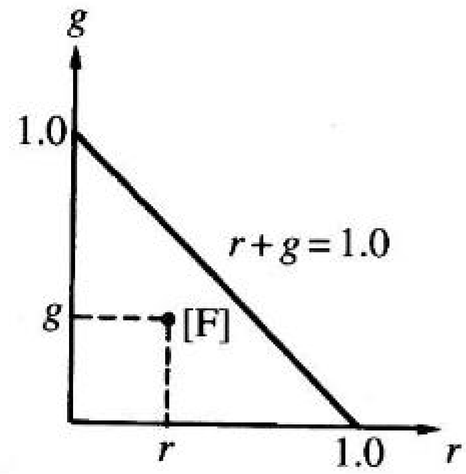
2. Color spaces

CIE 1931 RGB color specification system

The intersection (r,g,b) of the vector (F) and the plane R+G+B=1 are named chromaticity coordinates.

$$r = R/(R+G+B)$$
$$g = G/(R+G+B)$$
$$b = B/(R+G+B)$$

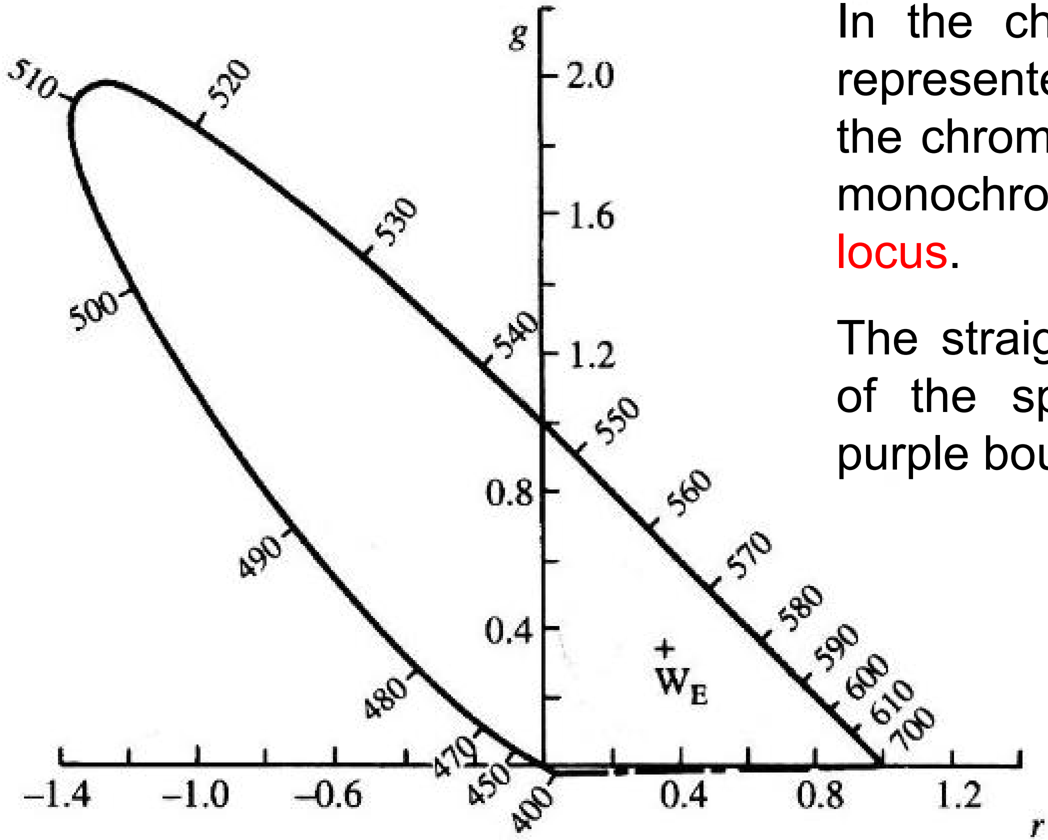




Two coordinates out of the three (r,g) are sufficient to locate the color (F) in the unit plane. The diagram showing two chromaticity coordinates in a plane is called a chromaticity diagram.

2. Color spaces

CIE 1931 RGB color specification system: chromaticity diagram



In the chromaticity diagram it is represented the curve representing the chromaticity coordinates of the monochromatic stimuli: spectrum locus.

The straight line joining each end of the spectrum locus is called purple boundary.

2. Color spaces

CIE 1931 RGB color specification system

Chromaticity diagram

1.- The color obtained by mixing two colors has its chromaticty coordinates in the straight line defined by joining the points representing in the diagram the primary stimuli in the mixing.

The distances to each primary are inverse to the amounts of each primary in the mixing.

2.- The colors that ca be obtained by mixing three primary stimuli have their chromaticity coordinates inside the triangle defined by the chromaticity coordinates of the three primaries.

3.- According to the previous properties and the Grassmann's laws, any real color has its chromaticity coordinates inside the region limited by the spectrum locus and the purple boundary.

The equi-energy white light has r=g=1/3.

2. Color spaces

CIE 1931 XYZ color specification system

A color specification system can be converted into a new one defined for different set of primaries just applying a linear transform which relates the tristimulus values in both systems.

In 1931 the CIE defined the CIE 1931 XYZ color specification system by transforming the RGB system. The premises for the new system were the followings:

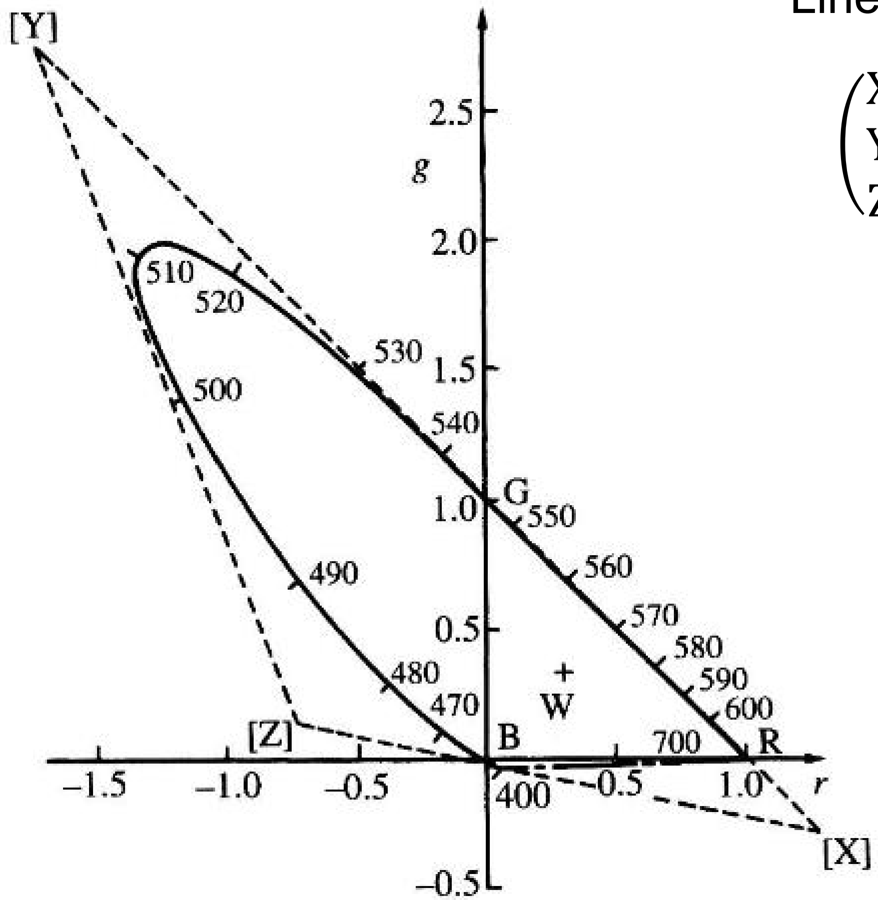
1.- Avoiding negative tristimulus values. For that it is necessary to take a set of imaginary primaries which defined a triangle in the chromaticity diagram which included all real colors.

2.- One of the new color-matching functions, should coincide with the function V_λ, that is the tristimulus value Y directly expresses a photometric quantity.

3.- The straight line connecting the primary stimuli (X) and (Y) in the chromaticity diagram is tangential to the spectrum locus at the long wavelength end (λ≥650 nm).

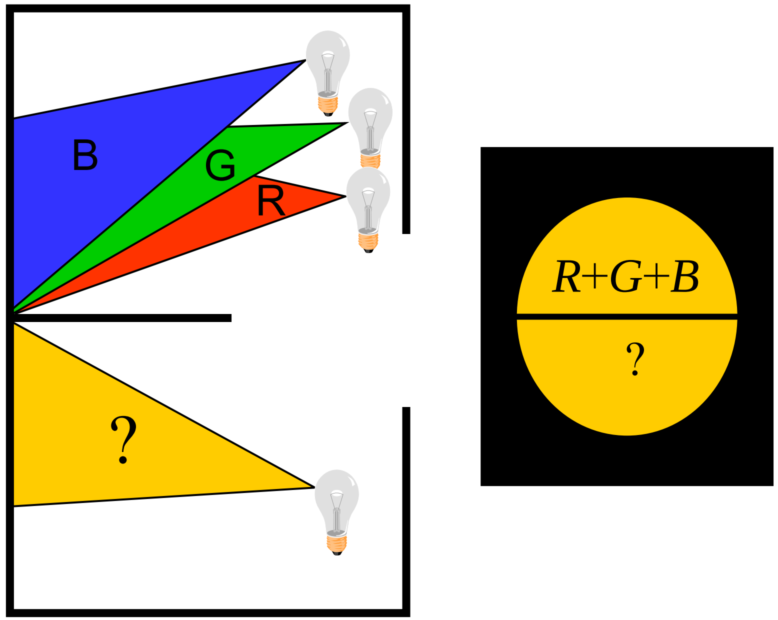
2. Color spaces

CIE 1931 XYZ color specification system



Linear transformation between color spaces

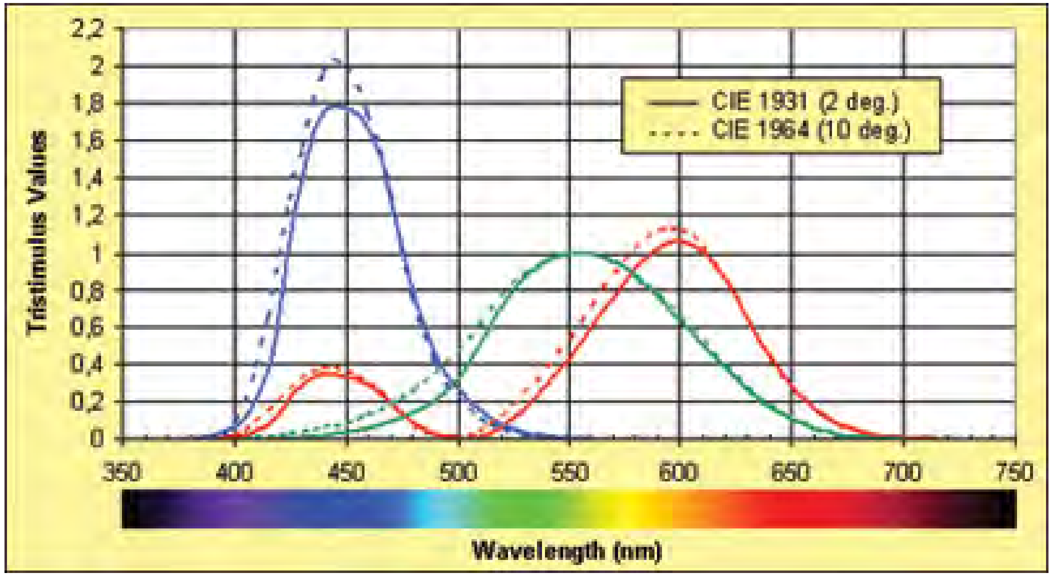
$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 2.7989 & 1.7517 & 1.1302 \\ 1.0000 & 4.5907 & 0.0601 \\ 0.0000 & 0.0565 & 5.5943 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$



2. Color spaces

CIE 1931 XYZ color specification system

As color-matching functions are tristimulus values, the new color-matching functions are defined from the previous by the linear transformation.



As the color-matching functions were experimentally obtained for a vision field of 2º, the virtual observer having these color-matching functions is called the CIE 2º Colorimetric Observer or the CIE 1931 Standard Colorimetric Observer.

2. Color spaces

CIE 1931 XYZ color specification system

Absolute tristimulus values can be computed as:

$$X = k \int_{vis} \Phi(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = k \int_{vis} \Phi(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z = k \int_{vis} \Phi(\lambda)\bar{z}(\lambda)d\lambda$$

If k=683 lm/w and Φ(λ) is the spectral radiance of the color stimulus, the value of Y is the luminance of the stimulus, roughly correlated with its brightness.

2. Color spaces

CIE 1931 XYZ color specification system

Normalized tristimulus values for a reflecting object, the color stimulus is $\Phi(\lambda)=R(\lambda)P(\lambda)$, where $R(\lambda)$ is the spectral reflectance of the object and $P(\lambda)$ is the SPD of the illuminating source.

$$X = k \int_{vis} R(\lambda)P(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = k \int_{vis} R(\lambda)P(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z = k \int_{vis} R(\lambda)P(\lambda)\bar{z}(\lambda)d\lambda$$

$$k = 100/\int_{vis} P(\lambda)\bar{y}(\lambda)d\lambda$$

Y is called luminance factor and it is roughly correlated with the lightness of the object color.

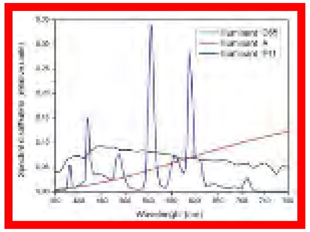
2. Color spaces

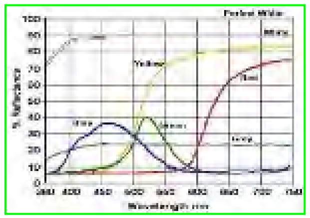
Basic and Advanced Colorimetry

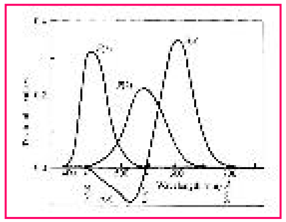
$$X = k\int_{vis} S(\lambda)R(\lambda)\bar{x}(\lambda)\,d\lambda$$

$$Y = k\int_{vis} S(\lambda)R(\lambda)\,\bar{y}(\lambda)\,d\lambda$$

$$Z = k\int_{vis} S(\lambda)R(\lambda)\,\bar{z}(\lambda)\,d\lambda$$



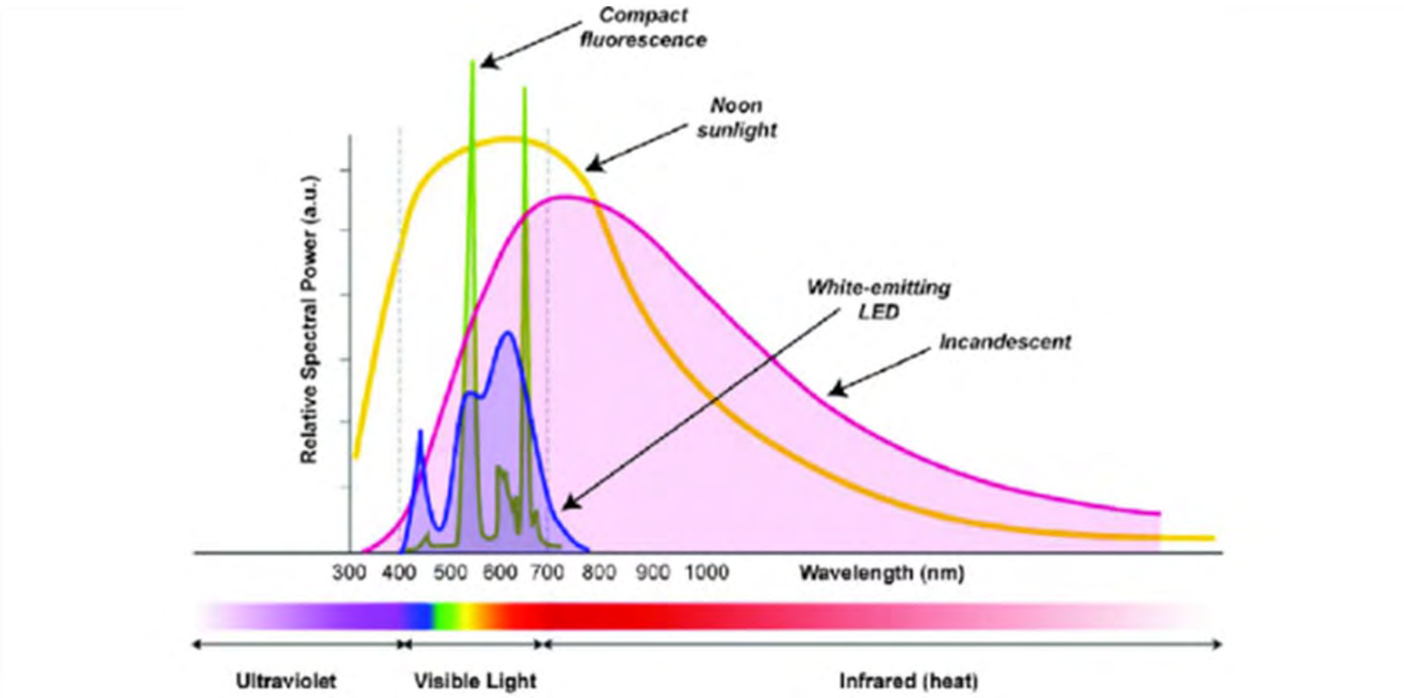




2. Color spaces

Spectral Power Distribution (SPD)

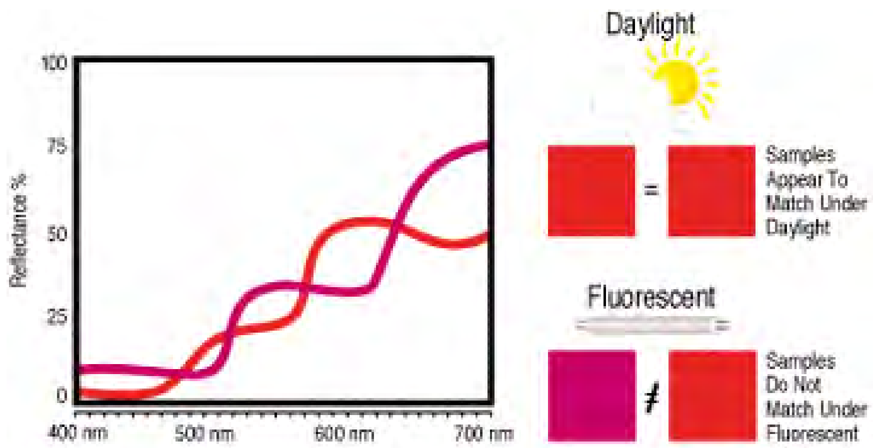
Representation of the spectral radiant flux, intensity or radiance of a source. It can be presented in absolute o relative terms.



https://www.researchgate.net/figure/Spectral-energy-distribution-for-different-light-emitting-sources-Taken-from-Ref-3_fig2_261702372

2. Color spaces

CIE 1931 XYZ color specification system

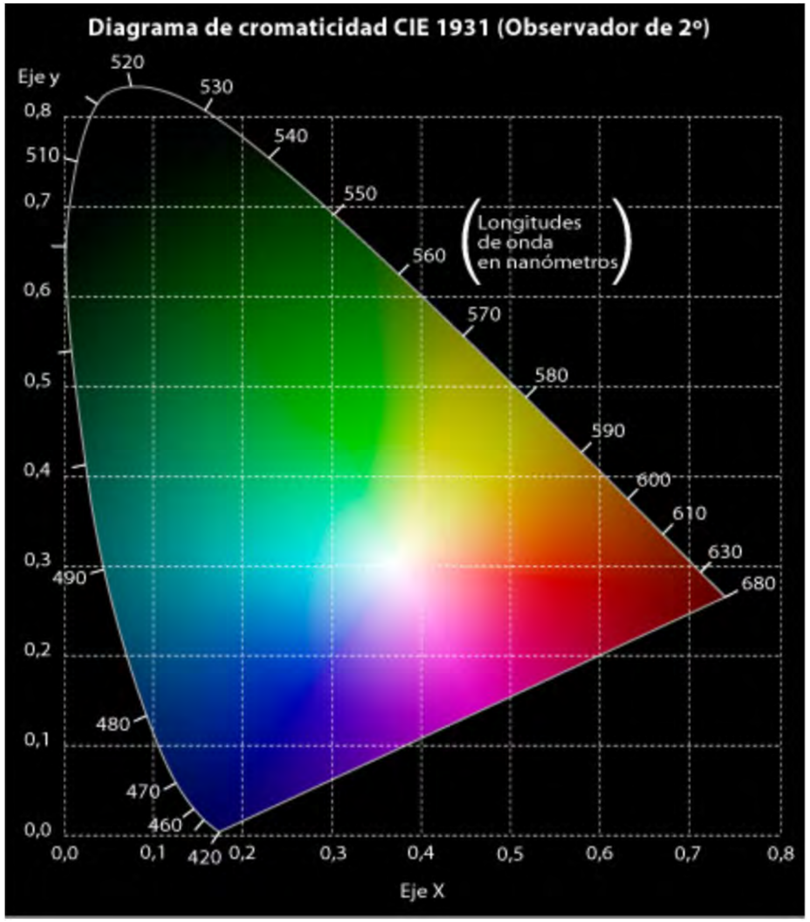


Reflectance Curves of a Metameric Pair

Metamerism of the illuminant: two object color with different spectral reflectances with the same tristimulus values under a specific illuminant.

2. Color spaces

CIE 1931 XYZ color specification system: (*x*,*y*) chromaticity diagram



$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

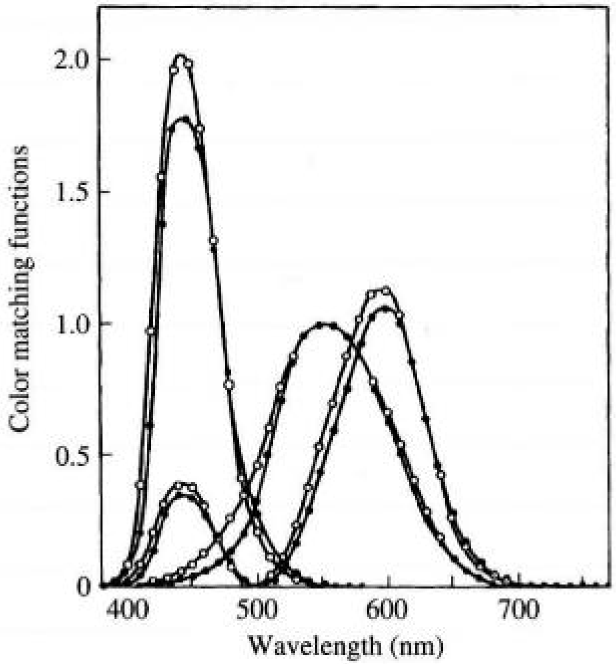
chromaticity coordinates

2. Color spaces

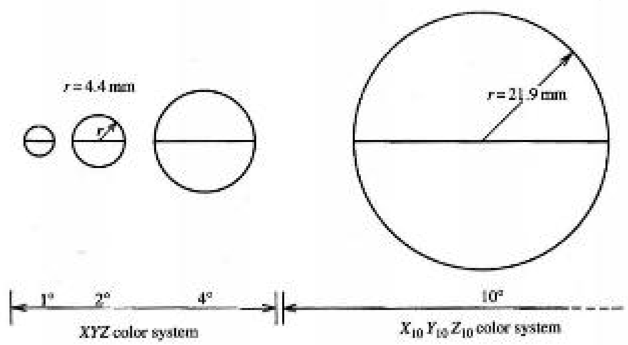
CIE 1964 XYZ color specification system

Color matching experiments change when the size of the vision field changes due to distribution of photoreceptors in the retina and the presence of macular pigment in the central field (around 4º).

Color-matching functions were experimentally measured for vision fields of 10º by Stiles and Burch (49 observers) and Speranskaya (27 observers). The result is the CIE 10º Colorimetric Observer or the CIE 1964 Standard Colorimetric Observer.



