Color Inconstancy Methods for Images

Nikora Elena

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Department of Computer Science and Statistics

University of Joensuu

Abstract

This thesis is dedicated to the problem of existence and other issues of the color inconstancy. Reasons of effect of the color inconstancy are discussed. Algorithm for predicting variations in color by using modern color appearance models is implemented.

The experimental part of the thesis consists of investigations of the color inconstancy methods for images and implementation of CIECAM97s and CIECAM02 models for simulating effects of different illuminants on images. This simulation allows resolving important problem for color technologies as under different lightning conditions same-colored objects can look completely different. Developed software allows predicting how the color sample will look on the monitors or printed on paper.

Keywords: color, color theory, color inconstancy, chromatic adaptation transform, CIECAM97s, CIECAM02.

List of Abbreviations[1]

CAT (Chromatic Adaptation Transform): A model for estimating color appearance under different illuminants.

CIE (Commission International de L'Eclairage): A French name that is translated to International Commission on Illumination, the main international organization concerned with color and color measurement.

CIELAB (OR CIE L*a*b*, CIE Lab): Color space in which values L*, a* and b* are plotted at right angles to one another to form an orthogonal coordinate system. Equal distances in the space approximately represent equal color differences. Value L* represents Lightness; value a* represents the Redness/Greenness axis; and value b* represents the yellowness/blueness axis.

CIE Standard Illuminants: Known spectral data established by the CIE for four different types of light sources. When using tristimulus data to describe a color, the illuminant must also be defined. These standard illuminants are used in place of actual measurements of the light source.

CIE Standard Observer: A hypothetical observer having the tristimulus color mixture data recommended in 1931 by the CIE for a 2° viewing angle (using for field of view from 1º to 4º). A supplementary observer for a angle larger then 4º using CIE Standard Observer (CIE 1964) with angular subtense equal to 10º.

CMC (Color Measurement Committee): UK Society of Dyers and Colourists.

Color Model: Color measurement system that numerically specifies the perceived attributes of color. Used in computer graphics applications and by color measurement instruments.

Color Space: A geometric representation of the colors that can be seen and/or generated using a certain color model.

Color Temperature: A measurement of the color of light radiated by an object while it is being heated. This measurement is expressed in terms of absolute scale, or degrees Kelvin, or kelvins.

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[1] Abbreviations were given accordingly to [1]

Lower Kelvin temperatures such as 2400 K are red; higher temperatures such as 9300 K are blue. Neutral temperature is gray, at 6504 K.

Gamut: The range of different colors that can be interpreted by a color model or generated by a specific device.

Hue: The basic color of an object, such as "red," "green," etc. Defined by its angular position in a cylindrical color space.

Illuminant: Incident luminous energy specified by its spectral distribution.

Illuminant A (CIE): CIE Standard Illuminant for incandescent illumination, yellow-orange in color, with a correlated color temperature of 2856 K.

Illuminant C (CIE): CIE Standard Illuminant for tungsten illumination that simulates average daylight, bluish in color, with a correlated color temperature of 6774 K.

Illuminants D (CIE): CIE Standard Illuminants for daylight, based on actual spectral measurements of daylight. D65 with a correlated color temperature of 6504 K is most commonly used. Others include D50, D55, and D75.

Intensity: Saturation or reflective energy as related to visible wavelengths of light. Reflect range of wavelengths at high intensity generates high saturation or chroma.

Visible Spectrum: The region of the electromagnetic spectrum between 380 and 720 nanometers. Wavelengths inside this span create the sensation of color when they are viewed by the human eye. The shorter wavelengths create the sensation of violets, purples, and blues; the longer wavelengths create the sensation of oranges and reds.

Wave: A physical activity that rises and then falls periodically as it travels through a medium.

Wavelength: Light consists of electromagnetic waves; wavelength is the peak-to-peak distance between two adjacent waves.

CONTENTS

1. INTRODUCTION

1.1. Overview

The world around us is full of colors. Each object from surrounding us environment has own color. Beauty of flowers, sunrise, sunset and nature at whole can be percepted due to color vision. But observation is not enough, from the ancient times human tried to reproduce colors of the nature on images. When computer graphic became widespread, a question about comparability of colors emerges. How we can determine that colors on monitor or printed are correct and look like original? How to predict color changes under different viewing conditions? Does the color constancy exist?

Although nowadays the color theory gave us answers on those questions, there are various approaches to the color phenomena and its interpretation. Colors do not exist by itself, they emerge from interaction of three components: light sources, objects and the human vision system (Fig. 1).

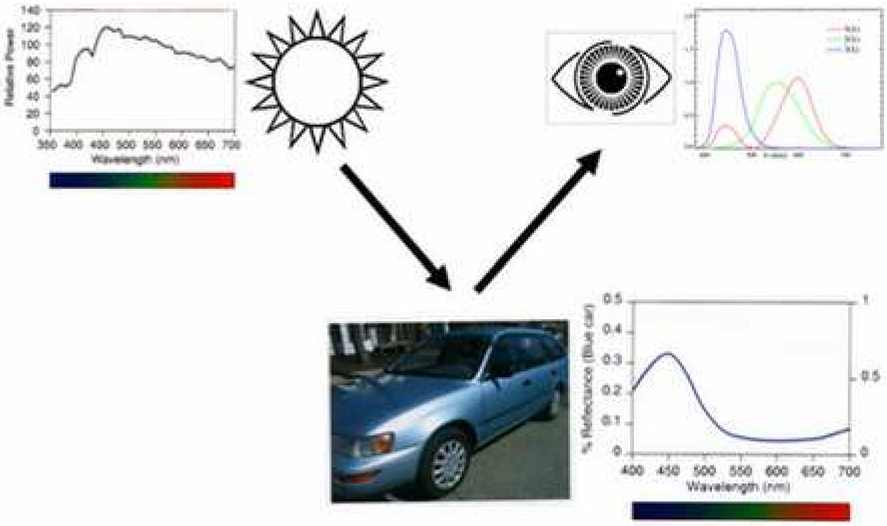


Figure 1: The color triangle: interaction of light source, object and human vision system create a color (Image taken from [2]).

Therefore for understanding nature of color we need to examine how this interaction proceeds and consider the structure of the color generating components.

Once we have color information we need to keep it. Color data can be kept in memory as a spectral image, in bitmap or other image format. Hence we should consider different color coding system. But colors are not always constant. Reasons of color changes lie not only in human vision system, but also in modifications of viewing conditions. For predicting color inconstancy depending on surround changes we should learn color appearance model and their implementation. Those topics are considered in this thesis.

The thesis is organized as follows:

Chapter 2 presents the theoretical background of the topic. First part of the chapter is dedicated to different aspects of the color phenomena, also mechanism of the human color vision and physical nature of light are explained. Various aspects of the color definition are given, and considered modern determination color due stimuli that allows accurate measuring of color data. Definitions of the color constancy and inconstancy are given and considered question about existence of the color constancy.

In second part of the chapter we investigate various methods for representation and storing of the color information. Spectral images, CIE XYZ and RGB color spaces are reviewed. This chapter also describes essence of color appearance models. Also considered evolving process of development of the chromatic adaptation transform on examples of CMCCAT97, CMCCAT2000 and their modifications. Discussed main points of the color appearance models: CIECAM97s and CIECAM02.

In chapter 3 we investigate algorithm of chromatic adaptation and applicability of CMCCAT2000 and CAT02 for the task of predicting variability of colors.

Chapter 4 describes process of the measurements and obtained results. For all results received graphical representation as a graph for visualization.

Chapter 5 accumulates all conclusions from previous chapters and reveals obtained results. Also some perspective of further work marked and given a general summary of the thesis.

1.2. Description of the problem and constraints

This project is dedicated to problem of the color inconstancy. Color inconstancy is the change in color of a single sample under different illuminants. It stands as a very important problem for color technologies as under different lightning conditions same-colored objects can look completely different. It is necessary to know how the color sample looks on the monitors or printed on paper. This topic is required for many industrial applications such as the prediction of color inconstancy for the paintwork industry, evaluating the color rendering property of light sources for the lighting industry, and achieving successful color reproduction under different light sources for the color reproduction industry. The developed software allows predicting changes in color if initial color and characteristics of illuminants are known.

For prediction of color changes only data obtained by measurements (spectral image of the samples, colorimetric data of colors of the sample) and some reference data (characteristics of the light sources) are used so we do not have possibility to implement full color appearance model that include post-adaptation non-linear response compression depend on psychophysics characteristics of human vision.

2. THEORETICAL BACKGROUND

In this chapter we will consider some theoretical questions that are needed to perform practical researches. We will give definition to fundamental concepts of color theory such as a color, aspects of human vision and physical nature of color, concept of the stimuli, constancy and inconstancy of the color. Also emission and reflectance spectra of electromagnetic radiation, color data representation as spectral images, various color spaces and color appearance models will be described.

2.1. Human vision

To understand the way artificial color systems work we should know physical nature of color and mechanism of the human color vision. Human vision is a complex process and currently is not yet completely understood. Many authors like J. Neitz, M. Neitz, G.H. Jacobs, G. Wyszecki, K. L. Günther, B. A. Wandell are studying different aspects of the visualization process in human eye. Their papers consider wide range of the theories of human vision but authors agree on the several generally recognized facts. The complex process of vision involves the nearly simultaneous interaction of the eyes and the brain through a network of neurons, receptors, and other specialized cells. Human eye acts like camera when cornea and lens working together to create image on retina like on photographic film. Every eye element participates in the process of visualization: the cornea, iris, pupil, a variable-focus lens, and the retina, as illustrated in Fig. 2.

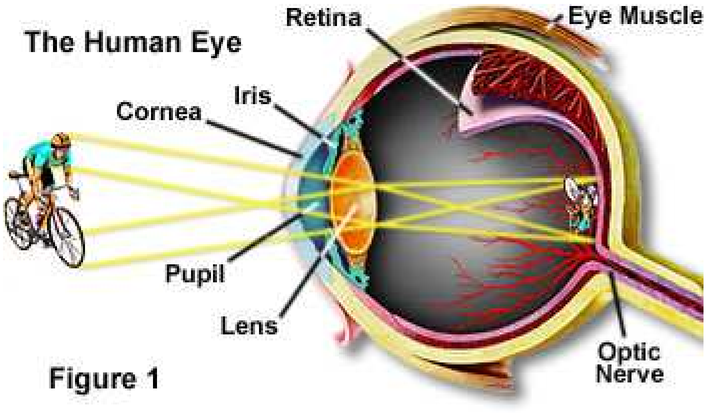


Figure 2: The human eye (Image taken from [3]).

Light reflects from objects and gets to the cornea that is the clear, dome-shaped surface covering the front of the eye. Cornea – strongest lens in optic system of the human eye. Reason of intense refraction is the great difference between index of light refraction in the air and index of light refraction of cornea’s material. Light passes through the cornea going to front cavity of eye that is filled with liquid and is situated between cornea and iris. Iris is the diaphragm with aperture in center called pupil. Diameter of the pupil can changes depending on the lightness level and regulates quantity of light percepted by the eye. Crystalline lens is placed beyond iris; it refracts light like cornea but with lesser optic strength. Crystalline lens is connected with ciliary muscle on inner surface of eye by suspensory ligament. These muscles can contract and relax, so crystalline lens’ radius of curvature is changed depending on muscles’ state and human can see both near and distant objects. Vitreous body is situated beyond lens and occupies most part of eye, its only function in preserving the form of an eyeball.

After passing through all structures described above, light falls on the retina that consists of the nine layers of cells and is needed to transform light energy to electric energy of nervous impulses. The most important part of retina for vision process is fovea. Fovea occupies area where visual angle of observation is equal to 2 degree in the centre of field of vision, so we have best vision in the area of fovea. Hence the standard angle of observation is equal to 2 degree.

There are two types of photoreceptors (light-sensitive retinal cells) – rods and cones which responsible for two different functions of vision. Rods are responsible for the twilight vision when observing image has low brightness. As brightness increases rods become saturated and cones begin to work as main light percepting cells. Vision by rods is called scotopic, cones vision is called photopic. If the both types of photoreceptors are working, the vision is called mesopic. Rods and cones have different spectral response: rods have only one peak of spectral response while cones have three peaks of response situated in different parts of the visible spectrum. The difference in the signals received from the three cone types allows human to perceive colors using opponent process of color vision. The three types of cones have some overlapping in the wavelengths of light to which they respond, so human visual system record differences between the responses of cones. The opponent color theory suggests that there are three opponent channels: red versus green, blue versus yellow, and black versus white (the latter type is achromatic and detects light-dark variation, or luminance). The light response of the rods curve almost entirely lies within the area of “blue” (450–495 nm) wavelength and they respond very little to another wavelengths, so for example we can not see red color in twilight and percept red image like dark or black. "All cats are grey in the night" is a good description of lack of rods' color perception sensitivity: in twilight human eye can not discern color of objects. Cones have wide range of perception; there are three types of cones. Each type has its own curve of spectral response. These three types of cones have following spectral sensitivity curves and are called L-, M- and S-cones (long-, middle-, short-wavelength) as illustrated in Fig. 3 below (image based on Dicklyon's PNG version, itself based on data from Stockman, MacLeod & Johnson (1993) Journal of the Optical Society of America A, 10, 2491-2521d).

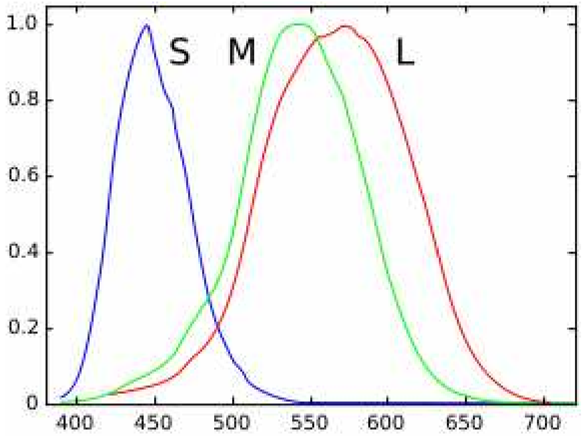


Figure 3: Simplified human cone response curves
(Image taken from [4]).

Image on the retina is converted to chemical and electric signals of photoreceptors that are processed by cells of neural network of the retina. In this process horizontal, bipolar, amacrine and retinal ganglion cells are engaged; axons of retinal ganglion cells form optic nerve which follows to lateral geniculate nucleus into thalamus – subcortical section of the cerebrum. Cells of lateral geniculate nucleus receive input signal from retinal ganglion cells and send them into first visual section of occipital lobe. Hence the occipital lobe is the visual processing center of human brain, containing most of the anatomical region of the visual cortex, analyzing and constructing visual image.