The CIE recommend these color-matching functions for a viewing angle exceeding 4º and the former for viewing angles less than 4º.



2. Color spaces

LMS color specification system

LMS (long, medium, short), is a color space which represents the response of the three types of cones of the human eye. The tristimulus values are related with the cone responses. This space is called cone excitations space.

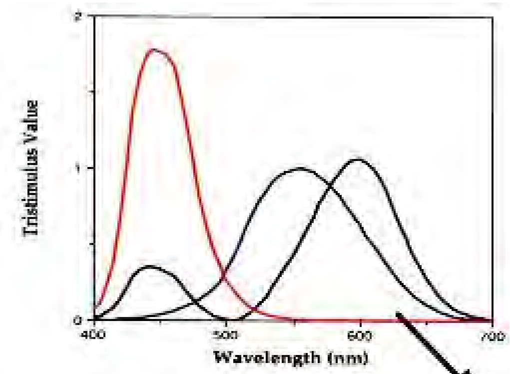
Color matching functions corresponds with the spectral sensitivities of the cones.

Fortunately, cone excitations can be reasonably approximated by a linear transformation (Hunt-Pointer-Estevez matrix) of CIE tristimulus values.

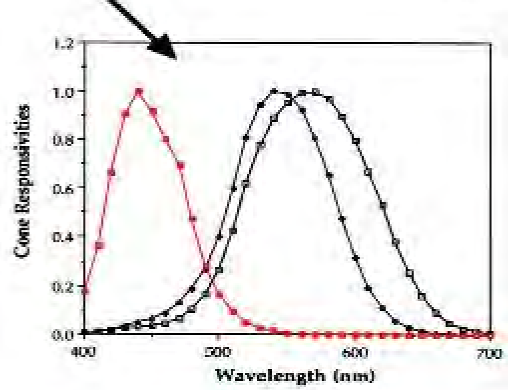
It is common to use the LMS color space when performing chromatic adaptation. It's also useful in the study of color blindness, when one or more cone types are defective or missing.

2. Color spaces

LMS color specification system



$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.400 & 0.708 & -0.081 \\ -0.226 & 1.165 & 0.046 \\ 0.000 & 0.000 & 0.918 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$



$$M_{HPE} = \begin{pmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0 & 0 & 1 \end{pmatrix}$$

Equal-energy illuminant

$$M_{HPE} = \begin{pmatrix} 0.4002 & 0.7076 & -0.0808 \\ -0.2263 & 1.1653 & 0.0457 \\ 0 & 0 & 0.9182 \end{pmatrix}$$

D65 illuminant

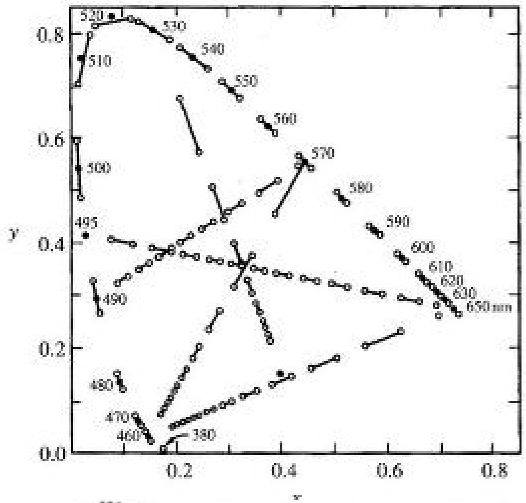
2. Color spaces

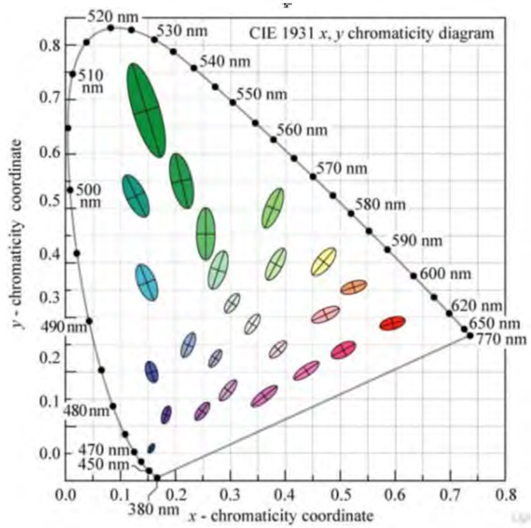
CIELAB color space

Non-uniformity of the CIE-1931 (xy) chromaticity: diagram when representing color discrimination data in the CIE (*x*,*y*) chromaticity diagram it is observed that equal perceived color differences do not correspond with equal distances on the diagram.

Wright reported pairs of color having the same small perceived difference at the same luminance (just-noticeable differences, jnd).

MacAdam conducted a experiment in order to obtain the region around a stimulus in the chromaticity diagram that includes the chromaticity coordinates of the stimuli that are seen indistinguishable to it. That is, the chromaticity-differential thresholds, obtaining the MacAdam ellipses.

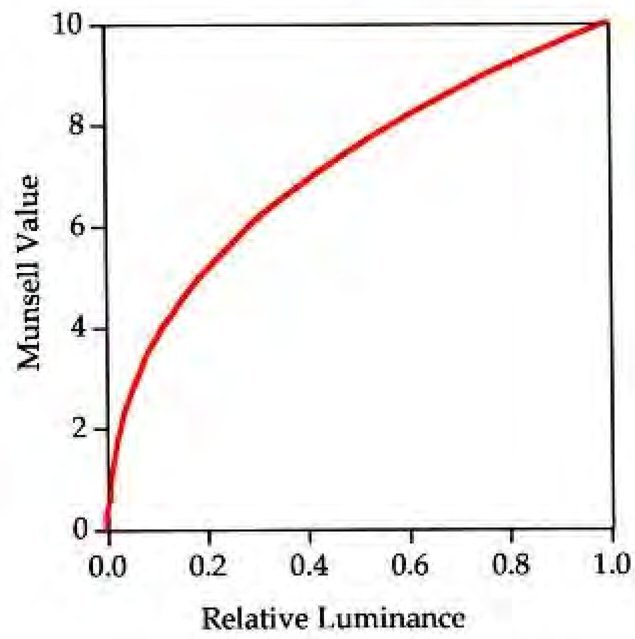




2. Color spaces

CIELAB color space

The luminance, *Y*, does not have a uniform scale with respect to lightness. More specifically, lightness does not increase linearly with *Y*.



The relationship between Munsell value *V* and relative luminance *Y* is nonlinear, and is given by the following fifth-order polynomial:

$$Y = 1.2219V - 0.23111V^2 + 0.23951V^3 - 0.021009V^4 + 0.0008404V^5$$

2. Color spaces

CIELAB color space

CIELAB as a color space to be used for color differences.

CIELAB uniform color space.

CIELAB can be considered a easy color appearance model.

$$L^* = 116\left(\frac{Y}{Y_o}\right)^{1/3} - 16 \quad if \left(\frac{Y}{Y_o}\right) > 0.008856$$

$$L^* = 903.3\left(\frac{Y}{Y_o}\right) \quad if \left(\frac{Y}{Y_o}\right) \leq 0.008856$$

Pauli correction

Modified von Kries chromatic adaptation transform by normalizing the stimulus tristimulus values by those of the white (X_o,Y_o,Z_o).

$$a^* = 500[f(X/X_o) - f(Y/Y_o)]$$

$$b^* = 200[f(Y/Y_o) - f(Z/Z_o)]$$

$$f(\alpha) = \alpha^{1/3} \quad \text{if } \alpha > 0.008856$$

$$f(\alpha) = 7.787\alpha + \frac{16}{116} \quad \text{if } \alpha \leq 0.008856$$

Pauli correction

2. Color spaces

CIELAB color space

CIELAB *L**, *a**, and *b** are Cartesian coordinates.

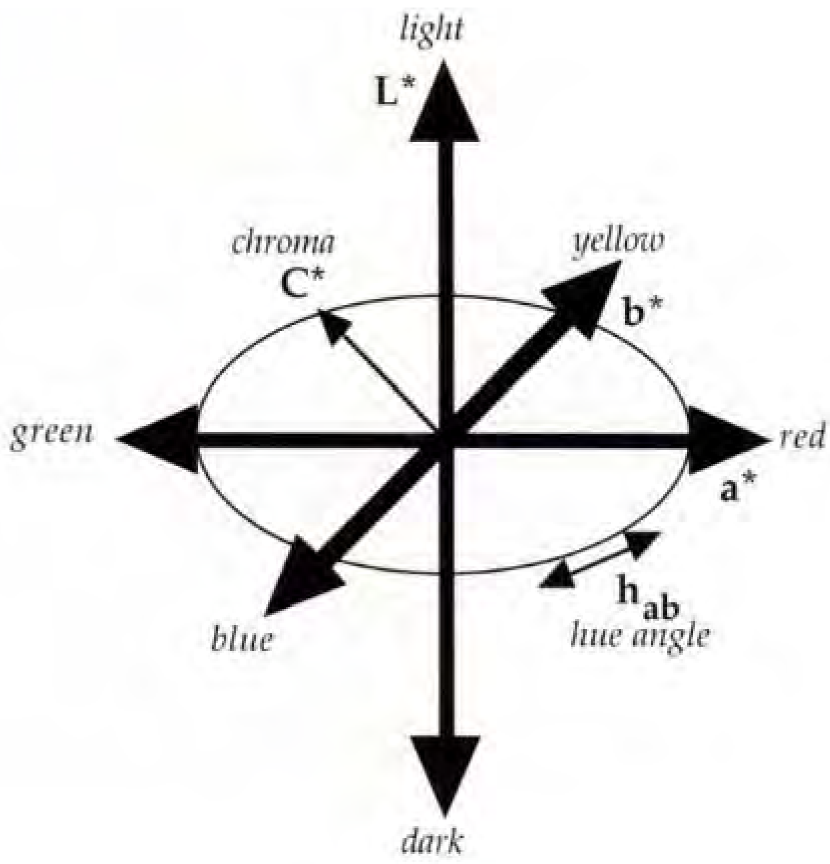
*L** is correlate to perceived lightness ranging from 0.0 to 100.0 for a diffuse white (>100 fluorescence, specular images..).

*a** and *b** correlate with red-green and yellow-blue chroma perceptions.

Cylindrical coordinates, which provides predictors of chroma C^*_{ab} and hue h_{ab}.

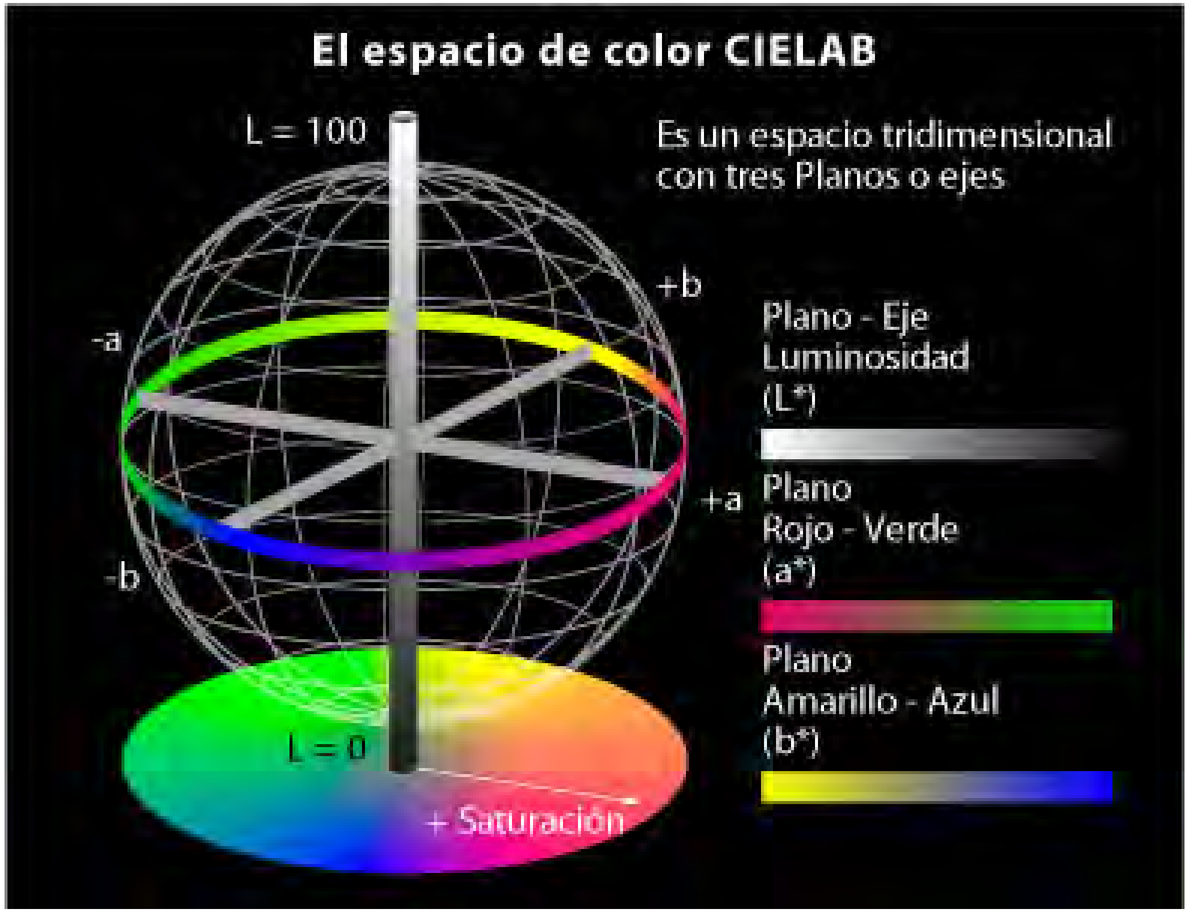
$$C^*_{ab} = \sqrt{(a^*)^2 + (b^*)^2}$$

$$h_{ab} = \arctan\frac{b^*}{a^*}$$



2. Color spaces

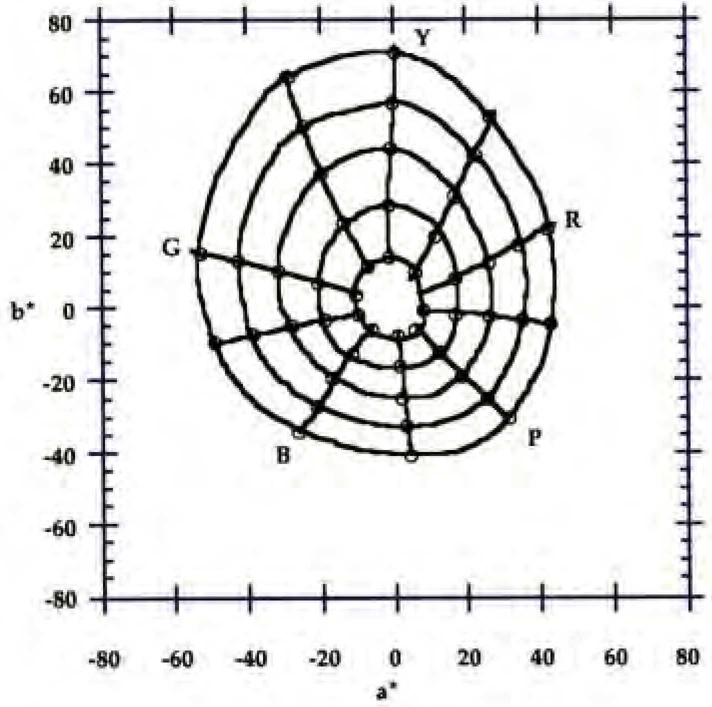
CIELAB color space



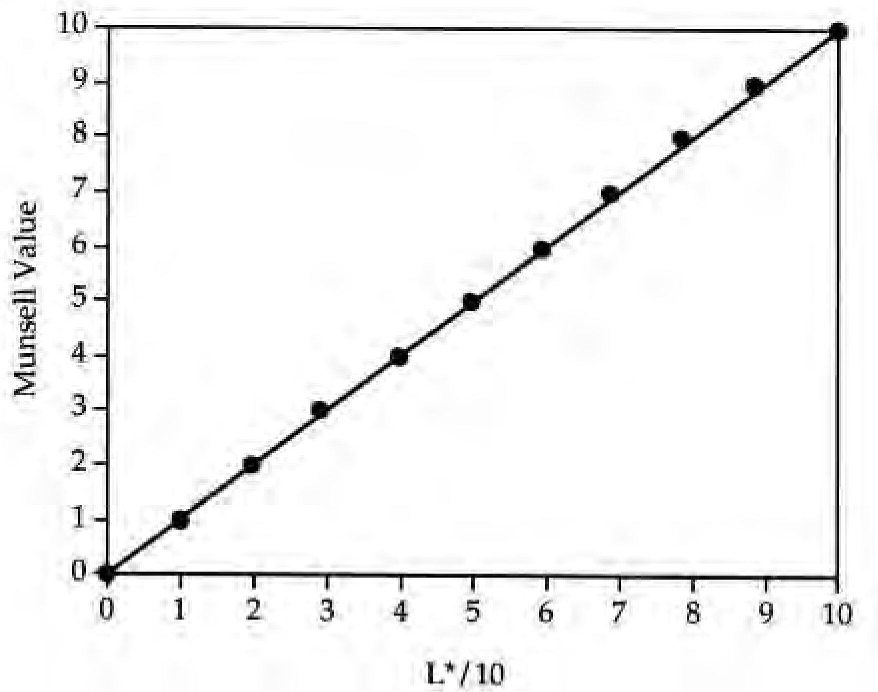
2. Color spaces

CIELAB color space

The perceptual non-uniformity of the CIELAB space.

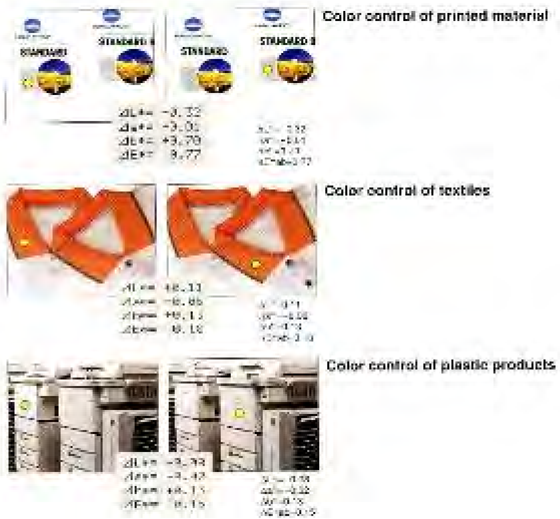


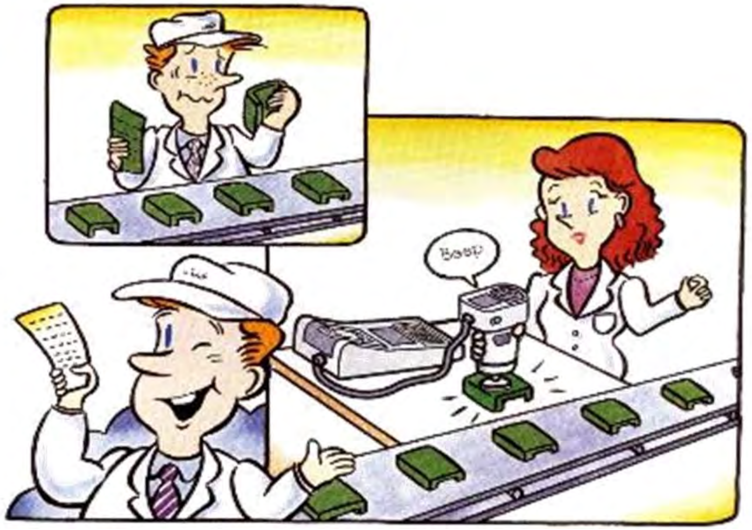
Plots of constant hue and chroma contours from the Munsell Book of Color



Munsell value as a function of *L**

3. Color difference formulas





3. Color difference formulas

Advanced colorimetry

Wyszecki describes the domain of advanced colorimetry as follow:

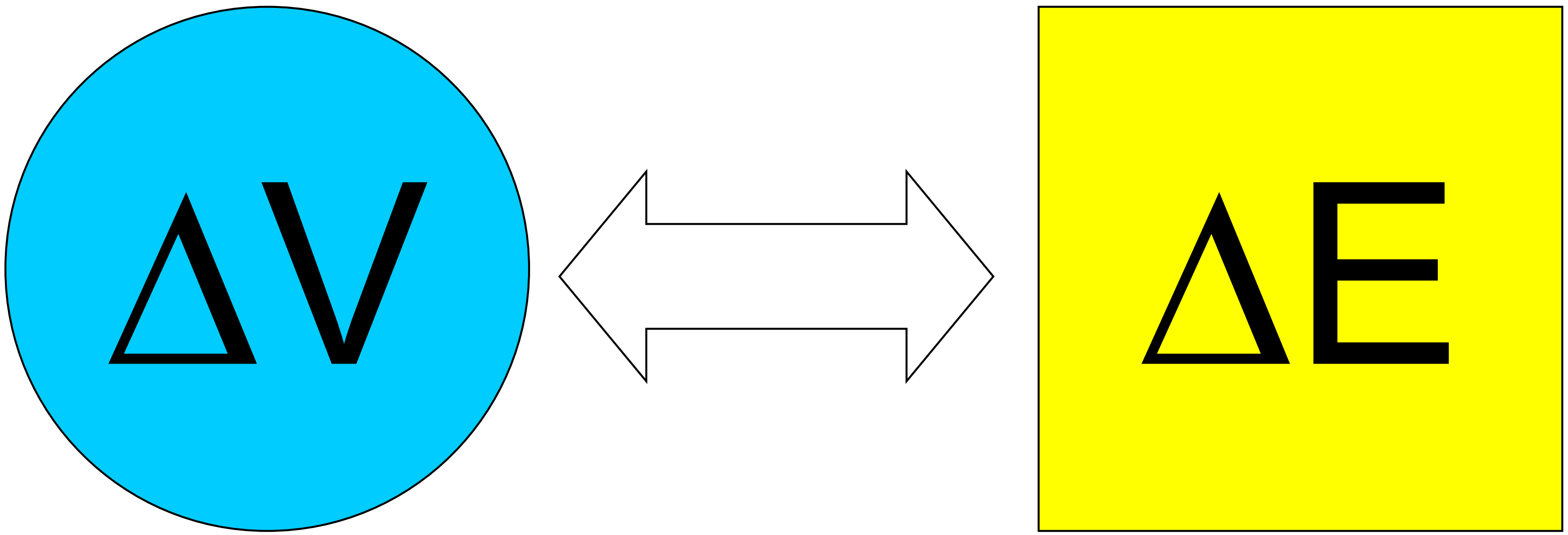
‘Colorimetry in its broader sense includes methods of assessing the appearance of colour stimuli presented to the observer in complicated surroundings as they may occur in everyday life. This is considered the ultimate goal of colorimetry, but because of its enormous complexity, this goal is far from being reached. On the other hand, certain more restricted aspects of the overall problem of predicting colour appearance of stimuli seem somewhat less elusive. The outstanding examples are the measurement of colour differences, whiteness, and chromatic adaptation. Though these problems are still essentially unresolved, the developments in these areas are of considerable interest and practical importance.’

Advanced colorimetry:

- Specification of color difference perceptions and color appearance.