Also we should consider visual mechanisms that influence human vision. Some cognitive visual mechanisms such as: memory color, color constancy, discounting the illuminant and object recognition impact on color appearance. When human recognize familiar objects he has a prototypical color that is associated with these objects correspondently. So human perceive colors of everyday seen objects like invariable under different illuminant because of color memory and discounting the illuminants. Observer recognizes similar object and its colors, interpret the lightning conditions and perceive the colors of object after discount influence of illuminant. These effects can prevent clear visual perception and we should be careful about environment of objects during experiments.

2.2. Physical aspects

Effect of the color inconstancy has a physical explanation. Human eye can not sense object by itself, but can percept light that is reflected (or emitted) by an object. An object reflects some portion of falling light depending on their physical characteristics. For each wavelength of falling light there is a given amount of light intensity to be reflected.

Let's present reflective characteristics of object as an array R of wavelengths and corresponding portions of light to be reflected on a frequency:

$$R = \begin{bmatrix} p_1 & p_2 & p_3 & \dots & p_{n-1} & p_n \\ l_1 & l_2 & l_3 & \dots & l_{n-1} & l_n \end{bmatrix} \quad (1)$$

where $l_1,...l_n$ - wavelengths;

$p_1,...p_n$ - portions of light reflected where p_i in interval [0, 1], $i \in 1..n$.

When an object is illuminated by some light with spectrum S:

$$S = \begin{bmatrix} a_1 & a_2 & a_3 & \dots & a_{n-1} & a_n \\ l_1 & l_2 & l_3 & \dots & l_{n-1} & l_n \end{bmatrix} \quad (2)$$

where $l_1,...l_n$ - wavelengths and $a_1,...a_n$ - intensities of illuminating light on corresponding wavelengths, $i \in 1..n$.

Reflected light can be presented as following array L (spectrum):

$$L = \begin{bmatrix} p_1 * a_1 & p_2 * a_2 & p_3 * a_3 & \dots & p_{n-1} * a_{n-1} & p_n * a_n \\ l_1 & l_2 & l_3 & \dots & l_{n-1} & l_n \end{bmatrix} \quad (3)$$

where $p_i * a_i$ are intensities on corresponding wavelengths l_i, $i \in 1..n$.

These equations can be presented in functional form as described below:

$L(l) = S(l) \times R(l)$, where *L(l)*—reflected light spectrum, *S(l)*—spectrum of illuminant, *R(l)*—reflectance spectrum of the object, where range of *R* = [0..1].

Hence, similar objects on different illuminations may produce different reflected spectrums and colors; while different objects on different lightning conditions may look similar.

2.3. Not color but stimulus

We discussed human vision system and physic aspects of the color, and we can try to answer on question “What color is?”.

- Perception of light by human?
- Property of object itself which human can see?
- Electromagnetic waves which can be measured somehow?
- Material waves which reach the eye?

There are many theories considering different aspects of color and giving us many explanation of this phenomenon. Followers of objectivism assume that color is mind-independent properties of objects and the color vision allows human to sense some of them [5]. Reflectance spectrum of the surface can be used as mind-independent characteristic of object according to this theory and determine the color of object uniquely. But problem of metamerism can not be solved using such way: we can have physically distinct spectra that will be percepted as same color. So it is not correct to use characteristic of object independent of human vision to determine the color. Also we know that color does not exist without light. Existence of color metamerism lead to conception that color is not an objective characteristic but can be defined by reference to effects on a human retina—anthropocentric theory [6]. C. L. Hardin in 1988 gave the following subjectivist explanation [7]:

“It is not as if there were no plausible alternative to all these Ptolemaic epicycles. There is, and it is simply this: render unto matter what is matter's. Physical objects seem colored, but they need not be colored. They do have spectral reflectances and the like, and such properties are sufficient to give us a straightforward and detailed account of the stimuli of color perception. To account for the phenomena of color we need not ascribe any other properties to those stimuli, and we find, furthermore, that when we try to do so, the chief result is obscurity in our understanding and caprice in our tactics. So stop the sun and the stars, and start up the earth. The sun's motions, which we so plainly see, are illusory: the movement is on our end.”

Hence we can not tell about colors itself but we can determine color due stimuli that effect on the system of human vision. Let’s give some definitions of the stimulus concept.

“Stimulus— any factor inside or outside an organism, but external to a sensory receptor, which initiates activity of some kind” — general description [Sports Science and Medicine. The Oxford Dictionary of Sports Science & Medicine].

“The stimulus is defined as the color element for which a measure of color appearance is described” — description is given by M. D. Fairchild [8] and determines stimulus like color factor that effects on human vision and should specified as viewing condition. Usually stimulus is taken as uniform patch with angular subtense according to two standard observers:

– for field of view from 1º to 4º using CIE Standard Observer (CIE 1931) with angular subtense equal to 2º;
– for field of view larger then 4º using CIE Standard Observer (CIE 1964) with angular subtense equal to 10º.

Some limitations is appeared when concept of the stimulus is used in color theory, reasons for these limitations are heterogeneity of the retina in context of color sensitivity and real field of view usually larger then 10º, but in general concept of the stimulus is effective for colorimetry.

2.4. Constancy and Inconstancy of the Color

Human eye can distinguish a great number of different colors depending on characteristics of the visual perception. This makes up to 150 different hue values, 25 values of saturation and 60 various values of luminance for good observer with the normal color vision in the well lit environment. We can define color and name it like “light grey”, “deep blue”, “brightly pink” but if condition of observation is changed color also changes. Modification of light, size, background, shape, surface characteristics and other conditions of observation influences perception of colors. But sometimes we can observe invariability of colors and percept color of objects that stays constant under different light conditions as shown in Fig. 4. So we are coming to a question—does the color constancy exist or it is just optical illusion?

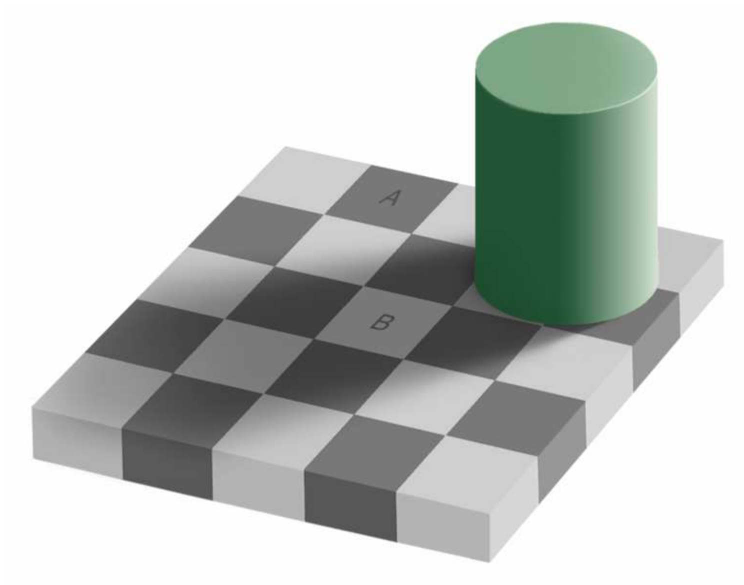


Figure 4: Color constancy makes square A appear darker than square B, when in fact they are both exactly the same shade of grey (Image taken from [4]).

Let's determine the color inconstancy as a change in color of a single sample under different light sources. The value of color inconstancy is referred as ΔE. Let's define ΔE according to CMC[2] standard (CMCCON). We can determine the degree to which colors change in appearance when color of the illuminant changed using next methods:

- checking visually by observing samples under various light sources
- instrumental method based on chromatic adaptation transform

We can obtain two sets of measurements of the tristimulus values of sample:

- X, Y, Z—for example under A (test illuminant);
- Xr, Yr, Zr—under D65 (reference illuminant).