3. Color difference formulas

Visual and computed color-differences in industrial applications



Visually-perceived color differences (subjective)

Instrumentally-measured color differences (objective)

3. Color difference formulas

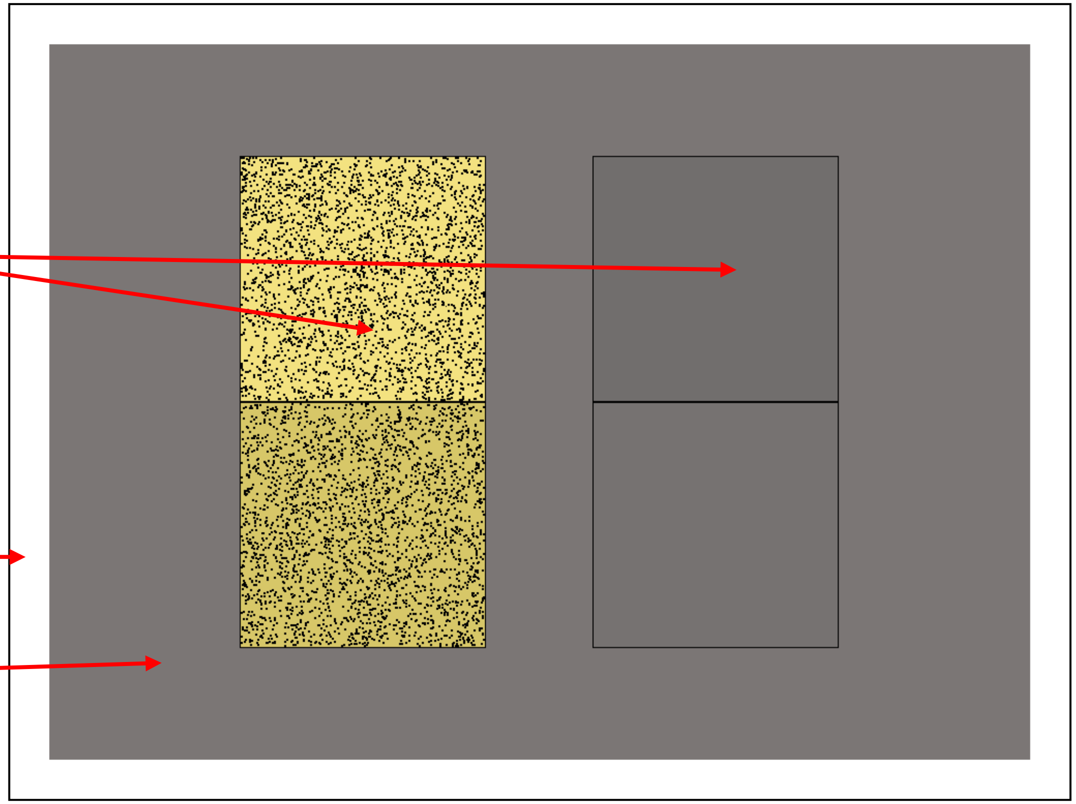
ΔV

Experiment with a Gray Scale

3. Color difference formulas

ΔV

Test pair and anchor pair



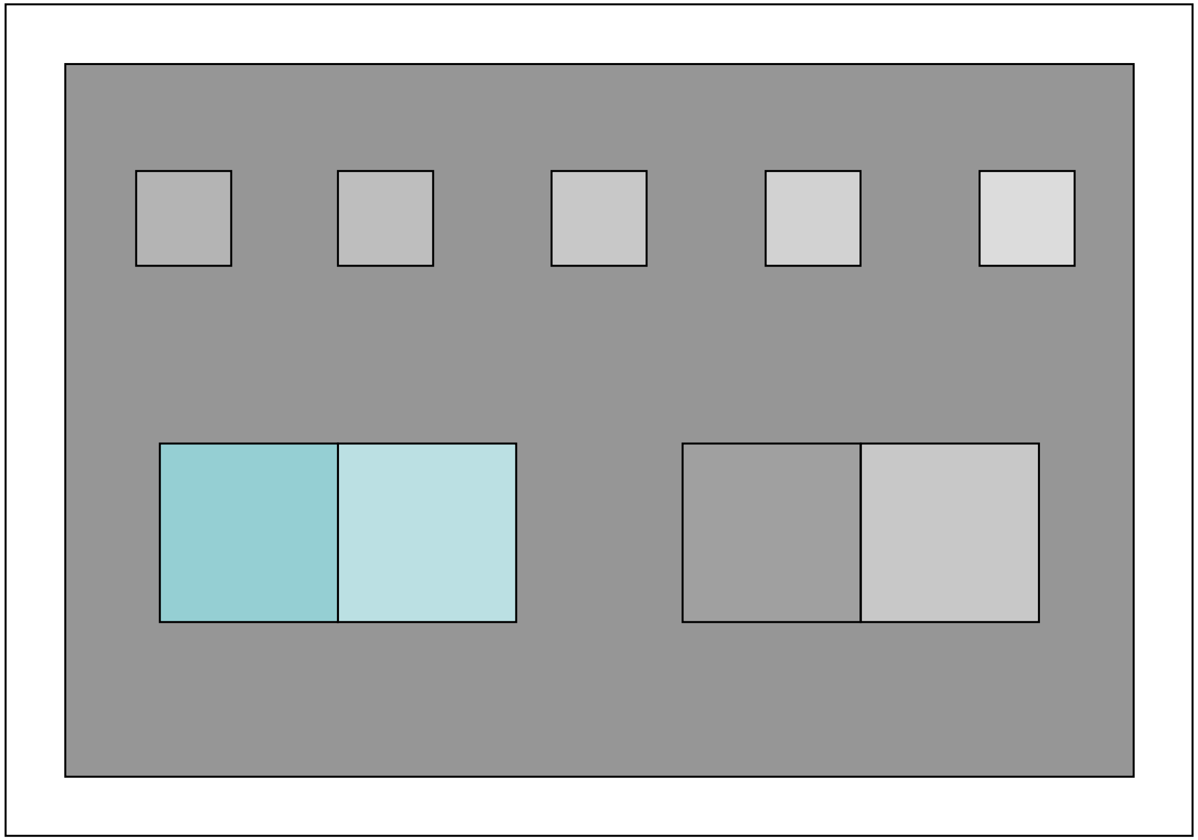
Surround

Background

Experiment with an Anchor Pair

3. Color difference formulas

ΔV



Experiment with a variable Anchor Pair

3. Color difference formulas

Why color assessment cabinets (light booths)?

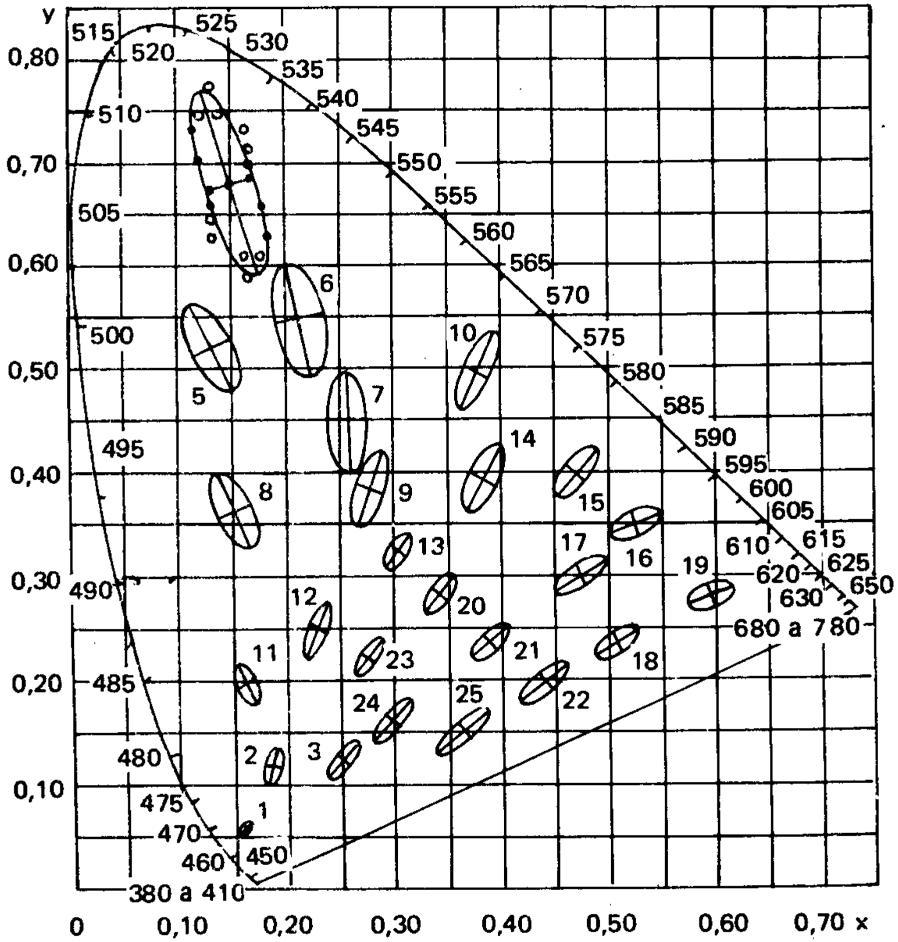
✓ To obtain “stable” lighting over time.

✓ To simulate different artificial illuminations. Note that natural illumination is not easy to simulate, both in spectral power distribution and illuminance level.

✓ To provide a combination of directional and diffuse lighting (a grey surround –the cabinet’s walls- is being assumed) allowing differences in texture be observable.

3. Color difference formulas

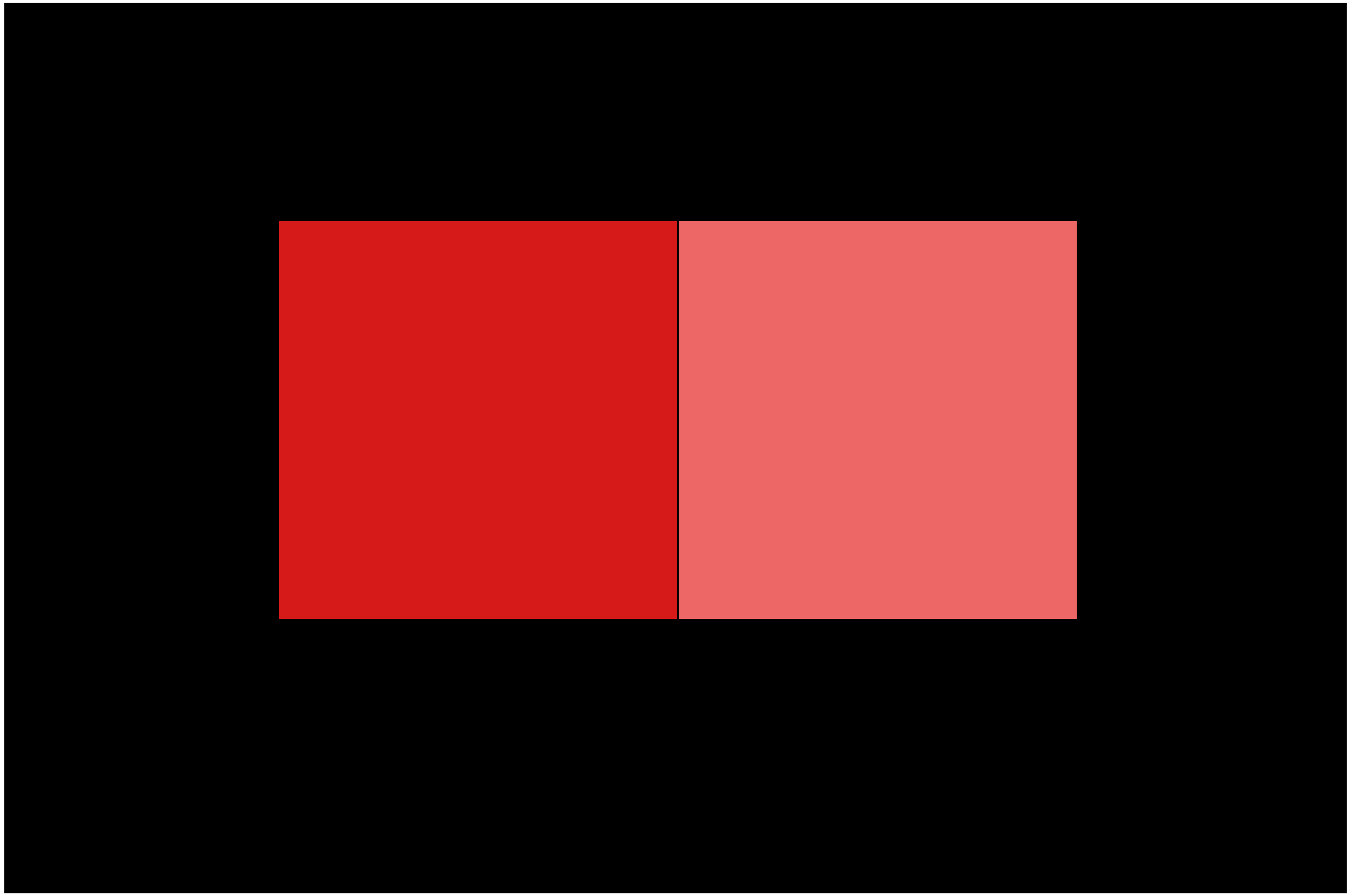
ΔV

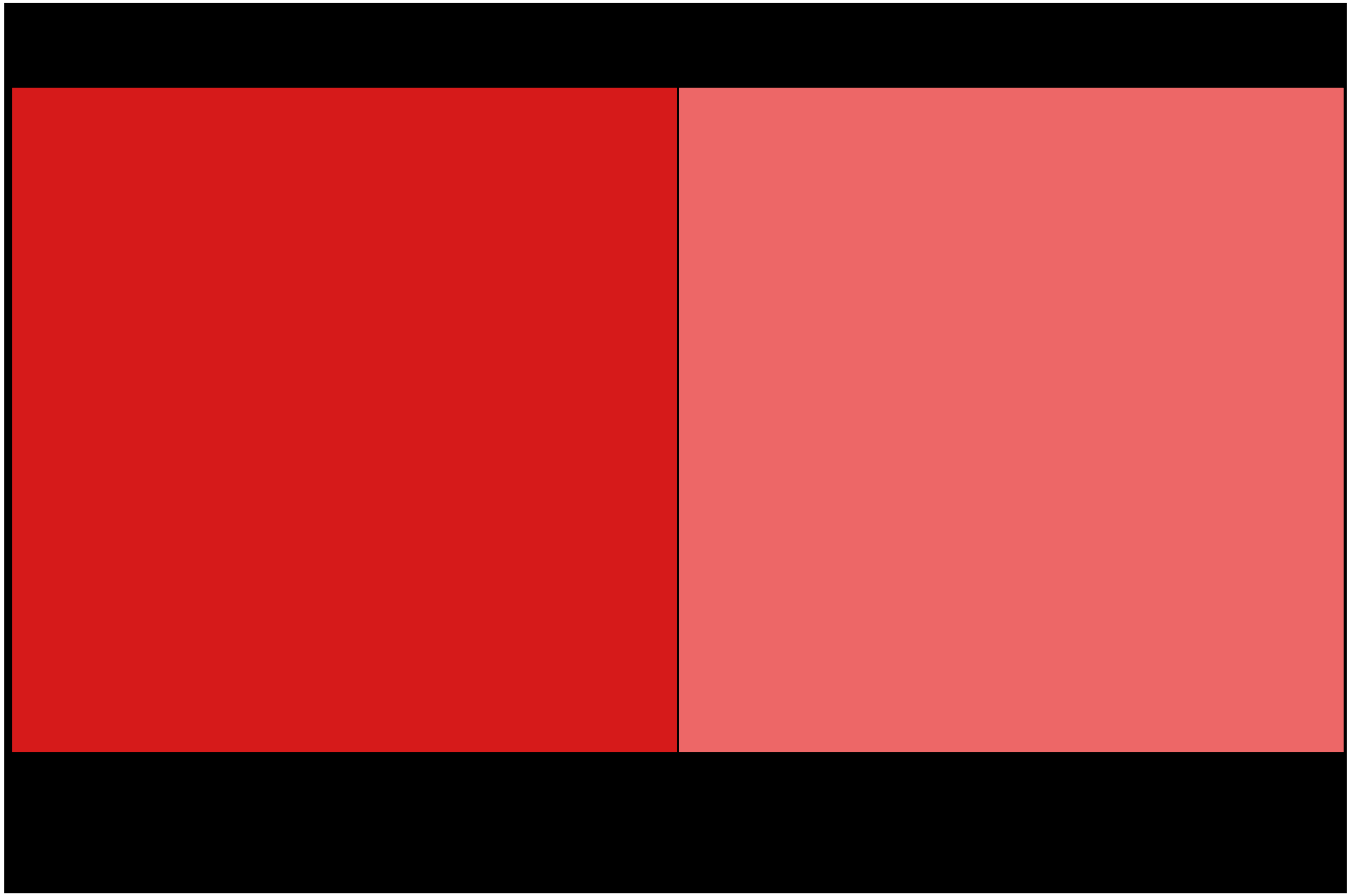


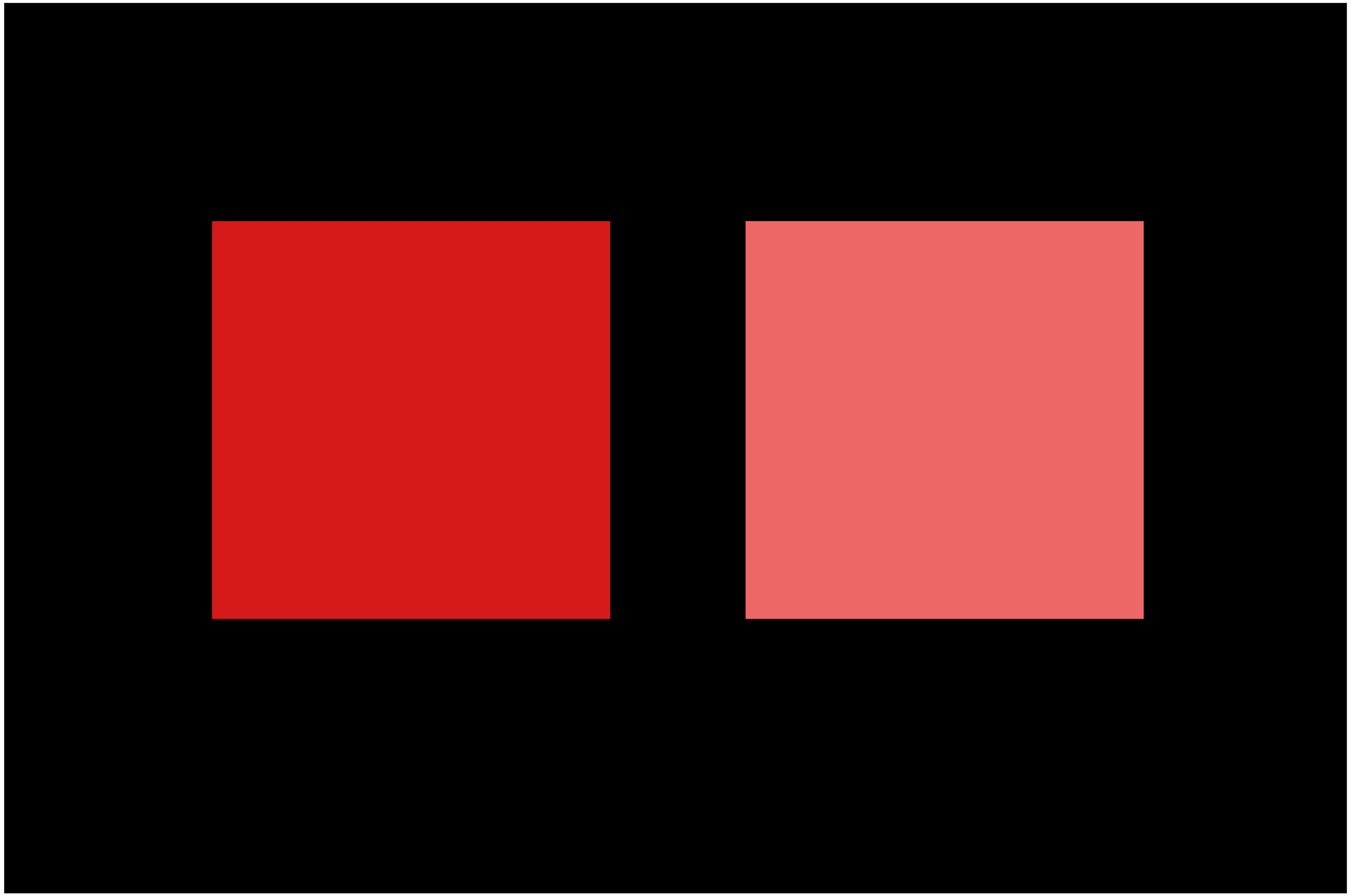
3. Color difference formulas

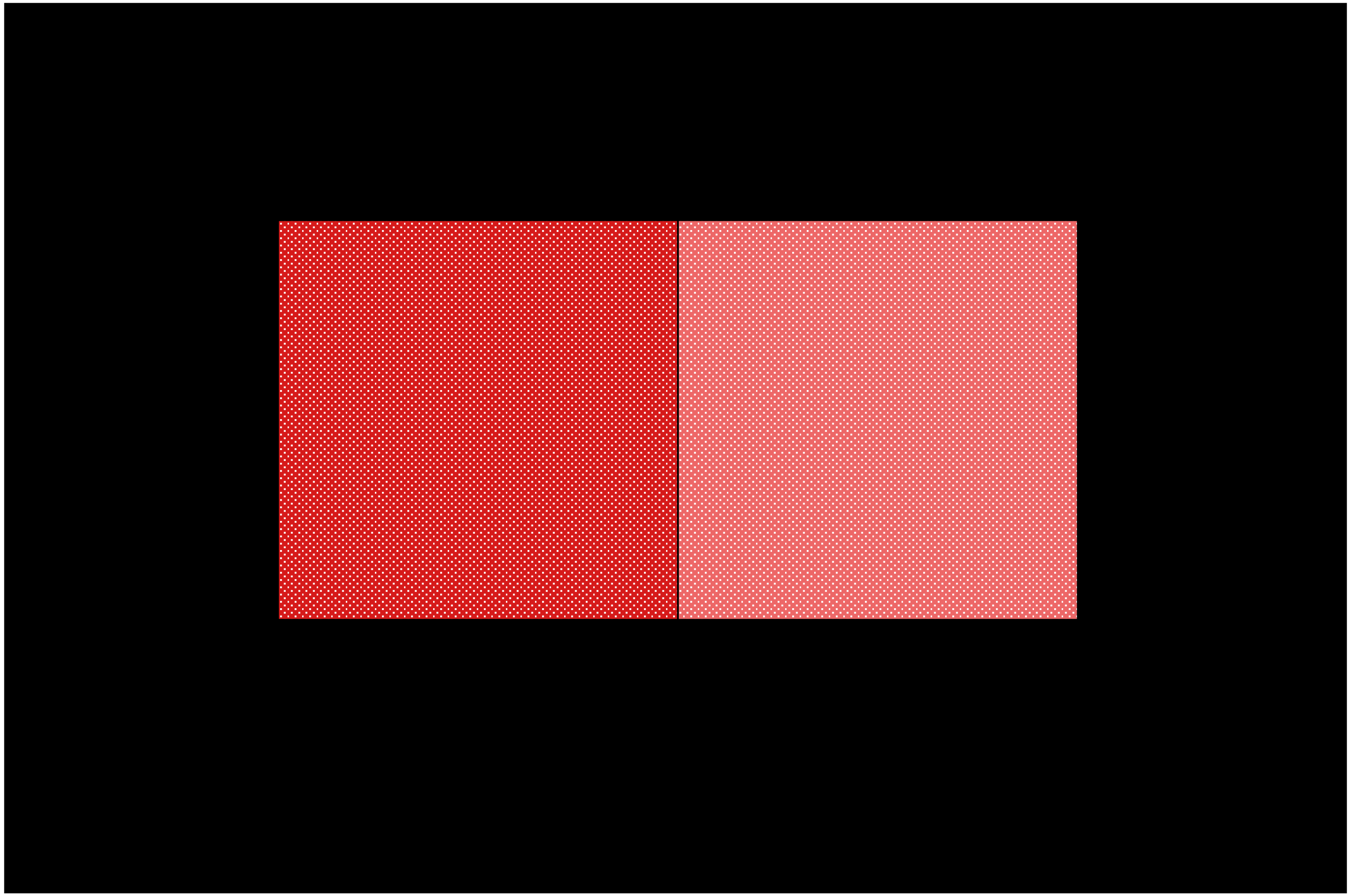
Parametric Effects to be considered for research in color-difference evaluation (A.R. Robertson):

- Sample size
- Illumination level
- Sample separation
- Texture
- Color of surround
- Luminance factor
- Size of ΔE
- Observer variability
- Duration of observation
- Monocular or binocular observing









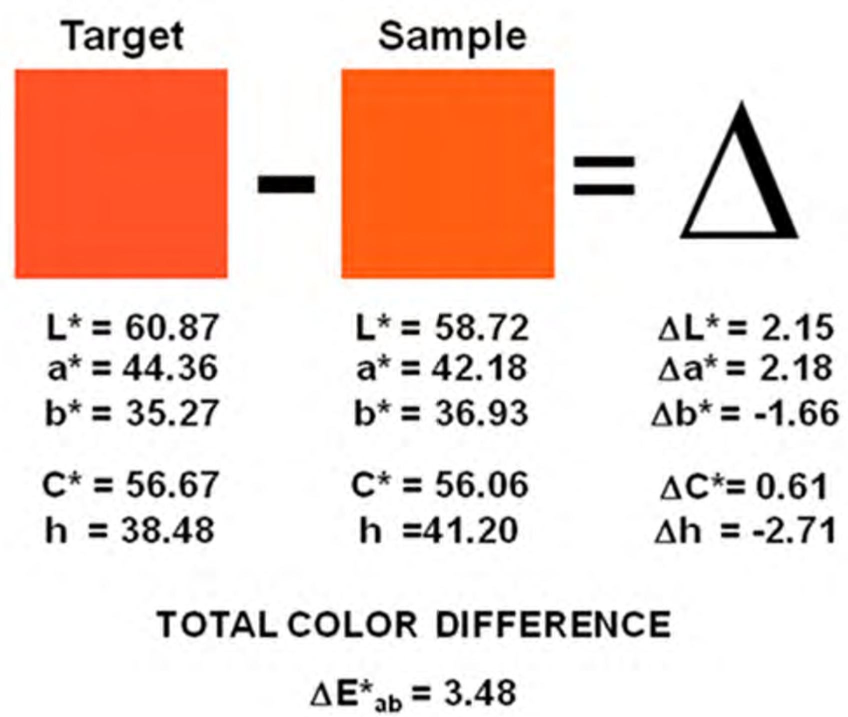
3. Color difference formulas

CIE reference conditions (1995)

- Illumination: CIE illuminant D65 simulator.
- Illuminance: 1000 lux.
- Observer: normal color vision.
- Background: uniform, achromatic, L^*=50.
- Viewing mode: object.
- Sample size: greater than 4° visual angle.
- Sample separation: direct edge contact.
- Sample color-difference magnitude: 0-5 CIELAB units.
- Sample structure: no visually apparent pattern or non-uniformity.