The difference between these two sets of values called illuminant colorimetric shift. X_c, Y_c, Z_c – tristimulus values of the sample of corresponding color in the daylight, which has the same appearance as color seen under A illuminant. The difference between X, Y, Z and X_c, Y_c, Z_c is called adaptive color shift and can be calculated using formulas of the chromatic

[2] Colour Measurement Committee

adaptation transform (CAT). CAT is used to predict values X_c, Y_c, Z_c for the corresponding color which under reference illuminant looks the same as sample's color under test illuminant. Magnitude of the color inconstancy ΔE is the color difference between X_r, Y_r, Z_r and X_c, Y_c, Z_c [9] as illustrated in Fig. 5. This difference ΔE provides the 1997 Color Inconstancy Index (CON97) and refers to the ΔE CMC[3] for a sample between D65 and a second light source.

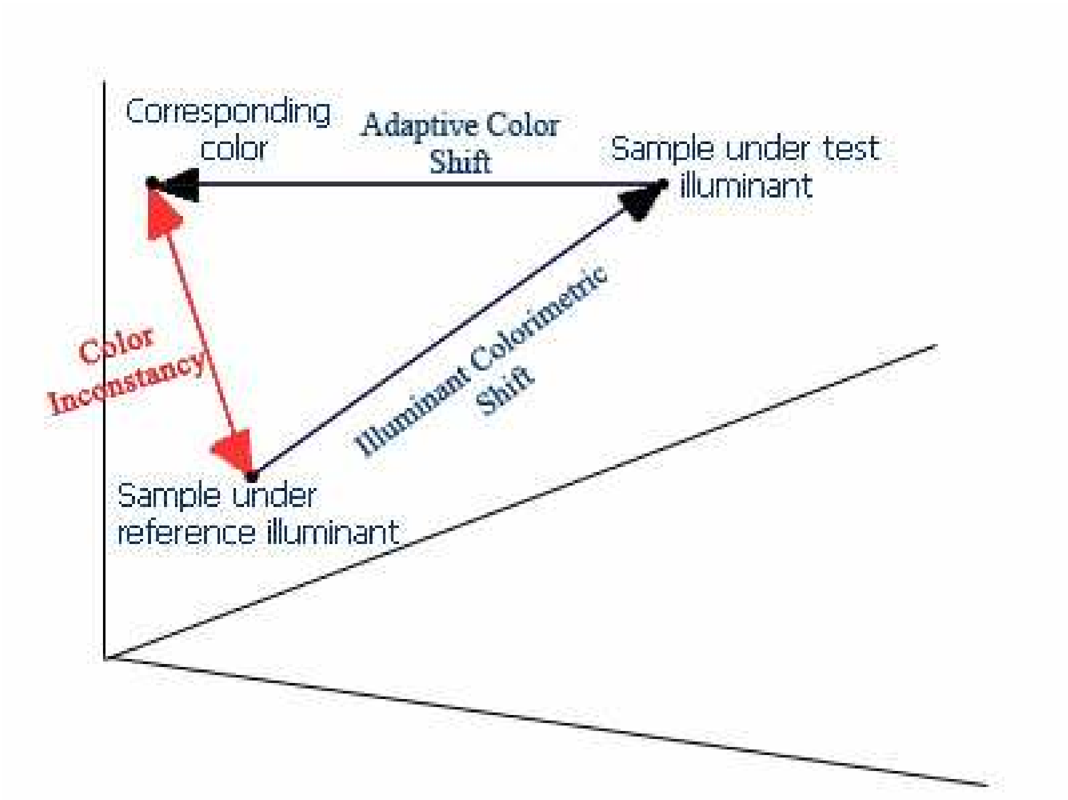


Figure 5: Definition of the color inconstancy due to adaptive color shift and illuminant colorimetric shift.

We should notice main difference between two similar phenomena: color inconstancy and metamerism. Color inconstancy is the change in color of a single sample and metamerism is the change in color difference between a pair of samples.

Consider two stimuli with identical coordinates in color space (CIE XYZ is taken as a color space); they will be the same in color for observer if the conditions of observation are identical. As long as we keep invariability of viewing conditions we will percept the colors of these stimuli as similar. But if observation's conditions are changed this similarity disappears. Hence we can determine color constancy only for colorimetric calculation models

[3] The abbreviation stands for ΔE Colour Measurement Committee of Dyers and Colourists. Built upon a color standard developed from CIELAB. Adopted as British Standard BS6923: 1988.

that don’t consider light source, type of surface, influence of background or temperature of the object. In the color theory of CIE, colorimetry is defined as a color appearance for many viewing conditions, so objects looking similar under one light source will mismatch under some other light sources. If we can eliminate or reduce effect of the illuminants and concentrate on the light reflected by surface we can obtain “true” colors. Necessary condition of color constancy existence is extracted information about reflectance spectrum.

Although concept of the color constancy does not exist in the context of theory of color appearance model but we can observe this phenomenon evidently. If we look at a sample through red optical filter under daylight and then under sunset light, the color of sample will be the same for observer. But it is just outward appearance and the spectrum of reflected light is different in each case. Explanation of the color constancy in this case lies in human color perception. As described above human eye has only three classes of cones receptors for coding of all colors of the world. We need infinite number of values for determination of received energy for each wavelength but information about color of objects is reduced to triplet. Hence we can’t obtain unique value for each color and seen only group of colors. When difference between colors is small eye percept these colors as the same, so concept of the color constancy existence is applicable to human vision.

2.5. Emission and reflectance spectra

Human eye can percept electromagnetic radiation with wavelengths approximately between 380 and 750 nm. This range is called the spectrum of visible light and present range in which natural source of light such as sun emits mostly. Graphical representation of the spectrum of visible light is illustrated in Fig. 6.

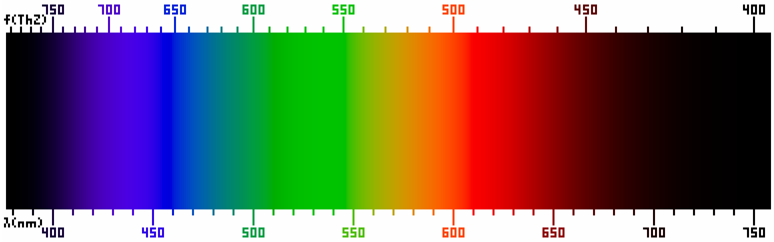


Figure 6: Spectrum of visible light, rendered in sRGB, so that the relative luminances are respected (Image taken from [4]).

Different wavelengths of electromagnetic radiation percepted by human eye as different colors, but as spectrum is continuous we can determine limits of wavelength for each color only approximately [10] (see Table 1).

Color	Wavelength interval	Frequency interval
violet	~ 400–450 nm	750–670 THz
blue	~ 450–490 nm	670–610 THz
green	~ 490–560 nm	610–540 THz
yellow	~ 560–590 nm	540–510 THz
orange	~ 590–630 nm	510–480 THz
red	~ 630–700 nm	480–430 THz

Table 1: The colors of the visible light spectrum [11].

Physical reason of the electromagnetic radiation from substance consists in that excited atoms of the substance emit energy of excitation in the form of quanta of electromagnetic radiation (photons). Dropping extra energy from the excited electrons and resetting them to ground state atoms turn to basic (unexcited) state where they can not emit energy anymore. Each excited atom tends to basic state and occasionally radiates photons with energy (wavelength or frequency) depending on the type of the atom (or ion) and excitation energy. Each type of atoms or ions can absorb or emit only allowed portion of the energy. Number of atoms may emit specific distributions of photons of the energy. In generally this distribution are called electromagnetic or optical emission spectrum.

There are three types of the electromagnetic spectra depending on the way of their interaction with a matter:

– absorption spectra;
– reflectance spectra;
– emission spectra.

The absorption spectrum shows which part of electromagnetic radiation is absorbed by the substance. Depending on physical characteristics of substance, radiations with some wavelengths are absorbed better than others. The absorption spectrum of the substance is complementary to the reflectance spectrum which shows which part of radiation reflected by the substance. Hence if substance absorbs red, yellow, orange and green light then under white light color of this object will contain blue as illustrated in Fig. 7.

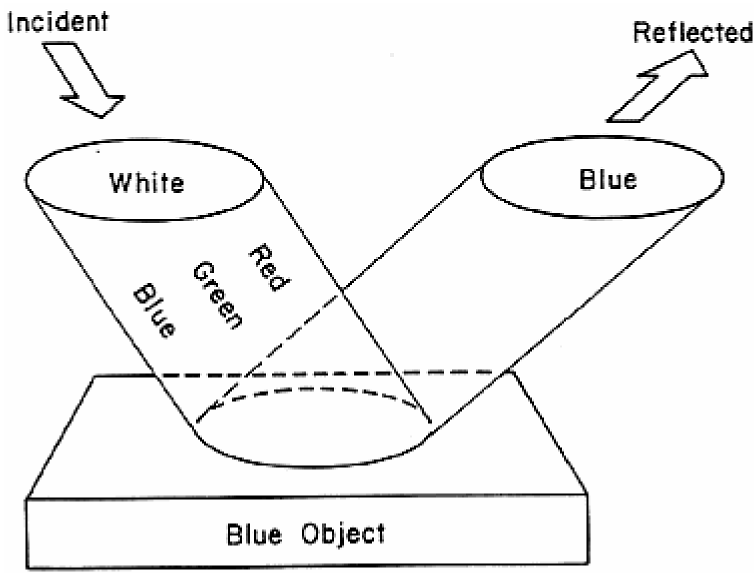


Figure 7: White light composed of all wavelengths of visible light incident on a pure blue object. Only blue light is reflected from the surface (Image taken from [12]).

The emission spectrum demonstrates radiation with which wavelengths will emits when substance will be in excited state. Analysis of absorption and reflectance spectra allows determination of some physical structure features of substance such as density of the substance and its concentration; the emission spectrum is unique for each chemical element and can be used to determine chemical structure of the substance [25]. If we have data about reflectance and absorption spectra of the substance of an object and emission spectrum of light source we can determine what will be color of an object.

2.6. Data representation as spectral images

There are different methods to save color information but representation color data as spectral image give us most accurate and comprehensive information. Spectral images are files which contain complete information about spectrum or some spectral information of the substance. Spectral data can be represented as graph of the spectral curve as illustrated in Fig. 8 which is visual representation of color. This curve is based on two coordinates: wavelength and intensity reflecting light. Spectral data of light sources that used for experiments presents on Chapter 4, Fig. 19—23.

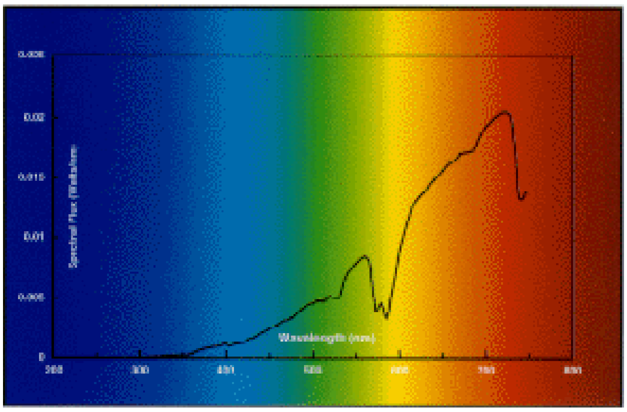


Figure 8: Chromalux Spectral Distribution
Curve (Image taken from [13]).

Spectral data describe characteristics of surface of the object and contain information about the way this surface interacts with light. Quantity of light which will be reflected, absorbed or emitted does not depend on light source or characteristics of color percept system; hence this representation can be used for exact determination of color of an object. For spectral measurements we use different types of spectrometers such as spectral camera, spectroscopes and others. For spectral data storing can be used following format of files: .mat: (binary data container format used by MATLAB; may include arrays, variables, functions, and other types of data), .raw (24-bit RGB graphic containing uncompressed, raw image data), .aix, .spb.

2.7. Color Spaces

Spectral data representation keeps fullest information about colors, but storing of this data requires a lot of memory and time to access grows accordingly to occupied space. There are other methods of storing color data when using color space model. Some color space models use special characteristics for color coding such as hue, saturation and lightness. Hue represents meaning which determine place of the color in spectrum, saturation represents depth of hue from grey to the color and lightness characterizes luminosity of color from 0 % (black) to 100 % (white). Representation of the color using three coordinates represent value of hue, saturation and lightness illustrated in Fig. 9.

Near “equator” of the sphere lies pure bright colors, but as the length of the color vector decreases colors became less saturated and transform to grey in centre. When traveling along vertical axis from top to bottom colors change from light to dark.

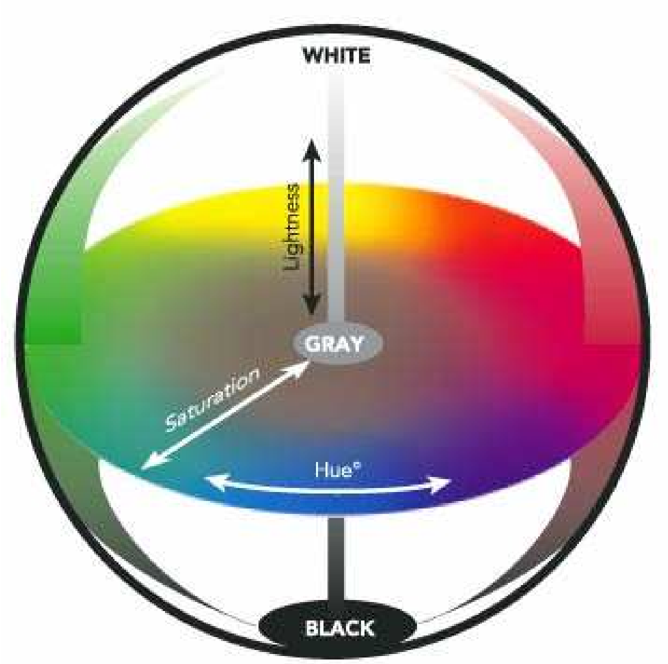


Figure 9: Example of the spherical representation of a color space (Image taken from [14]).

J. C. Munsell first represent color used 3D space and now exist various color space based on Munsell system. Gamut is the range of all colors accepted by the observer or reproduced by the device. There two base class of colors: additive colors (red, green and blue) and subtractive colors (cyan, magenta, yellow + black):

– Additive colors: on blending three base colors (red green and blue) in different proportions we can receive almost all colors percept by human eye. Absence of colors gives us black color and maximum quantity gives white color. Composition of two additive colors gives us one of base subtractive colors (Fig. 10a). Monitors use an additive color system.