3. Color difference formulas

ΔE



https://www.flexoglobal.com/flexomag/08-September/flexomag-ploumidis.htm

$$\Delta E = f\,(X_1, Y_1, Z_1, X_2, Y_2, Z_2, \text{etc.})$$

3. Color difference formulas

CIELAB

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$$

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta C^*_{ab})^2 + (\Delta H^*_{ab})^2]^{1/2}$$

$$\Delta L^* = L^*_1 - L^*_2$$

$$\Delta a^* = a^*_1 - a^*_2$$

$$\Delta b^* = b^*_1 - b^*_2$$

$$\Delta C^*_{ab} = C^*_{ab,1} - C^*_{ab,2}$$

$$\Delta h_{ab} = h_{ab,1} - h_{ab,2}$$

$$\Delta H^*_{ab} = 2(C^*_{ab,1} C^*_{ab,2})^{1/2} \sin(\Delta h_{ab}/2)$$

Measurement of color differences, in CIELAB space as the Euclidean distance between the coordinates for the two stimuli: ΔE^*_{ab}.

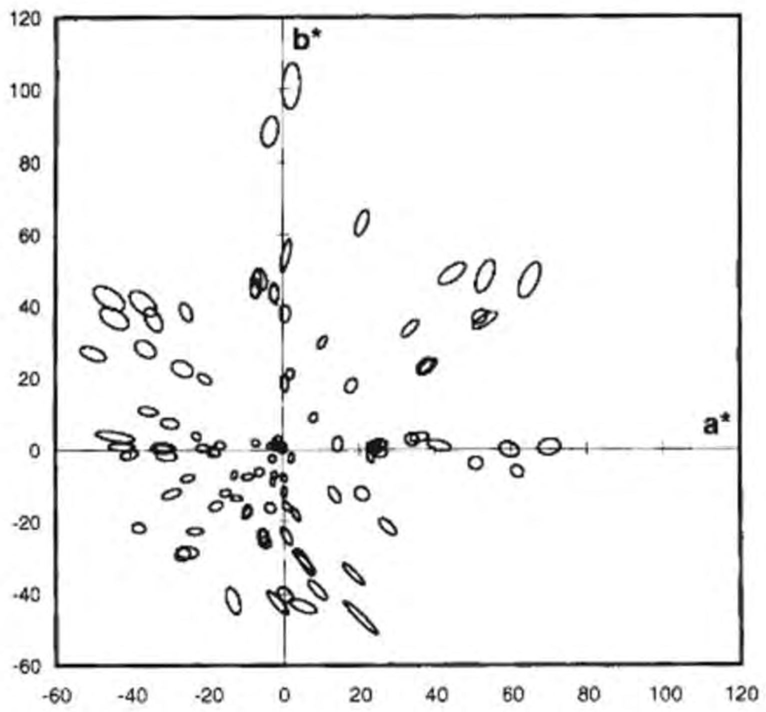
Color differences perceptually uniform throughout the space was not strictly achieved in the CIELAB color space.

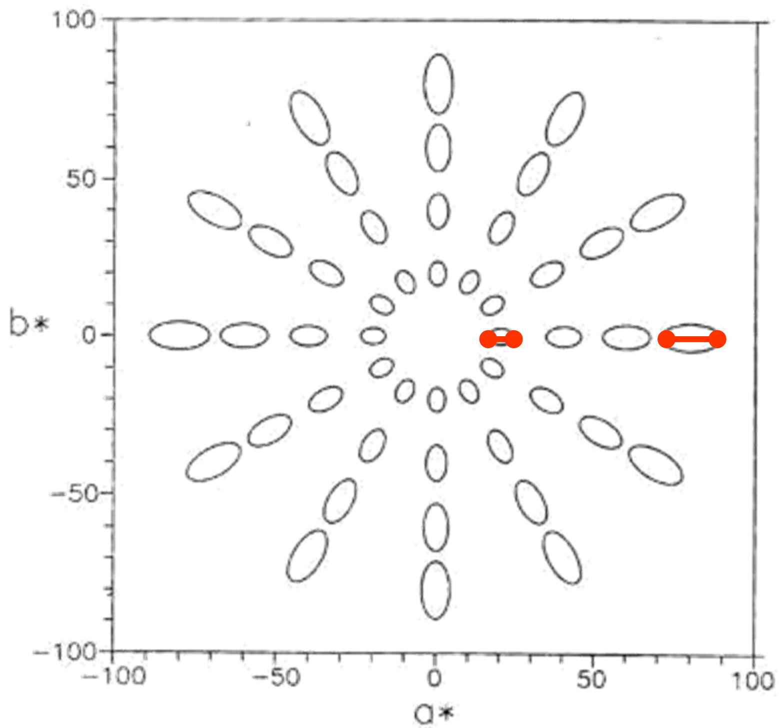
To improve the uniformity of color difference measurements, modifications to the CIELAB ΔE^*_{ab} equation: CMC, CIE94, CIEDE2000 (ΔE^*_{oo}), DIN99d.

3. Color difference formulas

CIELAB

Experimental and theoretical ellipsis





Elipses BFD-P in $a^{*}b^{*}$ (Col. Res. Appl., 26, 340-350, 2001)

3. Color difference formulas

CIEDE2000

Five corrections to CIELAB are introduced:

- New S_L function (crispening effect)
- The same S_C function proposed by CIE94
- New S_H function depending on both C^*_{ab} and h_{ab}
- Additional rotation term R_T
- New a^* scale (only for color-difference purposes)

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2 + R_T \left(\frac{\Delta C'}{K_C S_C}\right) \left(\frac{\Delta H'}{K_H S_H}\right)}$$

3. Color difference formulas

CIEDE2000

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2 + R_T \left(\frac{\Delta C'}{K_C S_C}\right) \left(\frac{\Delta H'}{K_H S_H}\right)}$$

$$L' = L^*$$
$$a' = (1 + G)a^*$$
$$b' = b^*$$
$$C' = \sqrt{a'^2 + b'^2}$$
$$h' = arctg\left(\frac{b'}{a'}\right)$$
$$G = 0.5\left(1 - \sqrt{\frac{\overline{C_{ab}^{*7}}}{\overline{C_{ab}^{*7}} + 25^7}}\right)$$

$$\Delta L' = L'_b - L'_s$$
$$\Delta C' = C'_b - C'_s$$
$$\Delta H' = 2\sqrt{C'_b C'_s}\sin\left(\frac{\Delta h'}{2}\right)$$
$$\Delta h' = h'_b - h'_s$$

3. Color difference formulas

CIEDE2000

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2 + R_T \left(\frac{\Delta C'}{K_C S_C}\right) \left(\frac{\Delta H'}{K_H S_H}\right)}$$

$$S_L = 1 + \frac{0.015\left(\overline{L'} - 50\right)^2}{\sqrt{20 + \left(\overline{L'} - 50\right)^2}}$$

$$S_C = 1 + 0.045\overline{C'}$$

$$S_H = 1 + 0.015\,\overline{C'}\,T$$

$$R_T = -\sin(2\,\Delta\theta)\,R_C$$

$$\Delta\theta = 30\exp\left\{-\left[\left(\overline{h'} - 275^\circ\right)/25\right]^2\right\}$$

$$R_C = 2\sqrt{\frac{\overline{C'^7}}{\overline{C'^7} + 25^7}}$$

$$T = 1 - 0.17\cos\left(\overline{h'} - 30^\circ\right) + 0.24\cos\left(2\overline{h'}\right) + 0.32\cos\left(3\overline{h'} + 6^\circ\right) - 0.20\cos\left(4\overline{h'} - 63^\circ\right)$$

3. Color difference formulas

CIEDE2000

Parametric factors, k_L, k_C, and k_H .

CIE reference conditions (1995):

- Illumination: CIE illuminant D65 simulator.
- Illuminance: 1000 lux.
- Observer: normal color vision.
- Background: uniform, achromatic, L^*=50.
- Viewing mode: object.
- Sample size: greater than 4° visual angle.
- Sample separation: direct edge contact.
- Sample color-difference magnitude: 0-5 CIELAB units.
- Sample structure: no visually apparent pattern or non-uniformity.

3. Color difference formulas

CIEDE2000

Experimental and theoretical ellipsis

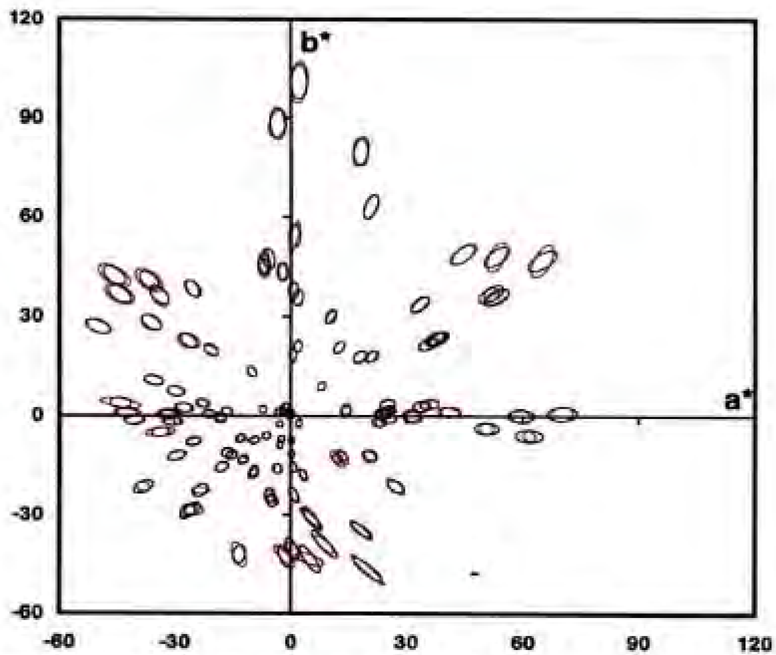
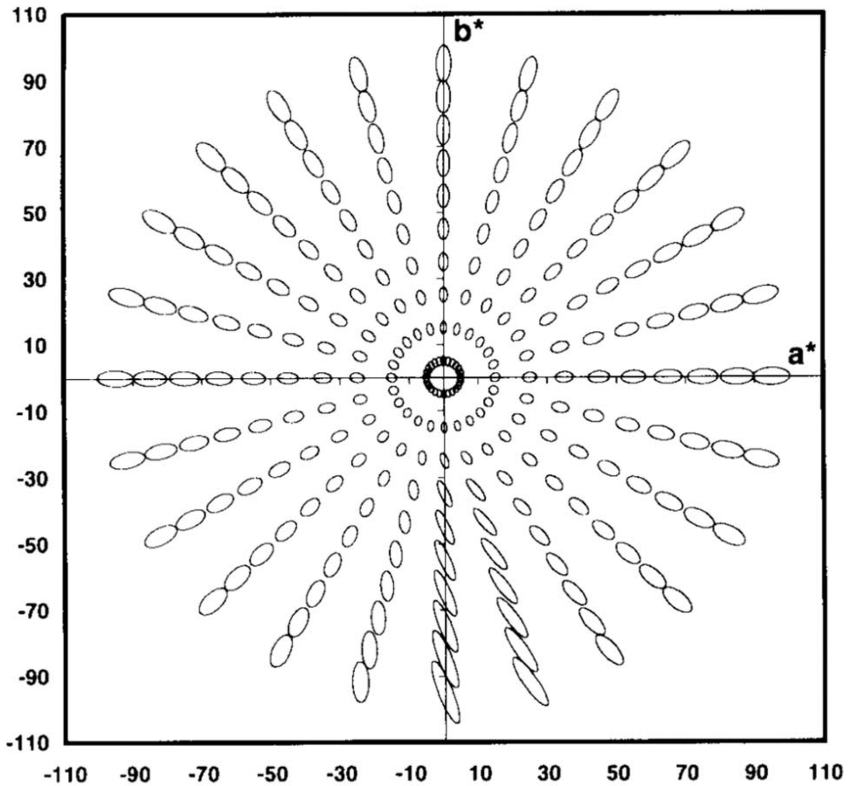


FIG. 8. RIT–DuPont and BFD experimental chromaticity discrimination ellipses (in red) compared to the corresponding ellipses from the *M2b* equation (in black).



3. Color difference formulas

DIN99d

$$\Delta E_{99d} = \sqrt{(\Delta L_{99d})^2 + (\Delta a_{99d})^2 + (\Delta b_{99d})^2}$$

$$X' = 1.12X - 0.12Z$$

$$L_{99d} = 325.22 \ln(1 + 0.0036L^*)$$

$$e = a^* \cos(50°) + b^* \sin(50°)$$

$$f = 1.14[-a^* \sin(50°) + b^* \cos(50°)]$$

Rotation of a*b* axis, and b* re-scaling

$$G = \sqrt{e^2 + f^2}$$

From CIE94 integration

$$C_{99d} = 22.5 \ln(1 + 0.06G)$$

$$h_{99d} = \arctan(f/e) + 50°$$

$$a_{99d} = C_{99d} \cos(h_{99d})$$

$$b_{99d} = C_{99d} \sin(h_{99d})$$

3. Color difference formulas

DIN99d

Ellipses in DIN99d space (right) are closer to circles than in CIELAB (left). Reduction of the scale in $a_{99d}b_{99d}$ plane with respect to a^*b^* in CIELAB tries to make more similar the chromaticity and lightness scales.

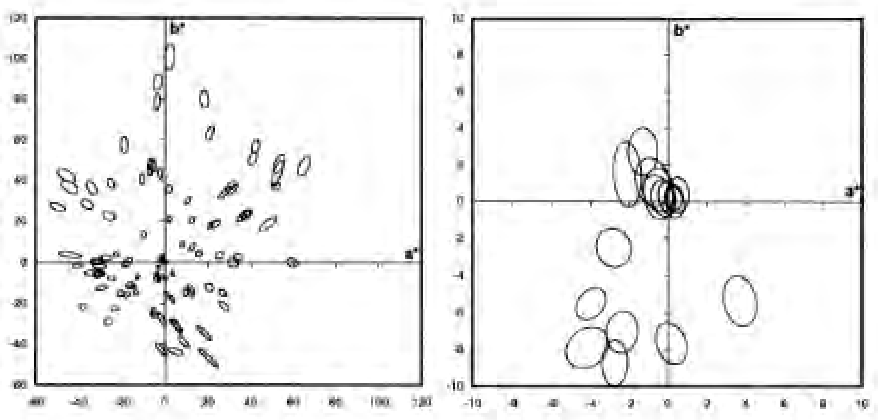

(a) All colours (b) Neutral region

FIG. 1 The experimental ellipses from the BFD-P and RIT-DuPont data sets plotted in the CIELAB a*b* plane.

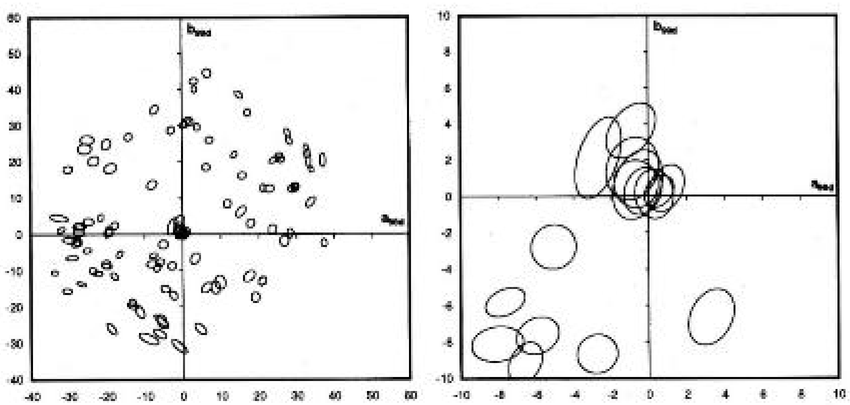

(a) All colours (b) Neutral region

FIG. 5. The experimental ellipses from the BFD-P and RIT-DuPont data sets plotted in the DIN99d a_{99d}, b_{99d} plane.

3. Color difference formulas

PF/3: agreement between perceived (Δ*V*) and measured (Δ*E*) color differences

$$PF/3 = \frac{100[(\gamma - 1) + V_{AB}] + CV}{3}$$

$$\log_{10}(\gamma) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\log_{10}\left(\frac{\Delta E_i}{\Delta V_i}\right) - \overline{\log_{10}\left(\frac{\Delta E_i}{\Delta V_i}\right)}\right]^2}$$

$$V_{AB} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\frac{(\Delta E_i - F\Delta V_i)^2}{\Delta E_i F \Delta V_i}}$$

$$F = \sqrt{\frac{\sum_{i=1}^{N}\Delta E_i/\Delta V_i}{\sum_{i=1}^{N}\Delta V_i/\Delta E_i}}$$

Scaling factors

$$CV = 100\sqrt{\frac{1}{N}\sum_{i=1}^{N}\frac{(\Delta E_i - f\Delta V_i)^2}{\left(\overline{\Delta E}\right)^2}}$$

$$f = \frac{\sum_{i=1}^{N}\Delta E_i \Delta V_i}{\sum_{i=1}^{N}\Delta V_i^2}$$

Perfect Agreement:

γ =1

V_{AB} =0

***CV* =0**

***PF/3*=0**

Luo et al. (1999).

3. Color difference formulas

PF/3: agreement between perceived (ΔV) and measured (ΔE) color differences

✓ A PF/3 of 30 roughly indicates an average disagreement of 30% between visual and computed differences.

✓ Initially a PF/4 index was proposed (Luo et al. 1982), considering also the linear correlation coefficient *r*. However *r* values were not in agreement with Gamma, V_{AB} and CV values, and therefore it was suppressed.

✓ PF/3 was generated because applying the Gamma, V_{AB} and CV indices, different conclusions were achieved for different experimental datasets.

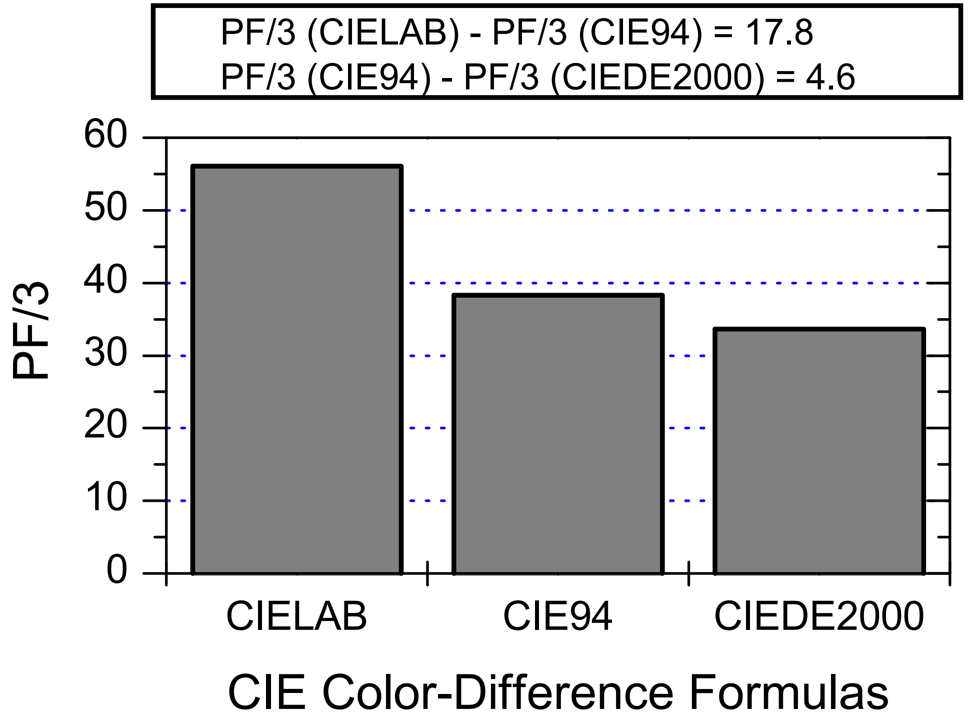
✓ Obviously, because PF/3 is an eclectic index, a flaw in any one of its 3 components (Gamma, V_{AB} and CV) is translated to PF/3.

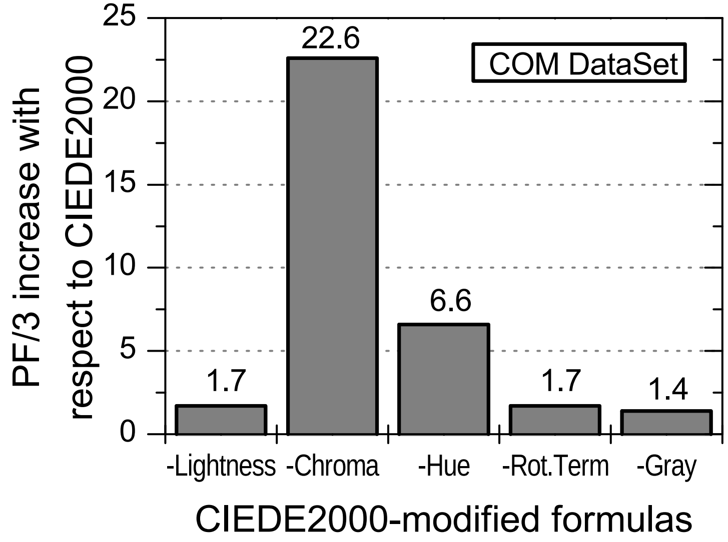
✓ PF/3 is not a standard statistical index. It cannot inform about the statistical significance of the differences between two formulas with similar PF/3 values.

✓ For industry a new standardized color-difference formula must compensate costs of retraining and software changes, being statistically significant better than the previous adopted formulas.