– Subtractive colors: these colors are opposite to additive colors. Blending of two subtractive colors give us additive color. Absence of colors gives us white color and maximum quantity gives dark grey color (Fig. 10b). Black color was added to three base subtractive colors because pure black color can not be received using only base colors. Color printers use a subtractive color system for the color output.

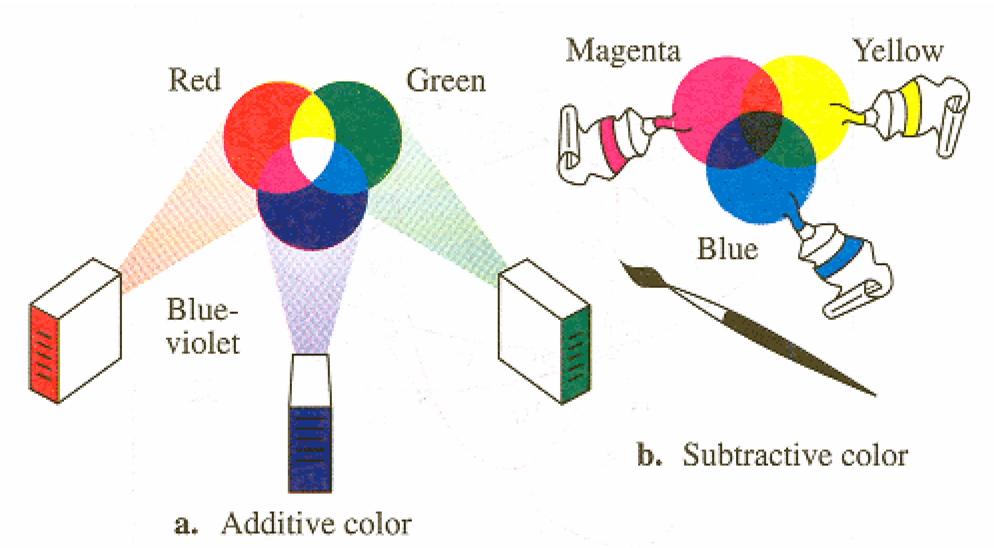


Figure 10: Additive color mixing and subtractive color mixing (Image taken from [15]).

Commission International de L'Eclairage approved some independent of devices color system describing human visual gamut. CIE XYZ (tristimulus) and RGB spaces use for representation measurements data of my practical research.

2.7.1. CIE XYZ color space

The CIE tristimulus values (XYZ) are calculated from CIE Standard Observer functions (for 2º and 10º observing field) considering illumination and reflectance spectrum of the object's surface (Fig. 11). This model use 3 base function ($\rho X(\lambda)$, $\rho Y(\lambda)$, $\rho Z(\lambda)$) depending on the wavelength, linear combinations these functions with non-negative attributes allow to represent all visible colors [16]. This color space based on direct measurements of the human eye capabilities and depends on reflectance curve which is unique for each object. So CIE XYZ space can be used as the basis from many other color spaces.

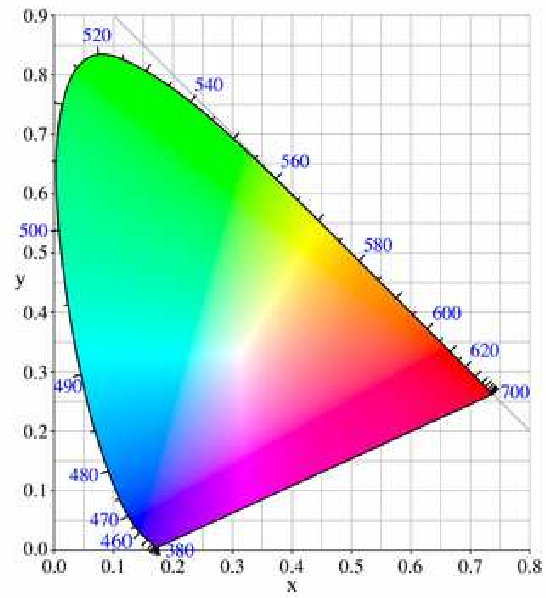


Figure 11: The CIE 1931 color space chromaticity diagram. The outer curved boundary is the spectral (or monochromatic) locus, with wavelengths shown in nanometers (Image taken from [4]).

2.7.2. RGB color space

RGB color space is an additive color space. A color can be represented by three coordinates of RGB dimension: chromaticity of red, green and blue primaries (Fig. 12). Each component is coded by 8 bits usually, so we have 16 777 216 vectors for color representation. Full specification of RGB color space also requires a white point chromaticity and a gamma correction curve. Disadvantages of RGB model are a small color gamut and dependence on the type of monitor. Not all colors that human can see may be represented by this model.

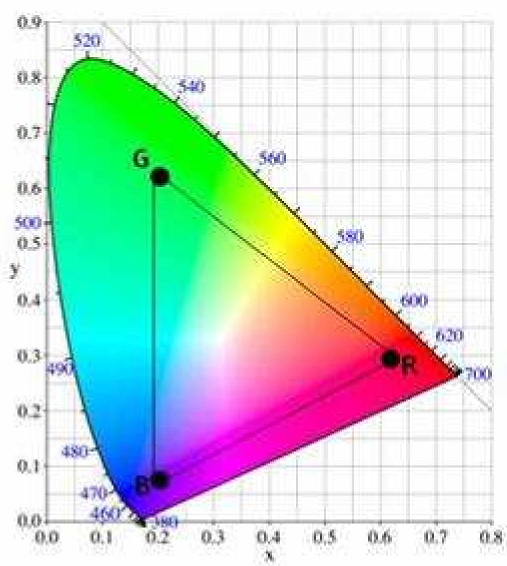


Figure 12: The triangle is a representation of the RGB color space on CIE XYZ chromaticity diagram (Image taken from [17]).

RGB space has many modifications such as sRGB, Adobe RGB 98, CIE (1931), ISO RGB, NTSC (1979) and others.

2.8. Color Appearance Model

Existence of large quantity of various color spaces that describe color in own color coordinates makes a jumble with color specifications. CIE Technical Committee 1-34 recommends some unified color models which should consider different aspects of colors variance and can be used for colors transform. Such models are called color appearance models and are determined according to CIE TC 1-34 in a following way: “a color appearance model is any model that includes predictors of at least the relative color appearance attributes of lightness, chroma, and hue. For a model to include reasonable predictors of these attributes, it must include at least some form of a chromatic adaptation transform. Models must be more complex to include predictors of brightness and colorfulness or to model other luminance-dependent effects such as the Stevens effect or the Hunt effect.” [8, p.184]

The color appearance models are based on CIE XYZ tristimulus values which obtained directly from measuring of the stimulus. Models transform these XYZ tristimulus values to cone responses in order defined by specifications of the model to create values closer to human vision system responses. CIELAB, Nayatani et al., the Hunt, RLAB, ATD models also can function as the color appearance model but with some constraints. Now most usable and widespread color appearance models are CIECAM97s and the newest version CIECAM02. At the heart of a color appearance model lies chromatic adaptation transform (CAT).

The chromatic adaptation, as dark and light adaptation, is one of the mechanisms of human color vision. Human eye can adapt to changes in lightness or colors and compensate these changes. Chromatic adaptation transform allows to predict corresponding colors. A pair of corresponding colors is the color observed under one illuminant and another color that has same appearance under second illuminant. This adaptation is not full color appearance model because it is not considering influence of attributes such as lightness, hue, chroma or specifications of human vision. Different models of the chromatic adaptation exist, such as von Kries model, Nayatani et al. model, Guth's model, Fairchild's model and others, but in this thesis described and implemented two CAT models: linear CMCCAT2000 for CIECAM97s model and modified CMCCAT2000 (CAT02) for CIECAM02 model.