3. Color difference formulas

***PF/3*: agreement between perceived (ΔV) and measured (ΔE) color differences**





3. Color difference formulas

STRESS: agreement between perceived (Δ_V_) and measured (Δ_E_) color differences

STRESS index (Kruskal's STRESS): STandardized REsidual Sum of Squares

$$STRESS = 100\left(\frac{\sum(\Delta V_i - F\Delta E_i)^2}{\sum \Delta V_i^2}\right)^{1/2}$$

$$F = \frac{\sum \Delta E_i \Delta V_i}{\sum \Delta E_i^{\,2}}$$

0 ≤ _STRESS_ ≤ 100

Ideal Value: _STRESS_=0

$$F = \frac{V_A}{V_B} = \frac{STRESS_A^2}{STRESS_B^2}$$

Assuming the same set of ΔV_i (i=1…N) data

$F < F_C \Rightarrow$ A is significantly better than B

$F > 1/F_C \Rightarrow$ A is significantly poorer than B

$F_C \leq F < 1 \Rightarrow$ A is insignificantly better than B

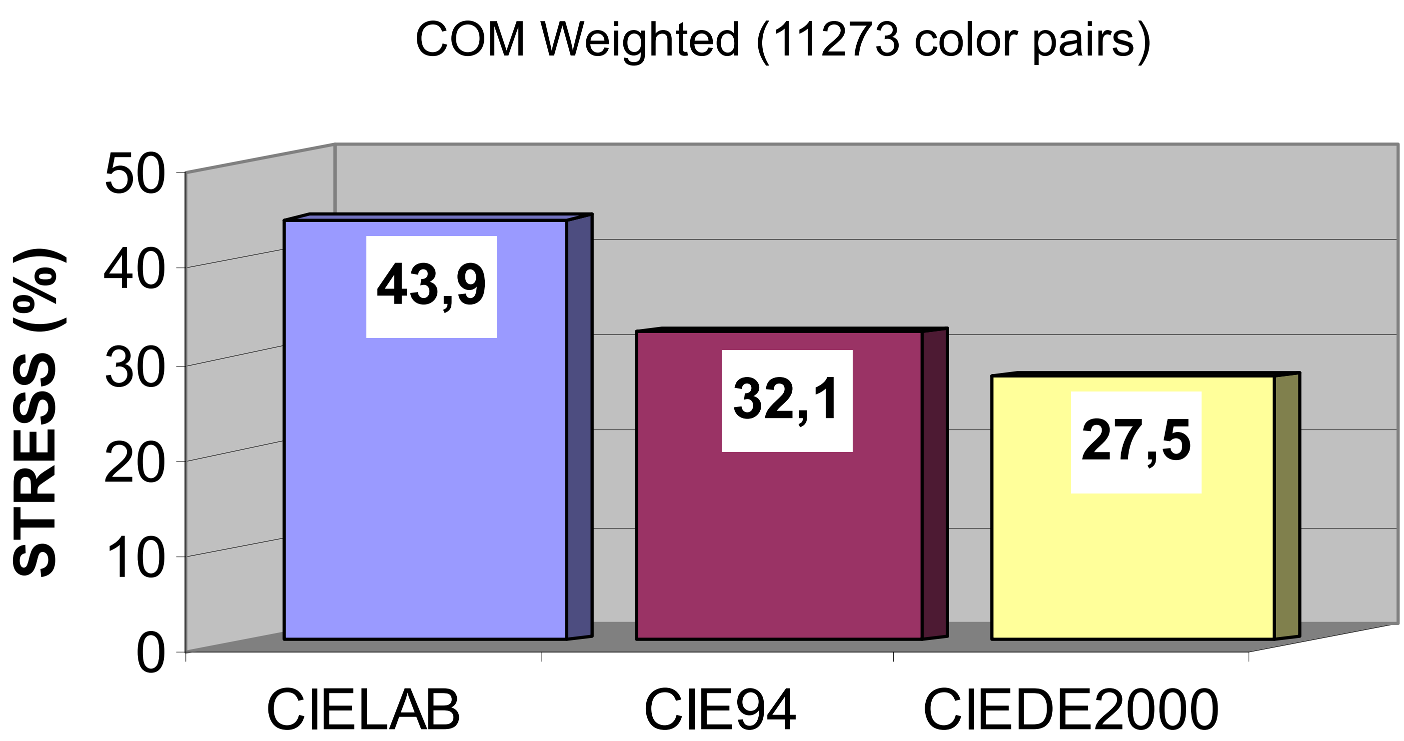
$1 < F \leq 1/F_C \Rightarrow$ A is insignificantly poorer than B

$F = 1 \Rightarrow$ A is equal to B

Luo et al. (1999).

3. Color difference formulas

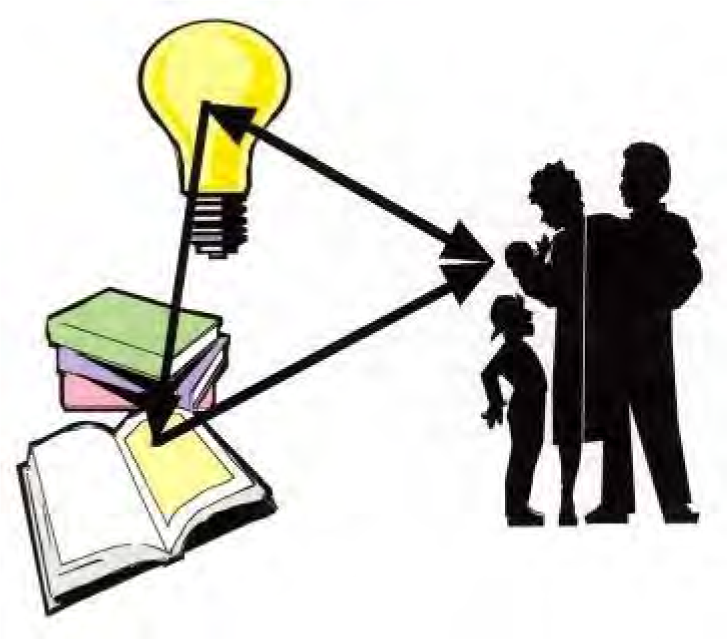
***STRESS*: agreement between perceived (ΔV) and measured (ΔE) color differences**



From CIE94 to CIEDE2000 STRESS decreased 4.6 units (2.5 times lower).

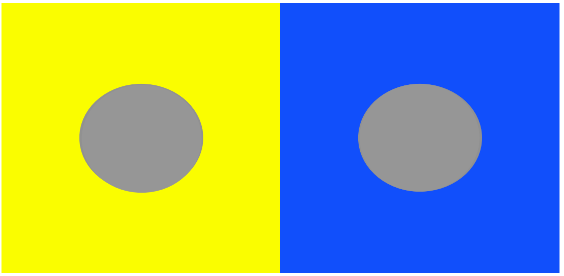
4. Color appearance

The fundamentals of basic colorimetry are well established and have been successfully used for decades.



The specification of the color appearance of stimuli under a wide variety of viewing conditions must include:

- Chromatic adaptation.
- Light adaptation.
- Luminance level.
- Background color.
- Surround color.
- etc.



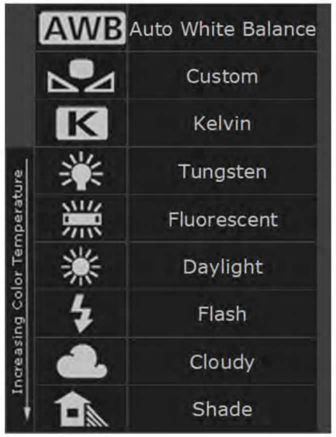
4. Color appearance

Color appearance models

Color appearance models have been the subject of research and required for practical applications. There are a variety of models that have been proposed.

Examples of application of color appearance models are:

- White balance in digital cameras.
- Proper combination of inks and halftone algorithms in a inkjet printer.
- In Windows Color System (WCS).



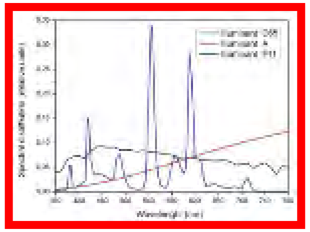
4. Color appearance

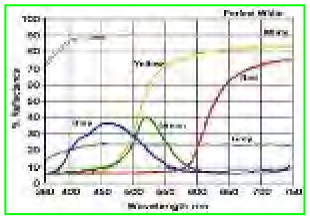
Basic and Advanced Colorimetry

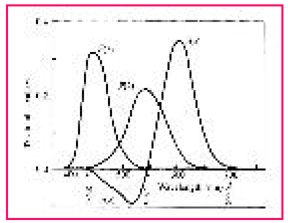
$$X = k\int_{vis} S(\lambda)R(\lambda)\bar{x}(\lambda)\,d\lambda$$

$$Y = k\int_{vis} S(\lambda)R(\lambda)\,\bar{y}(\lambda)\,d\lambda$$

$$Z = k\int_{vis} S(\lambda)R(\lambda)\,\bar{z}(\lambda)\,d\lambda$$



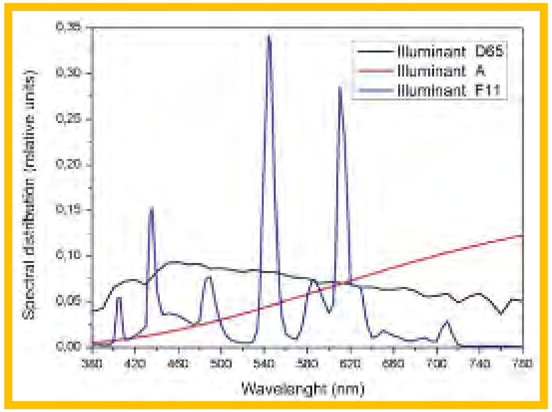


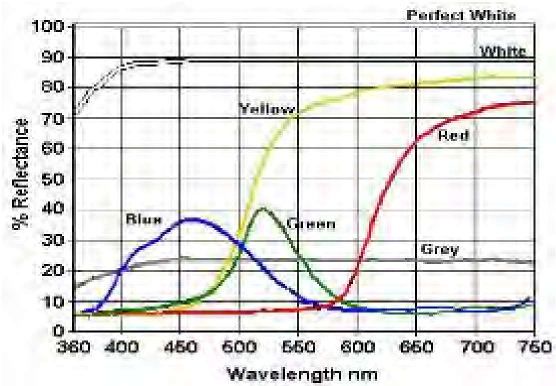


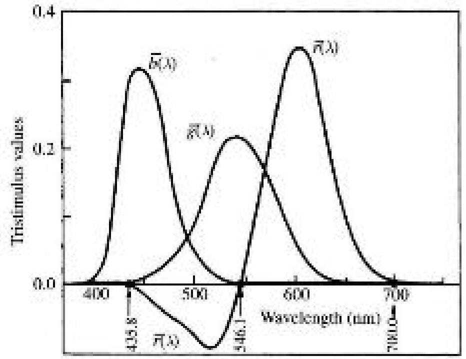
4. Color appearance

Color

- Light sources: spectral power distribution (SPD) and illuminants.
- Material objects: geometric and spectral reflectance or transmittance.
- The human visual system: color matching properties.



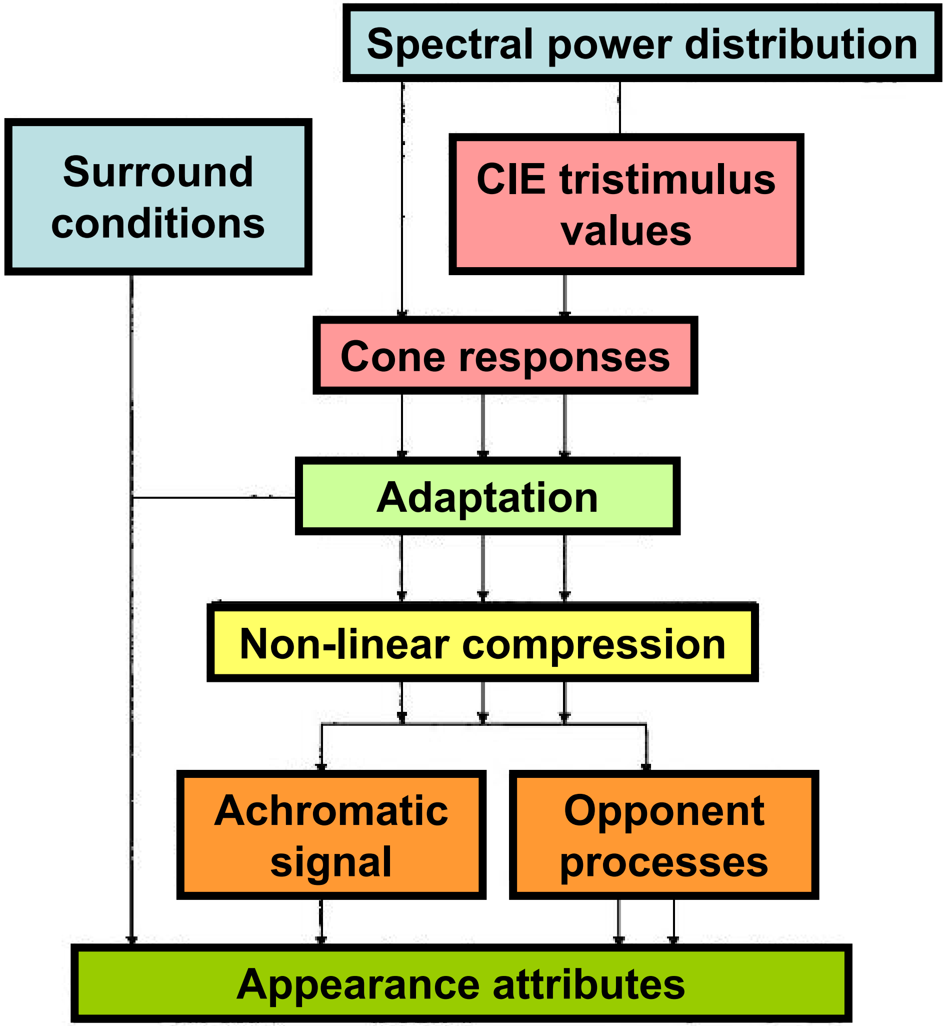




Colorimetry, as a combination of all these areas, draws upon techniques and results from the fields of physics, chemistry, psychophysics, physiology, and psychology.

4. Color appearance

Basic and Advanced Colorimetry

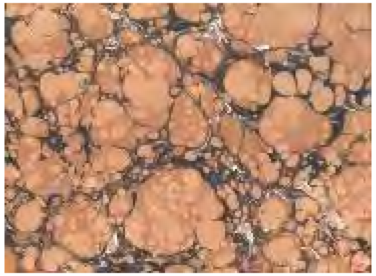


4. Color appearance

Appearance

Physical parameters relating to objects are influenced, at the perception stage, by the physiological response of the human visual system and, in addition by the psychological aspects of human learning, pattern, culture and tradition.

An attempt to measure appearance may be too bold. A sub-framework in terms of what can be measured to provide correlates of visual appearance: color, gloss, translucency and texture. Although these measures are not necessarily independent.



M Pointer. "*A framework for the measurement of visual appearance*". CIE Publication 175-2006: CIE TC1-65 Technical Report, 2006.

4. Color appearance

Appearance: color

Color measurement (colorimetry) is an established science.

- Modern materials: measurement at more illumination/viewing angle combinations is required (goniocolors).
- Traditional, CIE recommended colorimetric parameters are not able to predict the absolute appearance: Color Appearance Models.

4. Color appearance

Appearance: gloss

Gloss measurement is an established methodology.

- Doubt as to the scientific basis (a measurement made at a specific angle depending on the apparent gloss of the sample).
- Attempts to define alternative approaches: investigate the shape of the gloss peak.

Two identical objects having the same color but different surface gloss are experienced as being different.

Relationships between gloss and surface properties: quality, damage resistance, etc. The same gloss level can suit some materials but not others.

To select and analyse gloss, practical tools are needed in the form of samples (color atlas: samples in matt, semi-matt and glossy finish) and gloss scale (specification of gloss levels on new products and materials and gloss assessment on existing surfaces).

4. Color appearance

Appearance: translucency

Translucency is a subjective term that relates to a scale of values going from total opacity to total transparency.

This whole subject area needs investigation to find a rigorous measurement solution that will probably be industry specific.

4. Color appearance

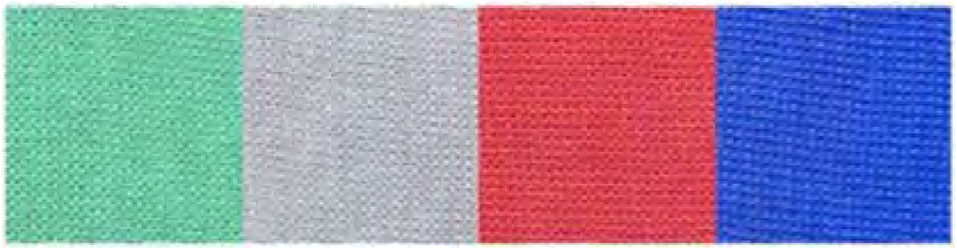
Appearance: texture

Texture is a harder variable to measure.

Digital imaging systems makes the acquisition of images relatively easy.

Characterizing these images to give accurate CIE based colorimetry to provide measurement scales that relate to the perceived texture.

The idea of establishing a series of 'standard' textures has been suggested.



4. Color appearance

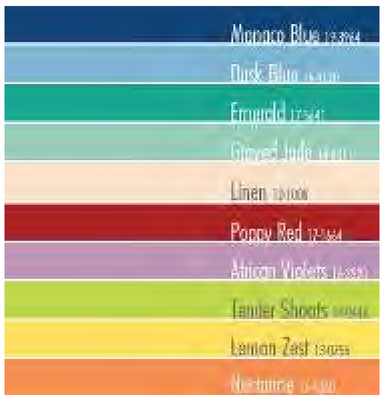
Color order systems

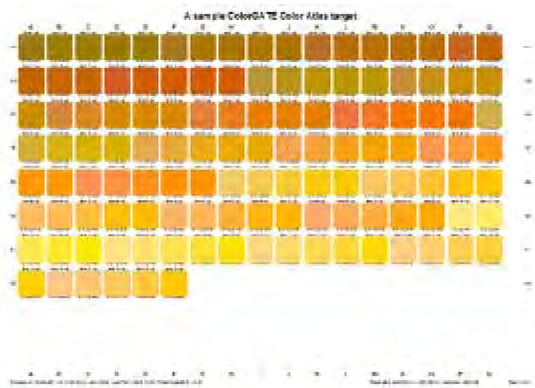
The most direct method to measure color appearance is through stimuli that embody the perceptual color appearance attributes in perceptually uniform scales.

A collection of such stimuli, appropriately specified and denoted, forms a **Color Order System**.

Color order systems provide data and a technique for specifying color appearance.

Interest in the development and testing of color appearance models, but cannot serve as a replacement for them.





4. Color appearance

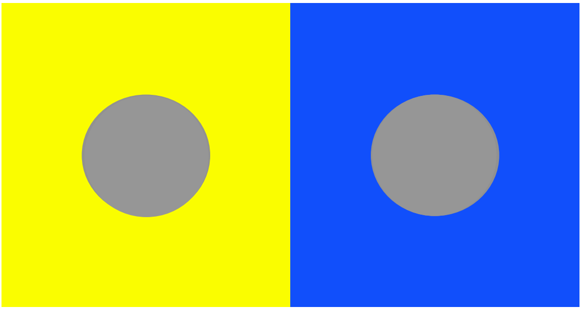
Color Appearance Phenomena

The CIE system of colorimetry has limitations.

Tristimulus values to state whether two stimuli match or not. The two stimuli must be viewed with identical surrounds, backgrounds, size, shape, surface characteristics, illumination geometry, luminance level , etc.

Tristimulus values incorporate none of the information necessary for specifying the color appearance of those matching stimuli. Additional information is needed to specify the color appearance.

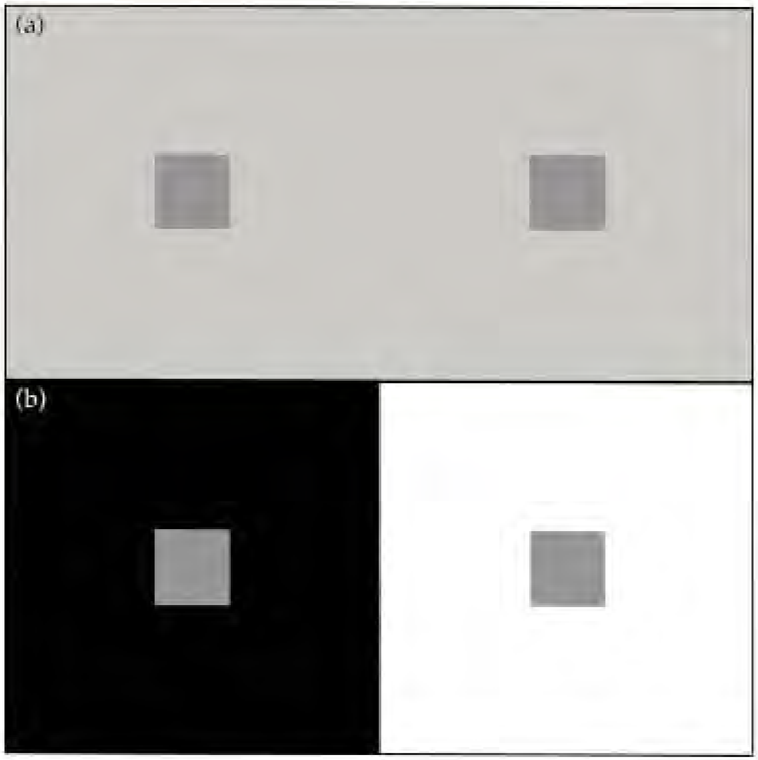
Color appearance phenomena break the simple XYZ tristimulus system. They help to understand what causes tristimulus colorimetry to fail. These phenomena justify the need to develop color appearance models and define the required input data and output predictions.



4. Color appearance

Color Appearance Phenomena: simultaneous contrast or induction

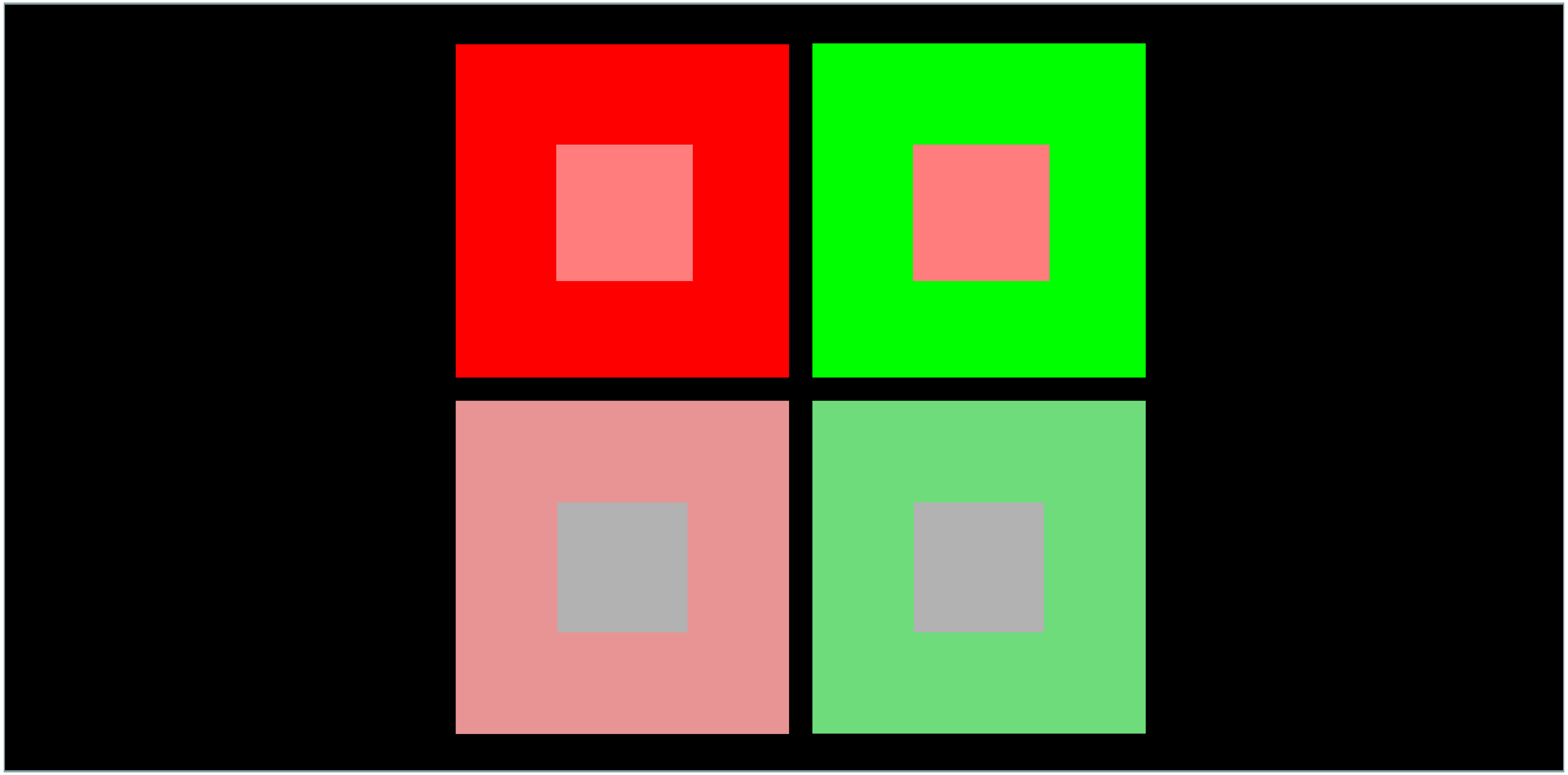
Simultaneous contrast is directly related to the spatial structure of the stimuli.



A model that includes the effect of background luminance factor would be required.

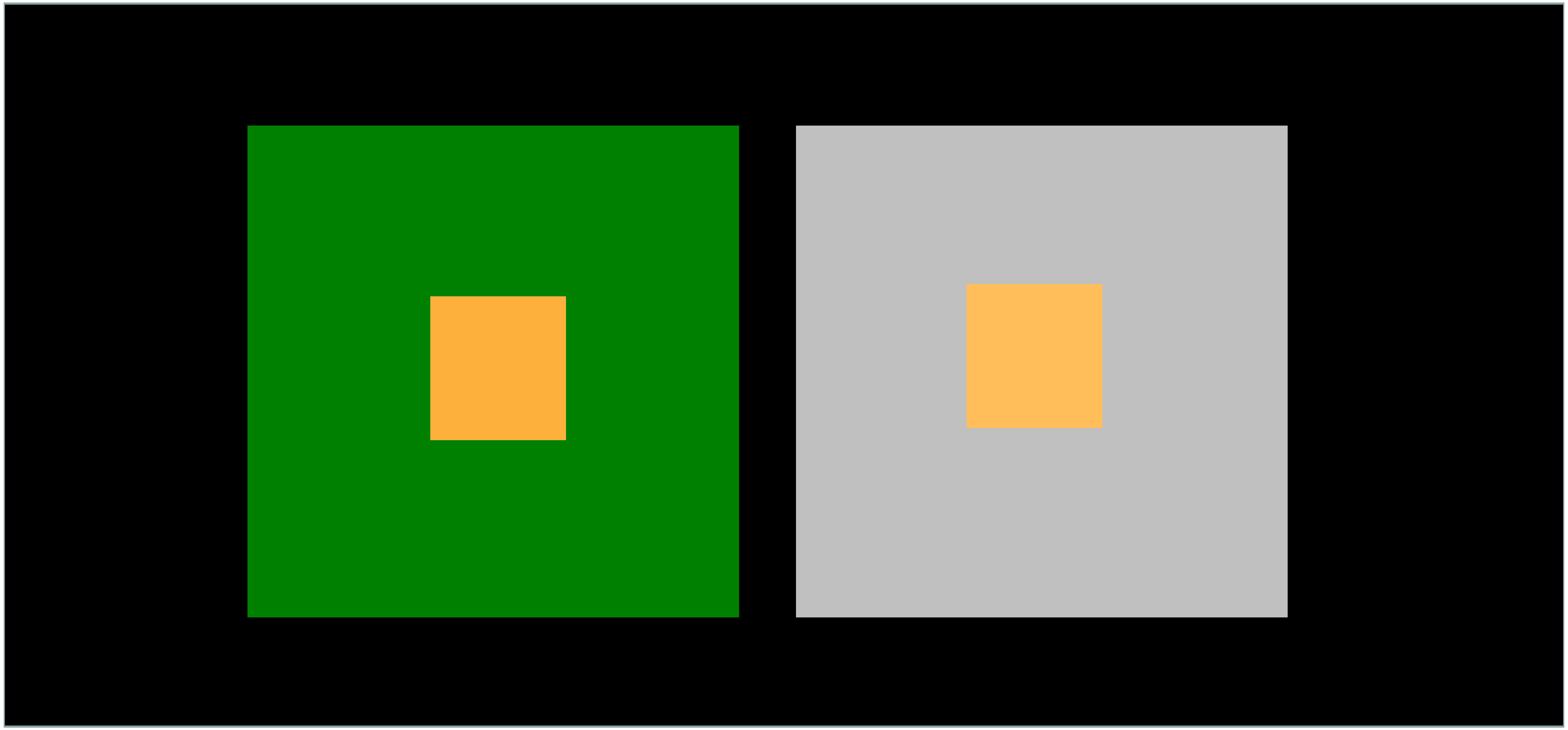
4. Color appearance

Color Appearance Phenomena: simultaneous contrast or induction



4. Color appearance

Color Appearance Phenomena: simultaneous contrast or induction

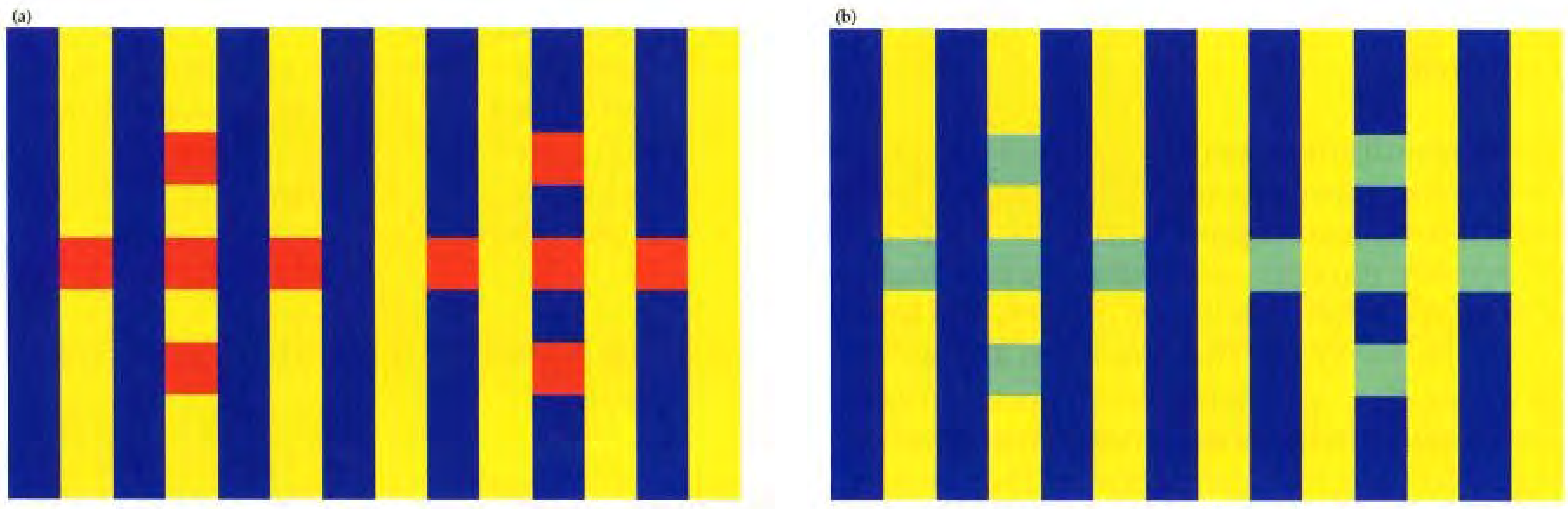


From J. Albers “Interazione dei colori (1975)”

4. Color appearance

Color Appearance Phenomena: simultaneous contrast or induction

‘Chromatic white effect’



4. Color appearance

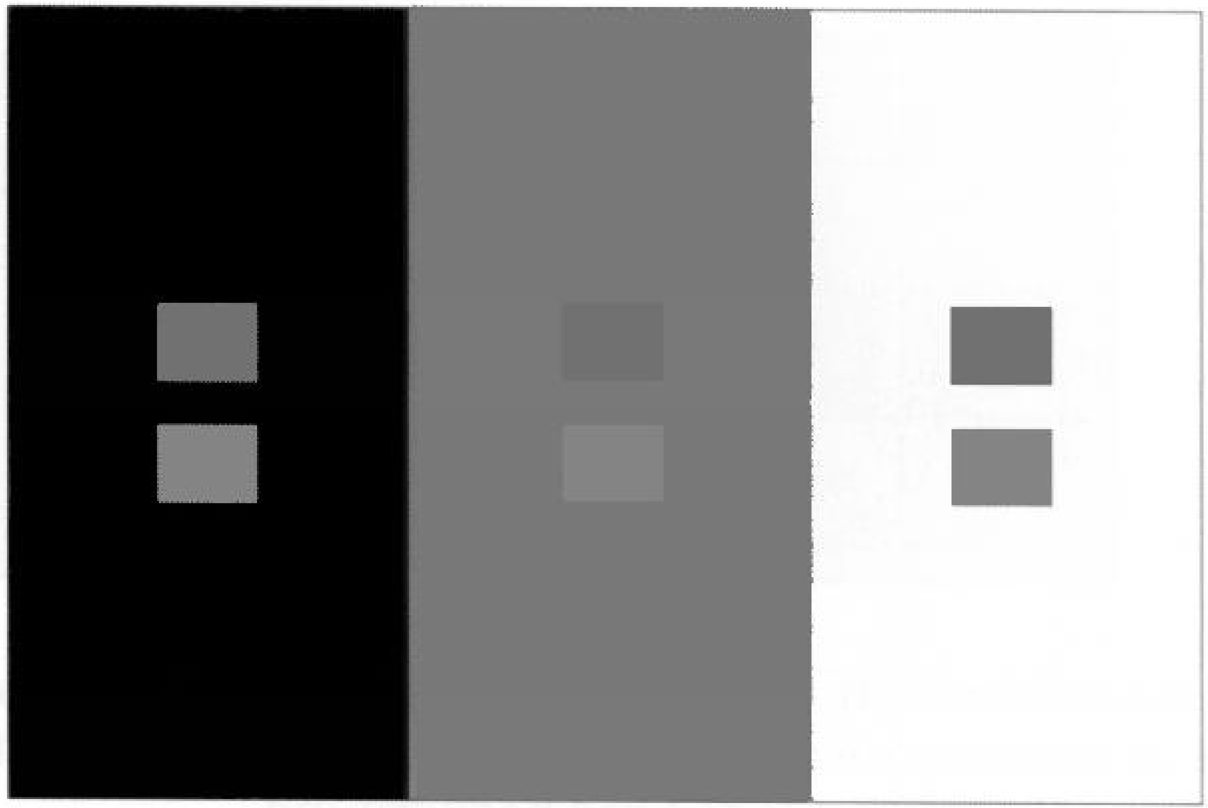
Color Appearance Phenomena: simultaneous contrast or induction

‘Chromatic white effect’

4. Color appearance

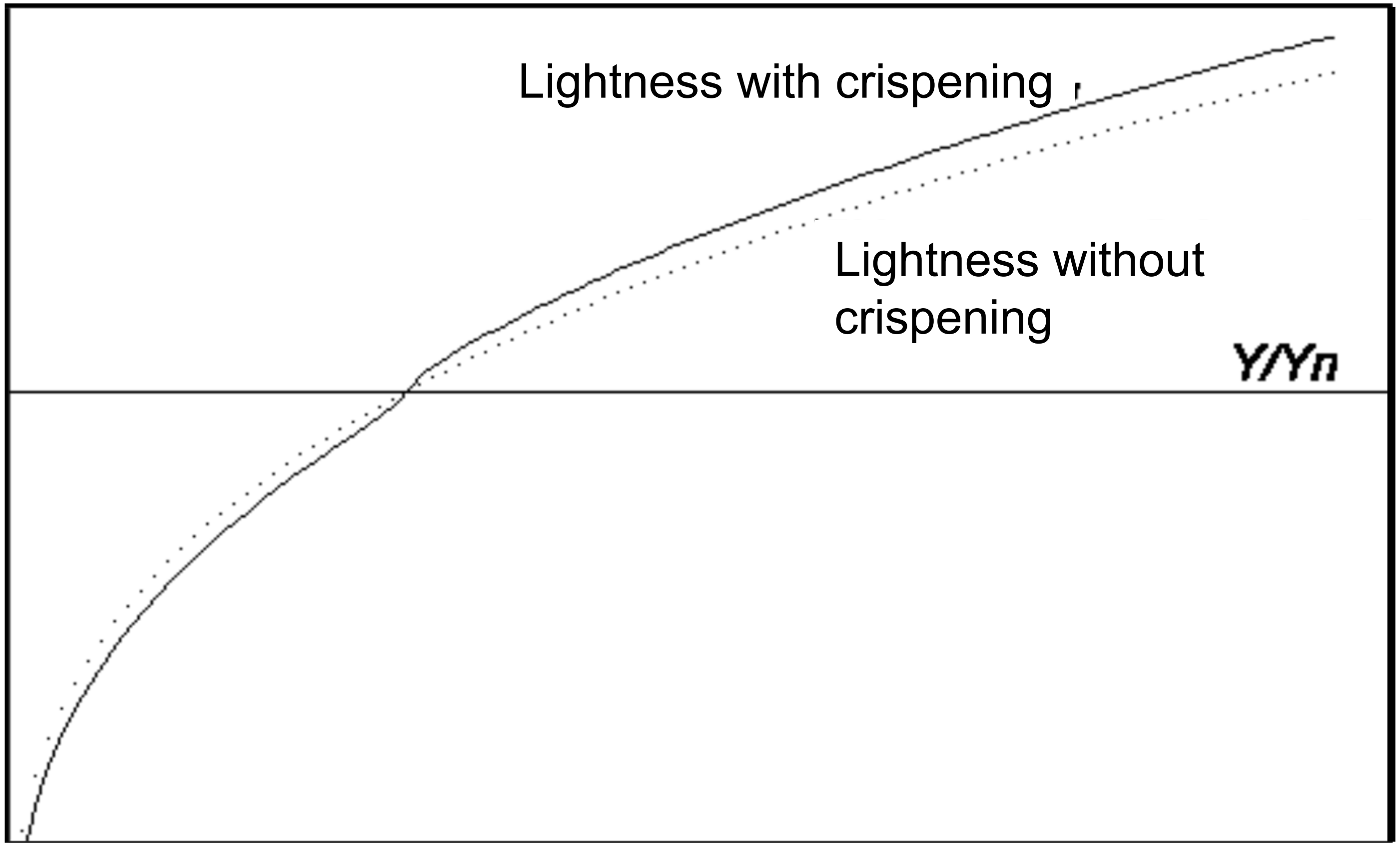
Color Appearance Phenomena: crispening

Crispening is directly related to the spatial structure of the stimuli.



4. Color appearance

Color Appearance Phenomena: crispening

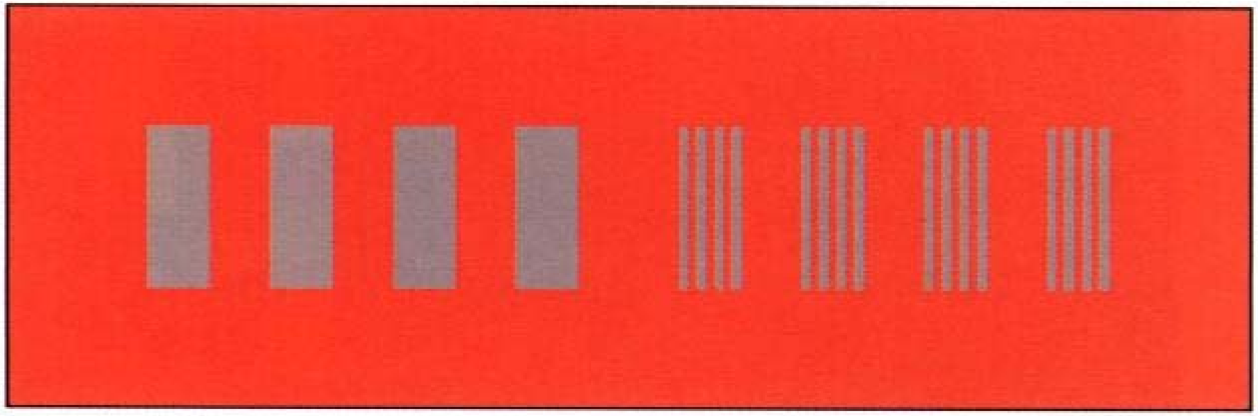


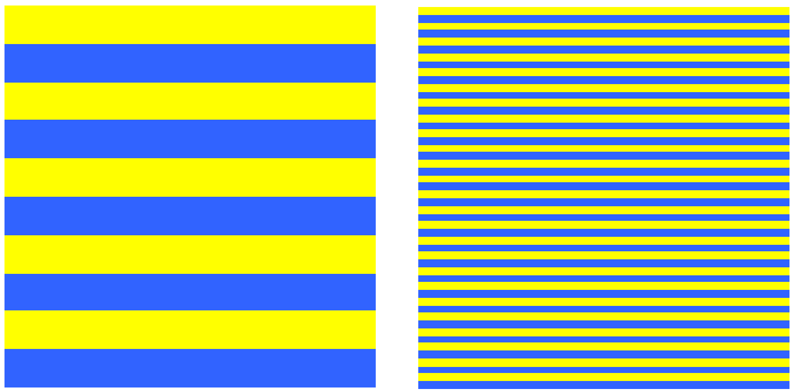
A model that includes the effect of background luminance factor would be required.

4. Color appearance

Color Appearance Phenomena: spreading

Spreading is directly related to the spatial structure of the stimuli.
Spatial frequency from simultaneous contrast to spatial fusion.





4. Color appearance

Color Appearance Phenomena: Hunt effect

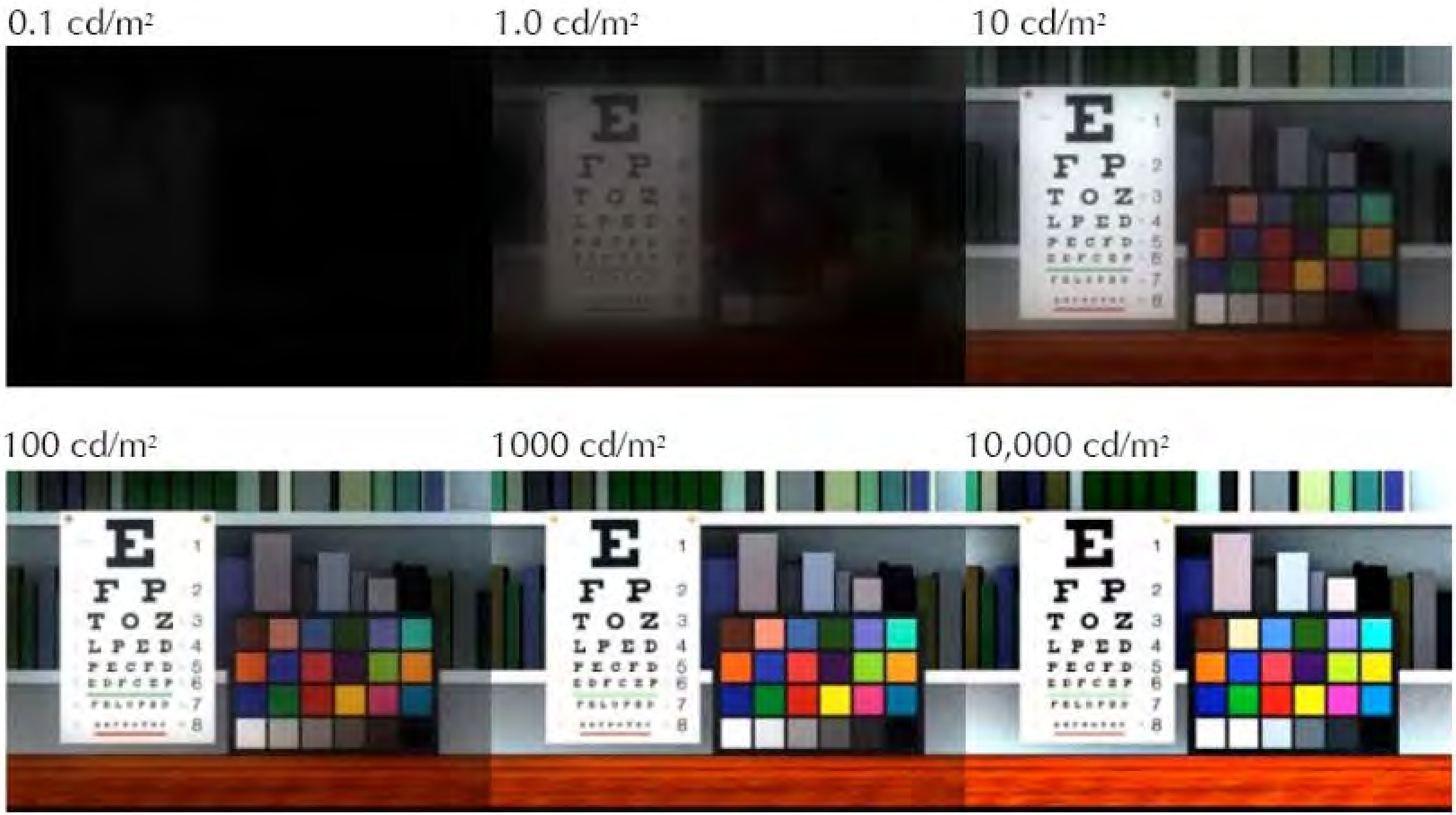
Increase in colorfulness (chromatic contrast) with luminance.

As the luminance of a color stimulus increases, its perceived colorfulness also increases.

Considering the absolute luminance level in color appearance models.

4. Color appearance

Color Appearance Phenomena: Hunt-Stevens effect



Absolute luminance level in color appearance models.

4. Color appearance

Color Appearance Phenomena: discounting the illuminant

Mechanisms of **chromatic adaptation** can be classified as sensory or cognitive.

Sensory mechanisms are not capable of complete chromatic adaptation.

Cognitive mechanisms (based on knowledge about objects, illumination, and the viewing environment) take over to complete the job.

'Discounting the illuminant' refers to the cognitive ability of observers to interpret the colors of objects based on the illuminated environment in which they are viewed. This allows observers to perceive the colors of objects more independent of changes in the illumination and is consistent with the typical notion that color somehow 'belongs' to an object.

4. Color appearance

Color Appearance Phenomena: discounting the illuminant

Discounting the illuminant is of importance in imaging applications where comparisons are made across various media.

Discounting the illuminant has been allowed for in some color appearance models (e.g., Hunt and RLAB).

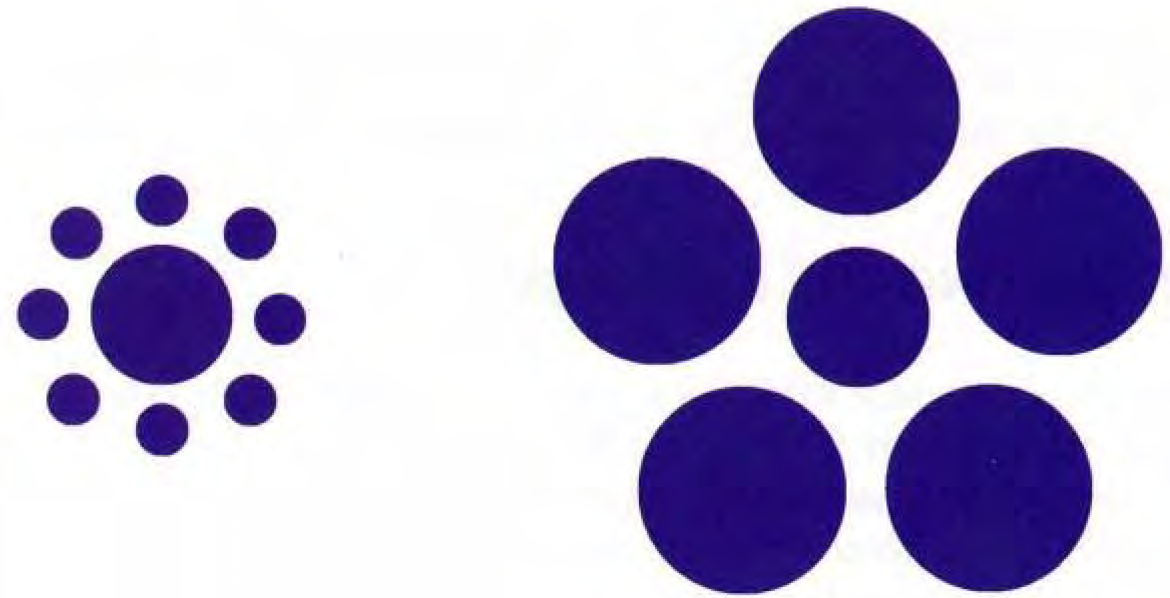
4. Color appearance

Color Appearance Phenomena: Other context and structural effects: cognitive aspect of color appearance

A wide variety of color appearance effects depend on the structure and/or context of the stimuli. These effects present interesting challenges to traditional colorimetry and color appearance modeling.