In 1997 M. R. Luo and R. W. G. Hunt modified the Bradform transform (BFD transform derived by K. M. Lam and B. Rigg[18]), this transform called CMCCAT97[19] and it was included in CIECAM97s. The CIECAM97s model was built on researches of many scientists in the color theory and represents most effective methods from their works. The model was formalized and published by the CIE in 1998 [20].

Input data to the CIECAM97s model:

- luminance of the adapting field;
- luminance of the source background in the reference conditions;
- tristimulus values of the sample in the reference conditions;
- tristimulus values of white point the reference conditions.

Additionally were used chromatic induction factor N_c, the constant c for the impact of surround, F_{LL} a lightness contrast factor, F factor for degree of adaptation. These factors were chosen accordingly to environment conditions.

First stage of CIECAM97s model is normalization of the tristimulus values of the sample and white point in the reference conditions. Then obtained values used for acquirement of spectral sharpened cone responses R, G, B that is used for CMCCAT97 adaptation. Post-adaptation signals for the sample and reference white point then transformed to the Hunt-Pointer-Estevez cone responses. Also red-green and yellow-blue opponent dimensions are calculated.

CMCCAT97 has two modes: forward mode for transform tristimulus values of the sample under a nondaylight illuminant to corresponding colors under daylight illuminant and reverse mode for obtaining corresponding colors from daylight to nondaylight illuminant. These modes should be reversible but there are some difficulties with reverse mode (with calculating parameter *p* that answers for the blue corresponding spectral response) and obtained values of two modes do not coincide. So in 2000 C. Li, M. R. Luo, B. Rigg and R. W. G. Hunt [21] developed simplified version of CMCCAT97 which has been adopted by the CMC as CMCCAT2000. This chromatic adaptation transform was implemented in developed software as CAT for CIECAM97s model.

The CIECAM02 color appearance model is based on CIECAM97s model but has some improvements and simplifications [28]. Chromatic adaptation transform used for the CIECAM02 model is the modified CMCCAT2000 transform (CAT02). CAT02 transform has similar performance to non-linear Bradford transform of CIECAM97s [23]. Also CIECAM02 includes a different from CIECAM97s hyperbolic post adaptation response compression function and changes to perceptual attribute correlates that allowed to achieve greater accuracy for a range of different data sets, considering specifications of the human vision system and invertibility. [22]

Input data to the CIECAM02 model:

- tristimulus values of the test stimulus;
- tristimulus values of the white point in reference and adapting conditions;
- adapting luminance;
- relative luminance of surround.

Changes in chromatic adaptation transform allow to use simpler model [24] for transform CIE tristimulus values of the sample and white point to corresponding RGB responses. Then D factor, answers for degree of adaptation, is calculated. With this factor tristimulus responses for the stimulus color are transformed to adapted tristimulus responses, this chromatic adaptation was implemented as CAT for CIECAM02 model in developed software. After CAT transform viewing-condition-dependent components are computed, post-adaptation non-linear response compression is similar to that one used in CIECAM97s but simplified and improved [22].

3. IMPLEMENTATION

In chapter 3 we will investigate algorithm of chromatic adaptation and applicability of CMCCAT2000 and CAT02 for the task of predicting variability of colors. The task was to develop software that simulates variance of illuminations and allows obtaining corresponding colors under adapting illuminant.

3.1. Chromatic adaptation algorithm

For solution of formulated task the algorithm of chromatic adaptation transform that is used in modern CIECAM models was chosen. As initial data given:

- original image (.spb or .tiff (.tif) files);
- specified light source (adapting illuminant);
- luminance of the reference and adapting illuminants.

Tristimulus values of each pixel of reference image obtained from image file and the tristimulus values of white point taken from illuminant specifications. The general flow chart for the CIECAM models that were used is shown in Fig. 13. Stages marked in Fig. 13 as CAT (chromatic adaptation transform) were performed for the simulation process. After transform gamma correction was performed to enhance quality of image built.

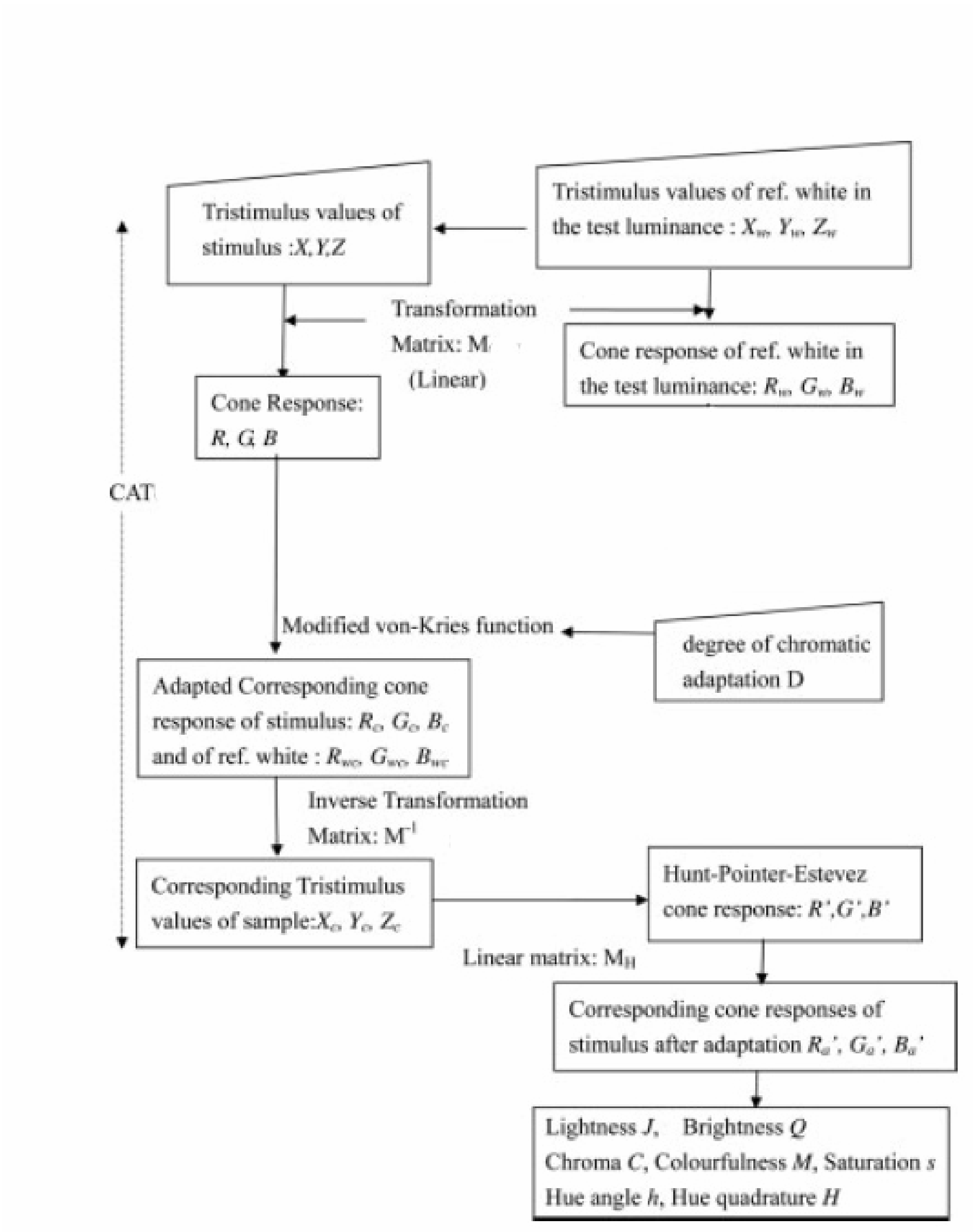


Figure 13: Flow chart of color appearance model (image adopted from [24]).