- Optical illusion

  There is an interaction between spatial and chromatic perceptions.

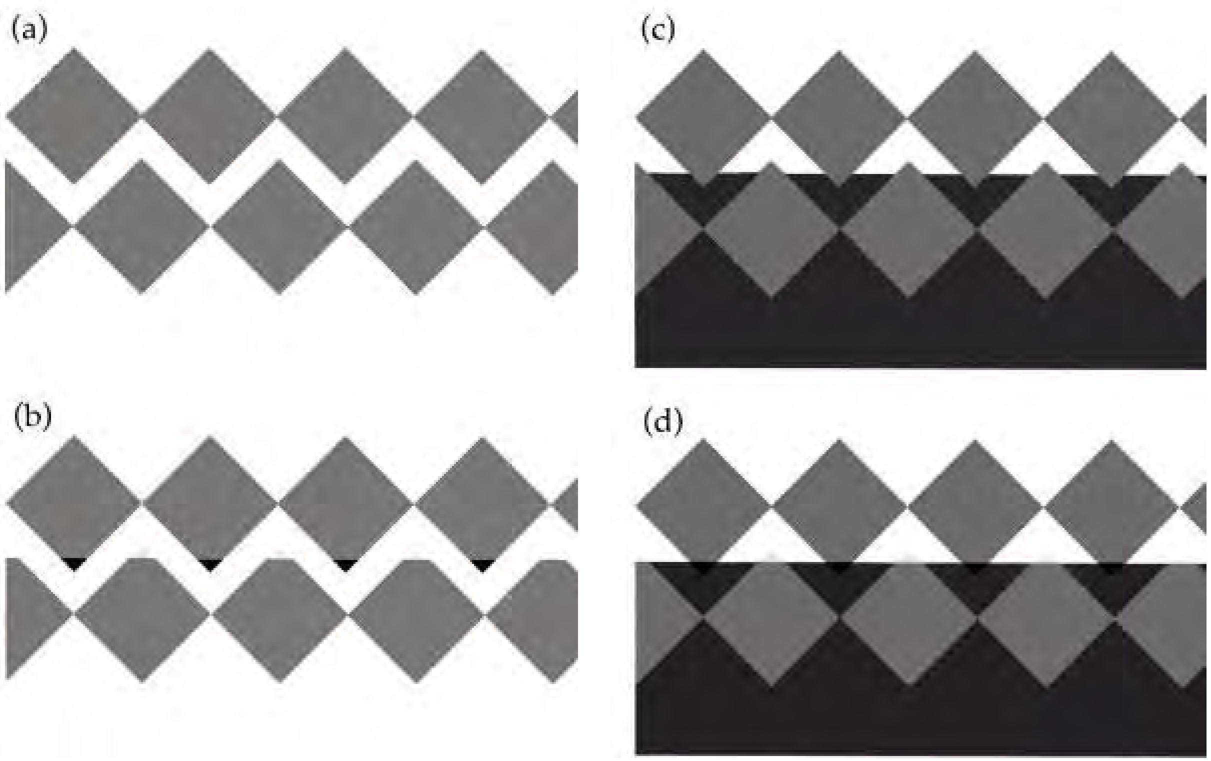


4. Color appearance

Color Appearance Phenomena: Other context and structural effects: cognitive aspect of color appearance

- Transparency effect

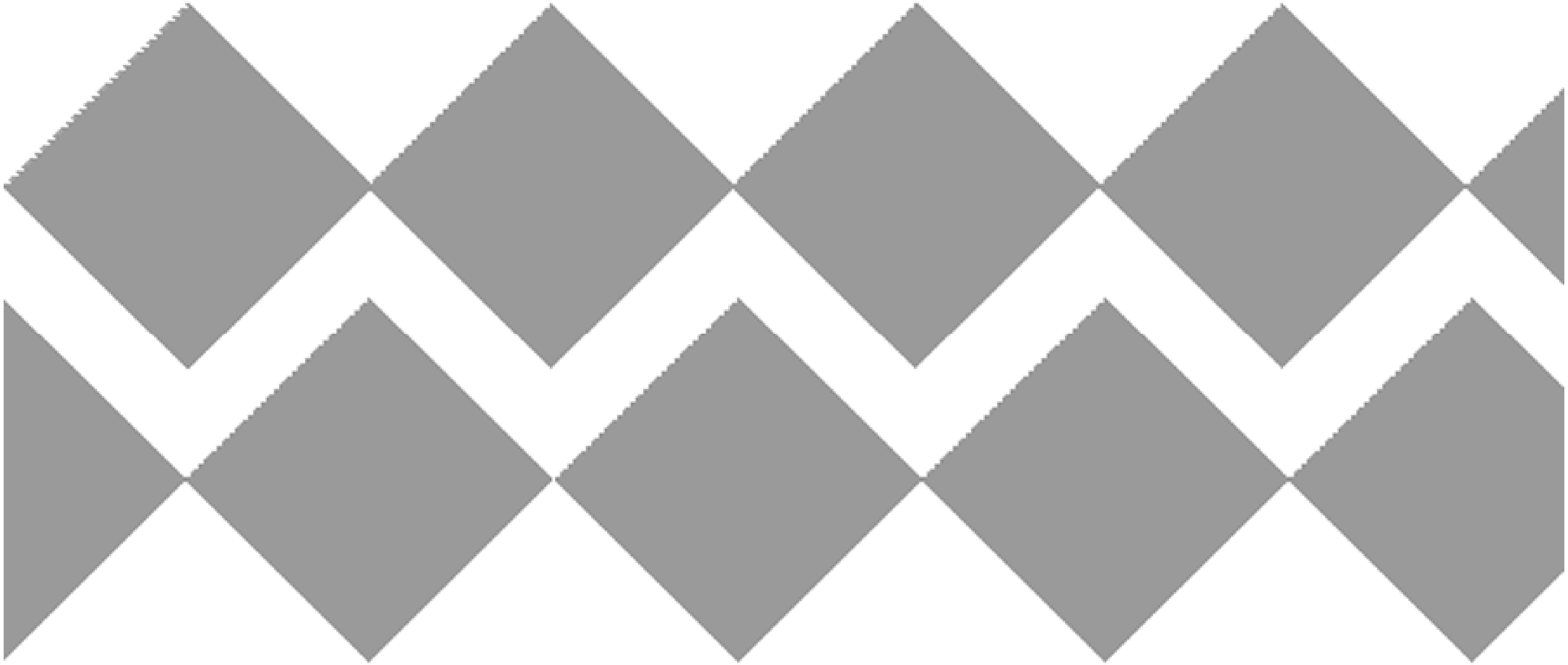
  Transparency effects illustrate the interaction of spatial and chromatic perceptions.



4. Color appearance

Color Appearance Phenomena: Other context and structural effects: cognitive aspect of color appearance

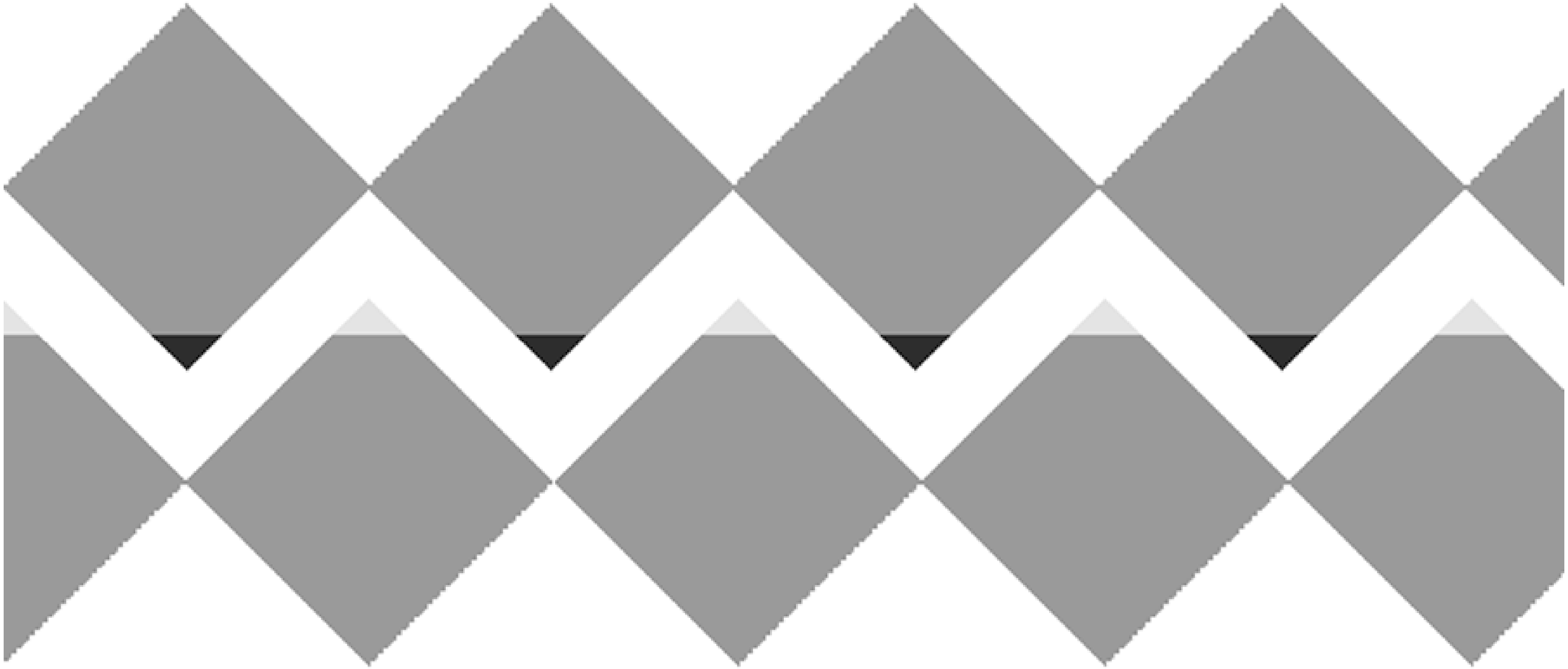
- Transparency effect



4. Color appearance

Color Appearance Phenomena: Other context and structural effects: cognitive aspect of color appearance

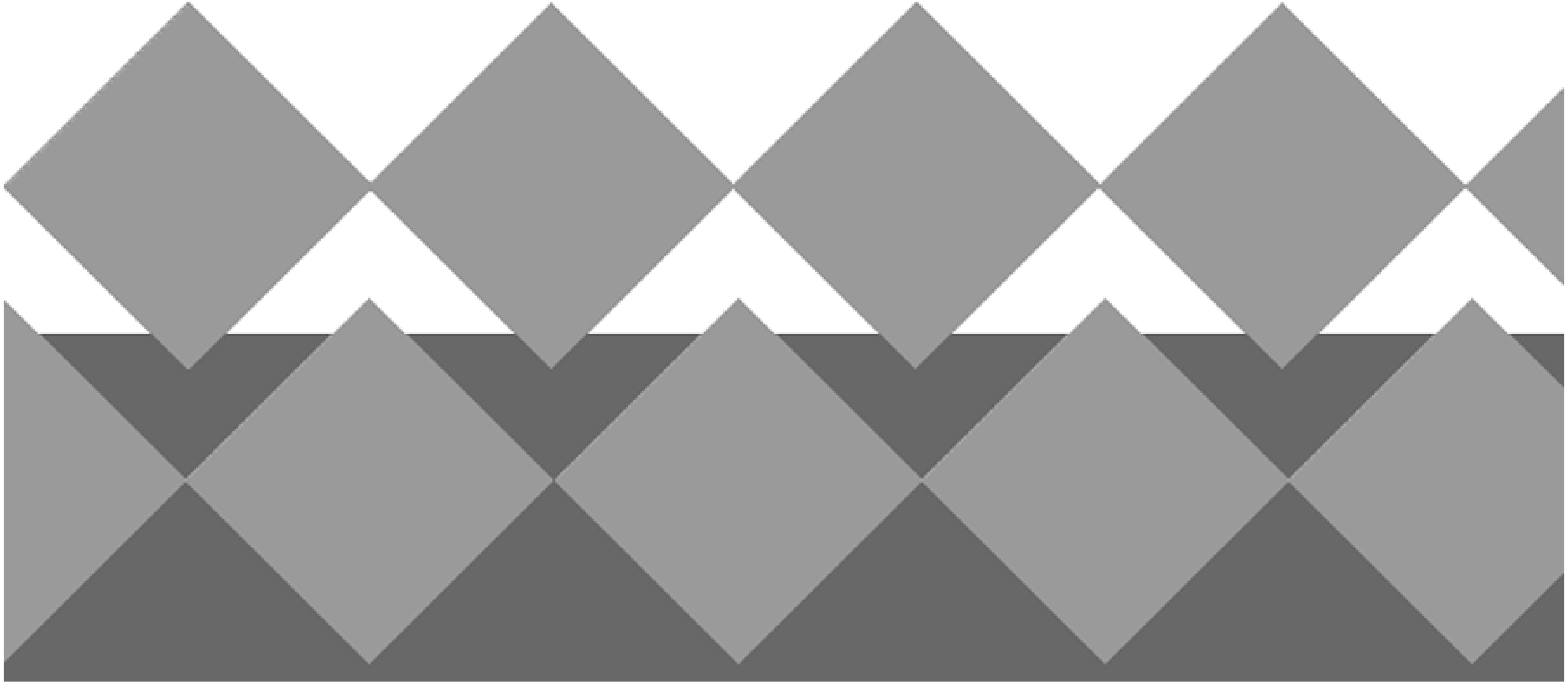
- Transparency effect



4. Color appearance

Color Appearance Phenomena: Other context and structural effects: cognitive aspect of color appearance

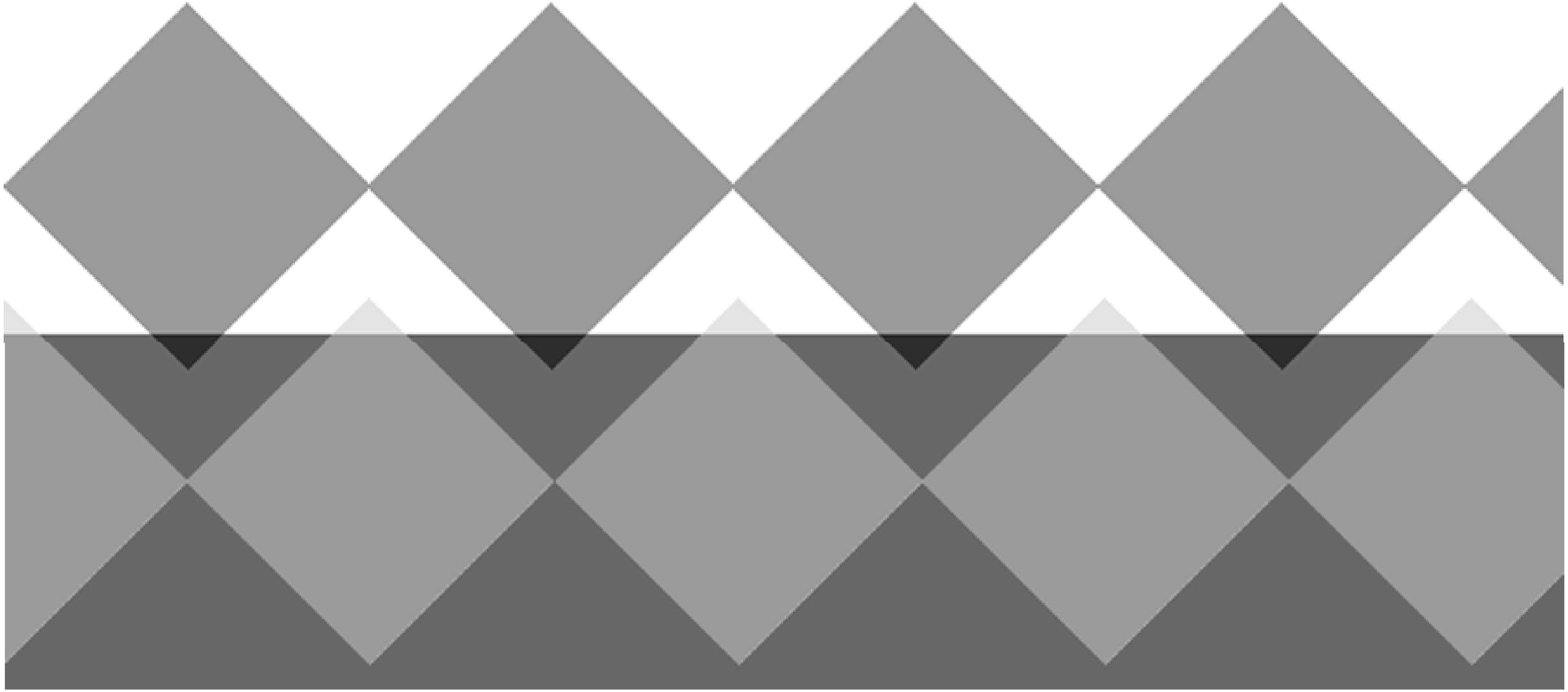
- Transparency effect



4. Color appearance

Color Appearance Phenomena: Other context and structural effects: cognitive aspect of color appearance

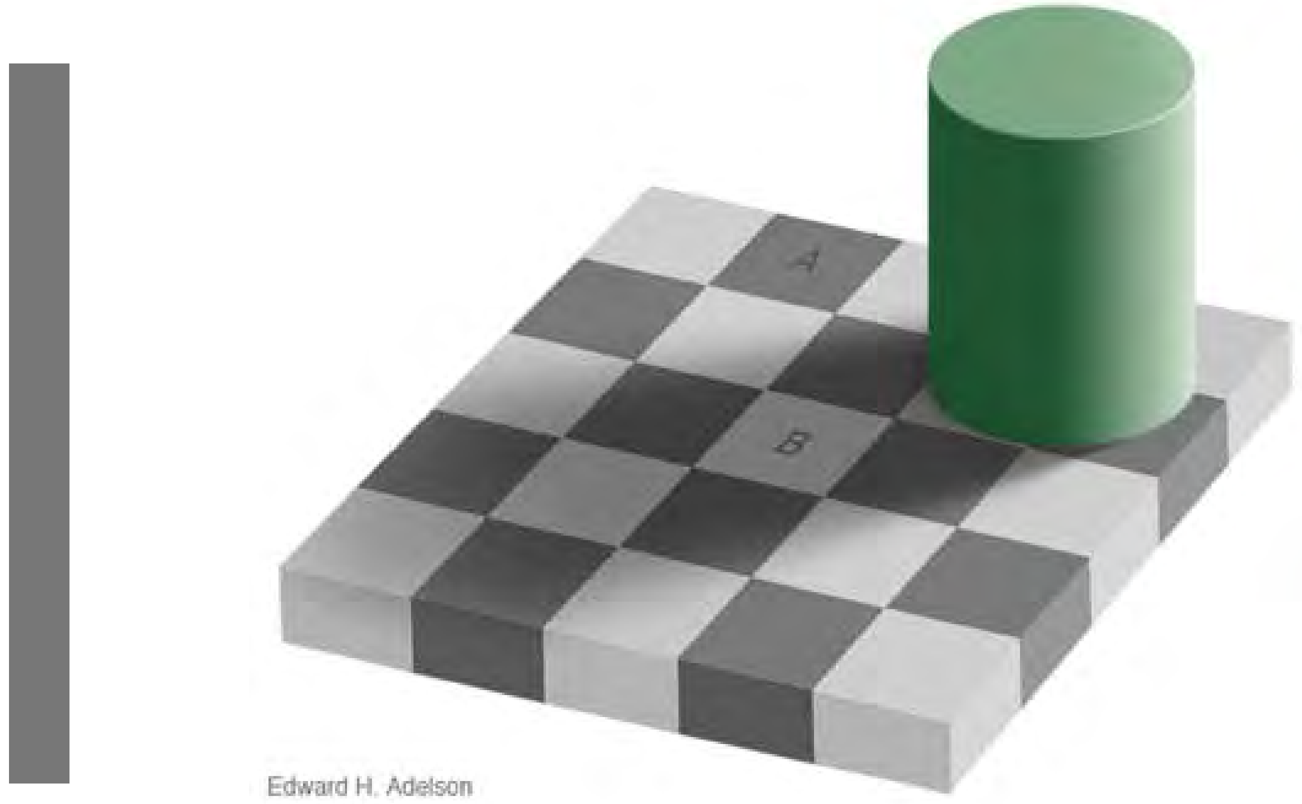
- Transparency effect



4. Color appearance

Color Appearance Phenomena: Other context and structural effects: cognitive aspect of color appearance

- Transparency effect



4. Color appearance

Color Appearance Phenomena: Other context and structural effects: cognitive aspect of color appearance

- Color surround

  Simple spatial structures were added to the surrounds of colored stimuli with profound effects that could not be explained by the usual theories of simultaneous contrast and adaptation. Such results highlight the importance of considering spatial and color variables in conjunction with one another, not as separate entities.

- Color category

  Color category influences visual perception, across a wide range of visual tasks, including color discrimination, color memory, and visual search for color.

- Interpretation of the structure and context of the stimuli.

  Cognitive interpretation of the structure and context of the stimuli: memory colors.

  These effects are small, but consistent, and reiterate the importance of observers' interpretations of stimuli.

10.2 Color Appearance Phenomena

Other context and structural effects: cognitive aspect of color appearance

Cognitive aspects of color appearance and recognition are of significant interest, and necessary to explain the phenomena and models of color appearance. While various color appearance models do include spatial variables in a simple way, more complex approaches along the lines of those suggested by Poirson and Wandell need to be explored further.

4. Color appearance

Color constancy

Color constancy is defined as human capacity to maintain the appearance the color of an object under changes in illumination.

Color constancy does not exist in humans! (i.e. metameric colors)

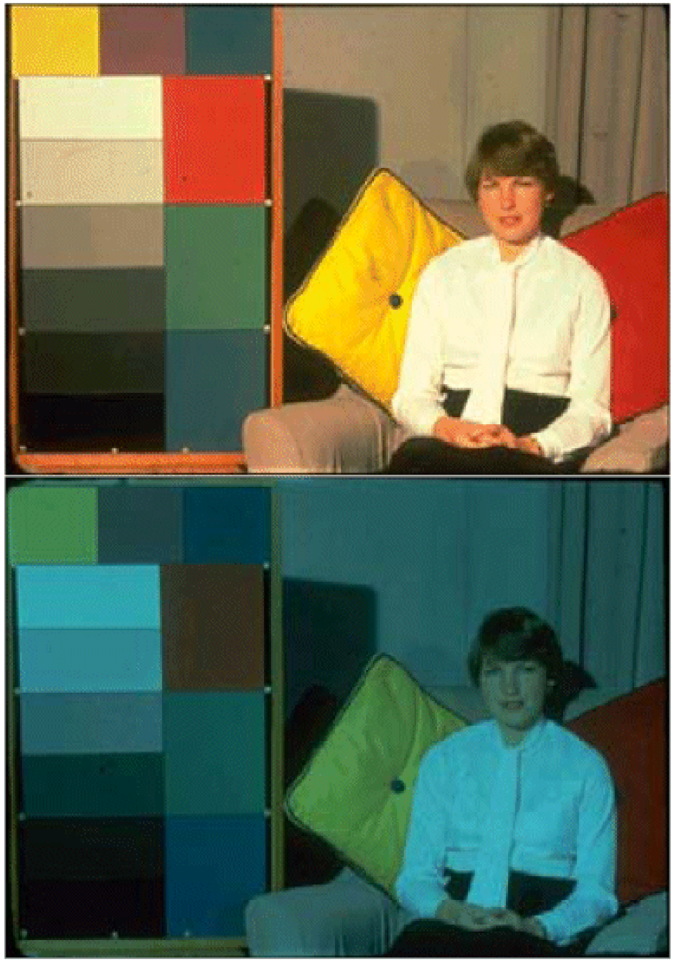
A quote from Evans explains why the term color constancy exists: '*. . . in everyday life we are accustomed to thinking of most colors as not changing at all. This is due to the tendency to remember colors rather than to look at them closely.*' When colors are closely examined, the lack of color constancy becomes extremely clear.

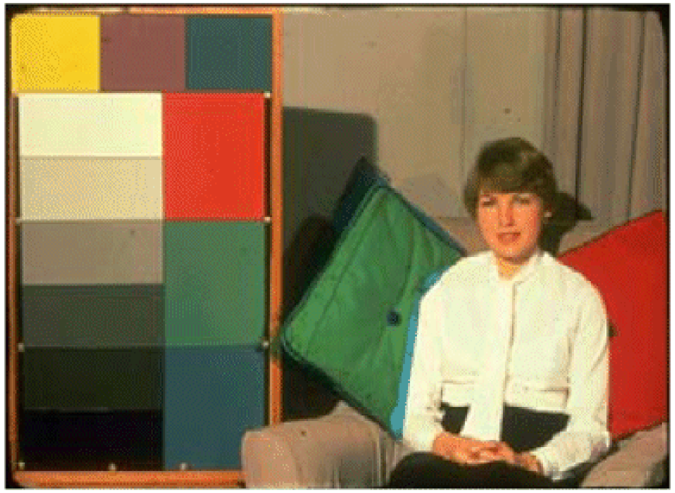
The study of color appearance and the derivation of color appearance models are aiming to quantify and predict the failure of color constancy: utility of the lack of color constancy (retaining information about the illumination, to important information about changes, such as weather, light, and time of day, and the constant physical properties of objects in the scene).

Interest in computational color constancy with applications in machine vision.

4. Color appearance

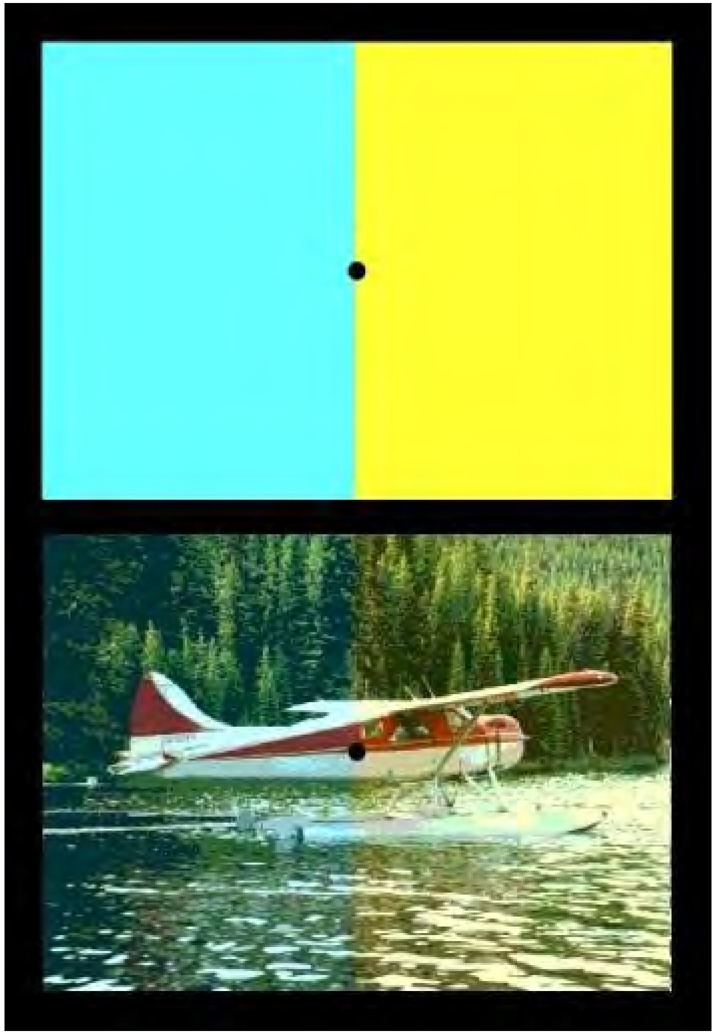
Color constancy





4. Color appearance

Light, dark, and chromatic adaptation

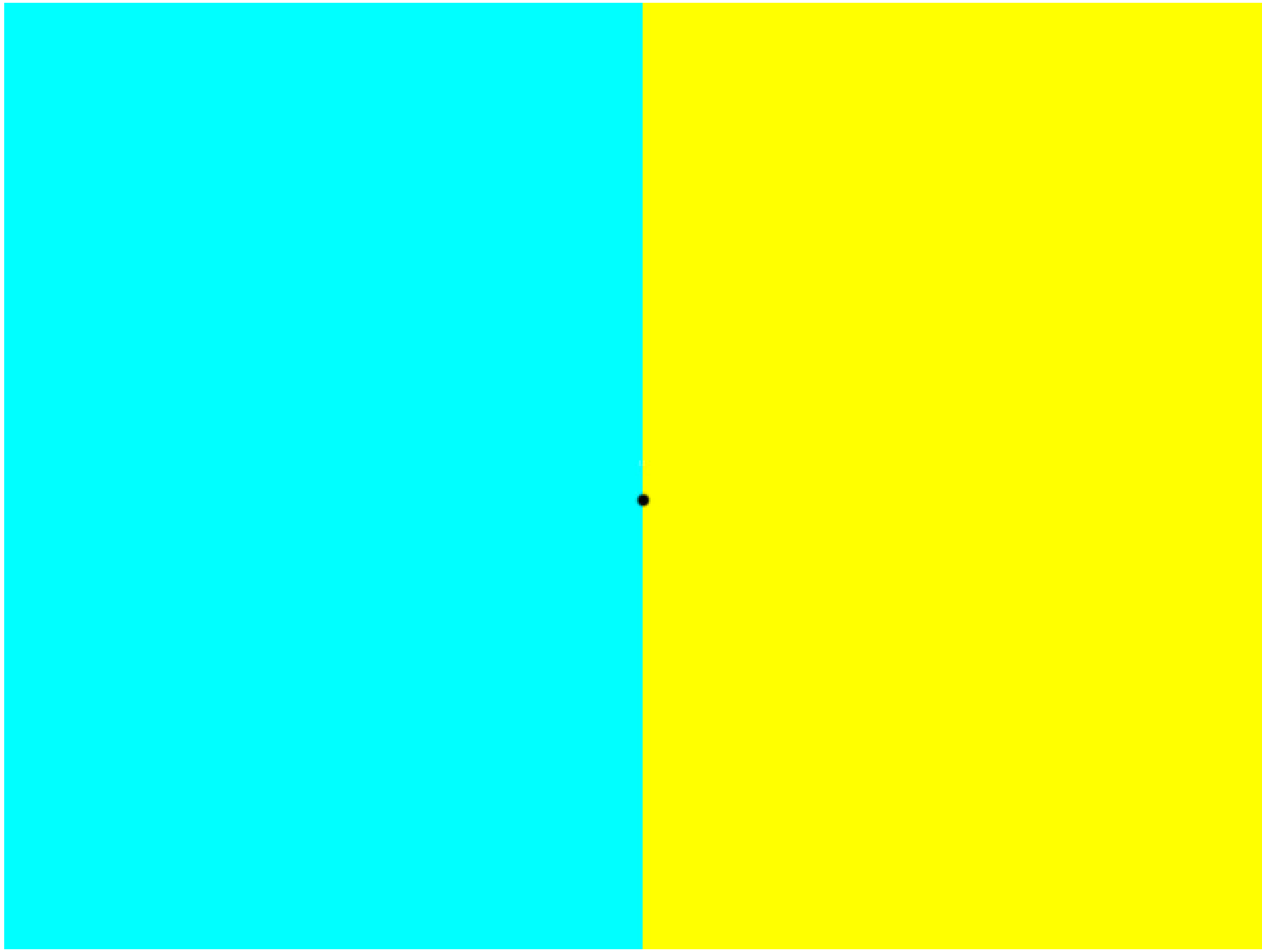


The term chromatic adaptation refers to the human visual system's capability to adjust to different colors of illumination in order to approximately preserve the appearance of object colors.

Basic colorimetry can predict matches or not in color under a wide range of viewing conditions, but appearance will change.

Color appearance phenomena illustrate that tristimulus colorimetry is not capable of describe appearance. Chromatic adaptation is clearly the most important first-order color appearance phenomenon. It has been widely studied.

4. Color appearance



4. Color appearance

4. Color appearance

Light adaptation

The decrease in visual sensitivity upon increases in the overall level of illumination.

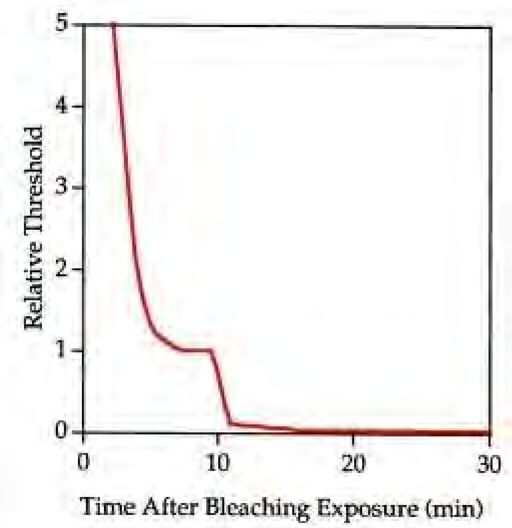
Light adaptation maps the useful illumination range in any given scene into the full dynamic range of the visual output.

4. Color appearance

Dark adaptation

The increase in visual sensitivity experienced upon decreases in luminance level. Dark adaptation is similar to light adaptation, but in the opposite direction.

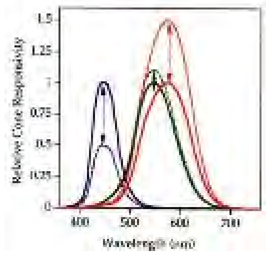
Dark adaptation maps the useful illumination range in any given scene into the full dynamic range of the visual output.

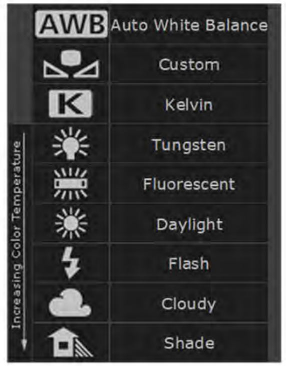


4. Color appearance

Chromatic adaptation

The largely independent sensitivity regulation of the mechanisms of color vision.





4. Color appearance

Chromatic adaptation

CAT

Raw D65 "Radiance" Image

Raw A "Radiance" Image

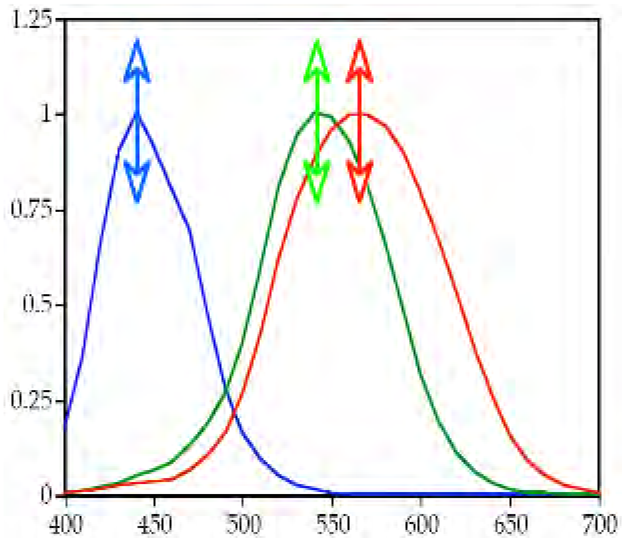
A Image Transformed to
Corresponding D65 Appearance

4. Color appearance

Physiology

The mechanisms of adaptation are classified:

- Reflex-like mechanisms: light and dark adaptation.
- Sensory mechanisms: light and dark, and chromatic adaptation.
- Cognitive mechanisms: chromatic adaptation.



4. Color appearance

CIECAM02 Color Appearance Model

- Linear chromatic adaptation transform.
- Correction of anomalous surround compensation.
- Correction of the lightness scale for perfect black stimuli.
- Correction of chroma scale expansion for color of low chroma.
- Inclusion of a continuously variable surround compensation.
- Improved response compression function to improve saturation correlate.

CIECAM02 is easier to invert.

CIECAM02 can predict all the phenomena that can be predicted by CIECAM97s.

CIECAM02 includes correlates of relative and absolute appearance attributes.

It can be applied over a large range of luminance levels and states of chromatic adaptation. Like CIECAM97s, CIECAM02 is not applicable to situations in which there is significant rod contribution to vision or at extremely high luminances.

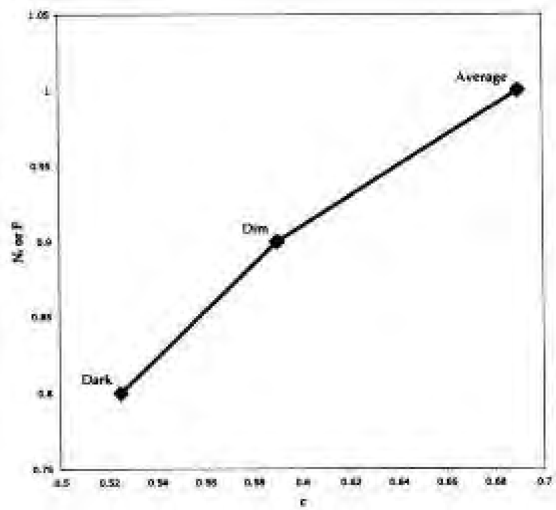
4. Color appearance

CIECAM02 Color Appearance Model: input data

- The relative tristimulus values of the test stimulus (XYZ) and the white point ($X_W Y_W Z_W$);
- The background relative luminance Y_b;
- The adapting luminance (20% of the luminance a white object) L_A, in cd/m^2;
- The relative luminance of the surround (dark, dim, average).

An exponential nonlinearity (c), the chromatic induction factor (N_c) and the maximum degree of adaptation (F).

Viewing condition	c	N_c	F
Average surround	0.69	1.0	1.0
Dim surround	0.59	0.9	0.9
Dark surround	0.525	0.8	0.8



4. Color appearance

CIECAM02 Color Appearance Model: input data

- A decision on whether discounting-the-illuminant.

  Discounting the illuminant: *D* factor is set to 1.0. Otherwise it is computed.

$$D = F\left[1 - \frac{1}{3.6} e^{\frac{-(L_A+42)}{92}}\right]$$

4. Color appearance

CIECAM02 Color Appearance Model: adaptation model

Linear von Kries-type chromatic adaptation transform.

All CIE tristimulus values calculated using CIE 1931 Standard Colorimetric Observer (2°).

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \mathrm{M}_{\mathrm{CAT02}} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \qquad XYZ \in [0,100]$$

$$\mathrm{M}_{\mathrm{CAT02}} = \begin{pmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{pmatrix}$$

4. Color appearance

CIECAM02 Color Appearance Model: adaptation model

Adapted tristimulus responses $R_c G_c B_c$.

$$R_c = \left(\frac{Y_W D}{R_W} + 1 - D \right) R; \quad G_c = \left(\frac{Y_W D}{G_W} + 1 - D \right) G; \quad B_c = \left(\frac{Y_W D}{B_W} + 1 - D \right) B$$

This chromatic adaptation transform can be used independently of the color appearance model only in the cases of Y_W=100.

4. Color appearance

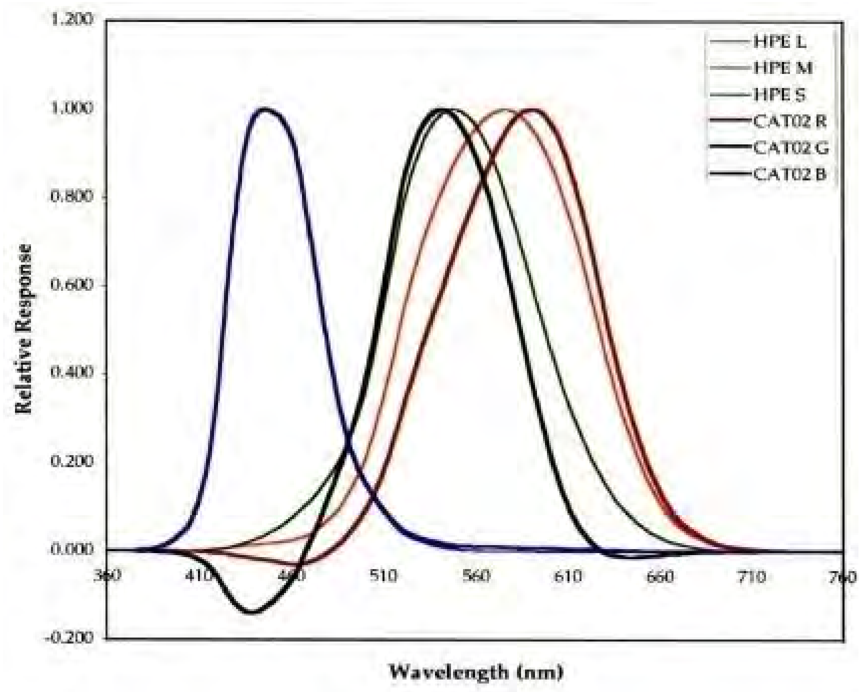
CIECAM02 Color Appearance Model: Post-adaptation nonlinear compression

Post-adaptation nonlinear compression in Hunt-Pointer-Estevez fundamentals.

$$\begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} = \mathrm{M}_{\mathrm{HPE}} \mathrm{M}_{\mathrm{CAT02}}^{-1} \begin{pmatrix} R_c \\ G_c \\ B_c \end{pmatrix}$$

$$\mathrm{M}_{\mathrm{CAT02}}^{-1} = \begin{pmatrix} 1.096124 & -0.278869 & 0.182745 \\ 0.454369 & 0.473533 & 0.072098 \\ -0.009628 & -0.005698 & 1.015326 \end{pmatrix}$$

$$\mathrm{M}_{\mathrm{HPE}} = \begin{pmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00000 & 0.00000 & 1.00000 \end{pmatrix}$$



4. Color appearance

CIECAM02 Color Appearance Model: Post-adaptation nonlinear compression

Viewing-condition-dependent components.

- A luminance-level adaptation factor F_L:

$$F_L = 0.2k^4(5L_A) + 0.1(1-k^4)^2(5L_A)^{1/3}; \quad k = \frac{1}{5L_A+1}$$

- Background brightness, N_{bb}, and chromatic brightness, N_{cb}, induction factors:

$$N_{bb} = N_{cb} = 0.725\left(\frac{1}{n}\right)^{0.2}; \quad n = \frac{Y_b}{Y_W}$$

- The base exponential nonlinearity z:

$$z = 1.48 + n^{1/2}$$

4. Color appearance

CIECAM02 Color Appearance Model: Post-adaptation nonlinear compression

$$R'_a = \frac{400\left(\frac{F_L R'}{100}\right)^{0.42}}{27.13+\left(\frac{F_L R'}{100}\right)^{0.42}} + 0.1$$

$$G'_a = \frac{400\left(\frac{F_L G'}{100}\right)^{0.42}}{27.13+\left(\frac{F_L G'}{100}\right)^{0.42}} + 0.1$$

$$B'_a = \frac{400\left(\frac{F_L B'}{100}\right)^{0.42}}{27.13+\left(\frac{F_L B'}{100}\right)^{0.42}} + 0.1$$

4. Color appearance

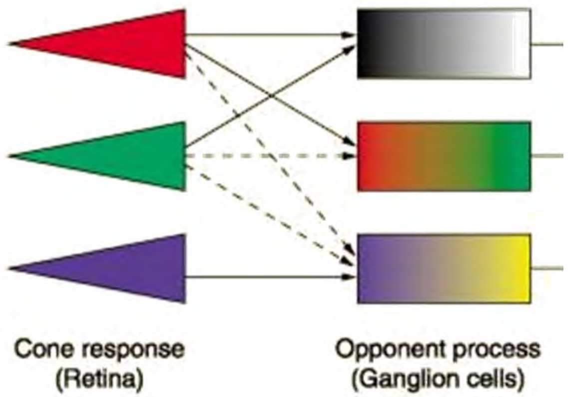
CIECAM02 Color Appearance Model: opponent color dimensions

Initial achromatic response (*A*) and initial opponent-type responses.

$$A = \left(2R_a^{'} + G_a^{'} + \frac{B_a^{'}}{20} - 0.305 \right) N_{bb}$$

$$a = R_a^{'} - \frac{12G_a^{'}}{11} + \frac{B_a^{'}}{11}$$

$$b = \frac{R_a^{'} + G_a^{'} - 2B_a^{'}}{9}$$



4. Color appearance

CIECAM02 Color Appearance Model: Hue (h) and hue quadrature (H) and hue composition (H_c)

Hue angle h:

$$\boxed{h = \arctan \frac{b}{a}}$$

Hue quadrature and hue composition through linear interpolation:

$$\boxed{H = H_i + \frac{100 \frac{h - h_i}{e_i}}{\frac{h - h_i}{e_i} + \frac{h_{i+1} - h}{e_{i+1}}}}$$

	Red	Yellow	Green	Blue	Red
i	1	2	3	4	5
h_i	20.14	90.00	164.25	237.53	380.14
e_i	0.8	0.7	1.0	1.2	0.8
H_i	0	100	200	300	400

e is an eccentricity factor: $$e_t = \frac{1}{4}\left[\cos\left(h\frac{\pi}{180} + 2\right) + 3.8\right]$$

4. Color appearance

CIECAM02 Color Appearance Model

Lightness (*J*)

$$J = 100\left(\frac{A}{A_W}\right)^{cz}$$

An achromatic response for the white, A_W, computed in a similar way.

Brightness (*Q*)

$$Q = \frac{4}{c}\sqrt{\frac{J}{100}}\left(A_w + 4\right)F_L^{0.25}$$

4. Color appearance

CIECAM02 Color Appearance Model

Chroma (*C*)

CIECAM02 chroma *C* is based on empirical fitting.

$$\boxed{C = t^{0.9}\sqrt{\frac{J}{100}}\left(1.64 - 0.29^{n}\right)^{0.73}}$$

$$t = \frac{\frac{50000}{13} N_c N_{cb} e_t \sqrt{a^2 + b^2}}{R_a' + G_a' + \frac{21}{20} B_a'}$$

4. Color appearance

CIECAM02 Color Appearance Model

Colorfulness (*M*)

$$\boxed{M = C F_L^{\,0.25}}$$

Saturation (*s*)

$$\boxed{s = 100\sqrt{\frac{M}{Q}}}$$

4. Color appearance

CIECAM02 Color Appearance Model

Cartesian coordinates (a_C, b_C, a_M, b_M, a_s, b_s)

In some applications it is useful to have the equivalent Cartesian coordinates.

$$a_C = C\cos(h)$$
$$b_C = C\sin(h)$$

$$a_M = M\cos(h)$$
$$b_M = M\sin(h)$$

$$a_s = s\cos(h)$$
$$b_s = s\sin(h)$$

4. Color appearance

CIECAM02 Color Appearance Model

Inverse model

CIECAM02 is a significant improvement over CIECAM97s in terms of simplicity of inversion. A step-by-step procedure:

1. Calculate t from C and J.
2. Calculate e_t from h.
3. Calculate A from A_W and J.
4. Calculate a and b from t, e_t, h, and A.
5. Calculate R'_a, G'_a, and B'_a from A, a, and b.
6. Use the inverse nonlinearity to compute R', G', and B'.
7. Convert to R_c, G_c, and B_c via linear transform.
8. Invert the chromatic adaptation transform to compute R, G, and B and then X, Y, and Z.