3.1.1 CMCCAT2000

CMCCAT2000 was implemented at first, this model is simplified and improved the CMCCAT97 and has following specifications unlike to previous model [26]:

- parameter *p* in CMCCAT97 is set equal 1 for solving reversibility problem;
- new transform matrix *M* is used;
- introduced new *D* function for predicting degree of incomplete chromatic adaptation.

Input data:

- tristimulus values under reference illuminant: *X*, *Y*, *Z* (obtained for each pixel of processed image);
- tristimulus values of the white point under reference illuminant: X_w, Y_w, Z_w;
- tristimulus values of the white point under adapting illuminant: X_{wr}, Y_{wr}, Z_{wr};
- luminance of reference and adapting illuminant (cd/m²): L_{A1}, L_{A2}.

Output data:

- corresponding tristimulus values under adapting illuminant: X_c, Y_c, Z_c.

Computation procedure for the chromatic adaptation (CMCCAT2000)

Step 1: Calculate inner RGB values of each pixel of the reference image.

$$\begin{pmatrix} R_{wr} \\ G_{wr} \\ B_{wr} \end{pmatrix} = M \begin{pmatrix} X_{wr} \\ Y_{wr} \\ Z_{wr} \end{pmatrix} \quad (4)$$

$$\begin{pmatrix} R_w \\ G_w \\ B_w \end{pmatrix} = M \begin{pmatrix} X_w \\ Y_w \\ Z_w \end{pmatrix} \quad (5)$$

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = M \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad (6)$$

where

$$M = \begin{pmatrix} 0.7982 & 0.3389 & -0.1371 \\ -0.5918 & 1.5512 & 0.0406 \\ 0.0008 & 0.0239 & 0.9753 \end{pmatrix} \quad (7)$$

Original matrix M that used in CIECAM97s model before modifications presented in Eq. 8 below (specified by Fairchild [8, p.261]).

$$M = \begin{bmatrix} 0.8951 & 0.2664 & -0.1614 \\ -0.7502 & 1.7135 & 0.0367 \\ 0.0389 & -0.0685 & 1.0296 \end{bmatrix} \quad (8)$$

Step 2: Calculate the degree of adaptation.

$$D = F\{0.08\,\log_{10}[0.5(L_{A1} + L_{A2})] + 0.76 - 0.45(L_{A1} - L_{A2})/(L_{A1} + L_{A2})\} \quad (9)$$

where parameter *F* is response for viewing conditions (F=1 for average surround, F=0.8 for dim- and dark-surround). If *D* greater than 1 or less than 0, set to 1 or 0, respectively [21].

Step 3: Calculate adapted RGB values [27].

$$R_c = R[\alpha(R_{wr}/R_w) + 1 - D] \quad (10)$$

$$G_c = G[\alpha(G_{wr}/G_w) + 1 - D] \quad (11)$$

$$B_c = B[\alpha(B_{wr}/B_w) + 1 - D] \quad (12)$$

where

$$\alpha = DY_w/Y_{wr} \quad (13)$$

Step 4: Calculate corresponding tristimulus values.

$$\begin{pmatrix} X_c \\ Y_c \\ Z_c \end{pmatrix} = M^{-1} \begin{pmatrix} R_c \\ G_c \\ B_c \end{pmatrix} \tag{14}$$

where

$$M^{-1} = \begin{pmatrix} 1.076450 & -0.237662 & 0.161212 \\ 0.410964 & 0.554342 & 0.034694 \\ -0.010954 & -0.013389 & 1.024343 \end{pmatrix} \tag{15}$$

After the chromatic adaptation transform we obtained corresponding colors under adapting illuminant and built adapted image on them.

3.1.2 CAT02

Second modes of developed software based on newest version of chromatic adaptation transform. CAT02 is a modified CMCCAT2000 transform that was described in [22]. CAT02 gave more precise results for a range of data sets and has a change in linear chromatic adaptation transform that allowed obtaining values closer to cone response of human visual system.

Input data:

- tristimulus values under reference illuminant: X, Y, Z (obtained for each pixel of processed image);
- tristimulus values of the white point under reference illuminant: X_w, Y_w, Z_w;
- tristimulus values of the white point under adapting illuminant: X_{wr}, Y_{wr}, Z_{wr};
- luminance of the adapting illuminant (cd/m²): L_A;
- parameters of adaptation depending on surround condition (Table 2 below is used to set the values):
  - c is exponential nonlinearity;
  - N_c is chromatic induction factor;
  - F is maximum degree of adaptation.

Output data:

– corresponding RGB responses under adapting illuminant: R´, G´, B´.

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

Table 2: Input parameters for CAT02 (Table taken from [8, p.267]).

Computation procedure for the chromatic adaptation (CAT02)

Step 1: Calculate inner RGB values of each pixel of the reference image.

$$\begin{pmatrix} R_{wr} \\ G_{wr} \\ B_{wr} \end{pmatrix} = M \begin{pmatrix} X_{wr} \\ Y_{wr} \\ Z_{wr} \end{pmatrix} \quad (16)$$

$$\begin{pmatrix} R_{w} \\ G_{w} \\ B_{w} \end{pmatrix} = M \begin{pmatrix} X_{w} \\ Y_{w} \\ Z_{w} \end{pmatrix} \quad (17)$$

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = M \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad (18)$$

$$\mathbf{M}_{CAT02} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix} \quad (19)$$

Step 2: Calculate the degree of adaptation.

$$D = F\left[1 - \left(\frac{1}{3.6}\right)e^{\left(\frac{-L_A - 42}{92}\right)}\right] \quad (20)$$

Step 3: Calculate adapted RGB values [24].

$$R_c = [D(Y_w/R_w) + 1 - D]R \tag{21}$$

$$G_c = [D(Y_w/G_w) + 1 - D]G \tag{22}$$

$$B_c = [D(Y_w/B_w) + 1 - D]B \tag{23}$$

Step 4: Transform adapted RGB values to Hunt-Pointer-Estevez fundamentals.

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \mathbf{M}_H \mathbf{M}_{CAT02}^{-1} \begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix} \tag{24}$$

where

$$\mathbf{M}_{CAT02}^{-1} = \begin{bmatrix} 1.096124 & -0.278869 & 0.182745 \\ 0.454369 & 0.473533 & 0.072098 \\ -0.009628 & -0.005698 & 1.015326 \end{bmatrix} \tag{25}$$

$$M_H = \begin{bmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00000 & 0.00000 & 1.00000 \end{bmatrix} \tag{26}$$

After the chromatic adaptation transform we obtained corresponding colors under adapting illuminant and built adapted image on them.

3.2. Interface and manipulation of the developed software

The software is implemented using IDE MATLAB R2007a by the MathWorks, Inc., because to this IDE convenience and simplicity of programming for such tasks. The primary task of developed software is simulation change of illumination for images and obtaining corresponding colors under different illuminants.

In Fig. 14 presents main interface window of the software. Description of the interface elements is given in Table 3 below.

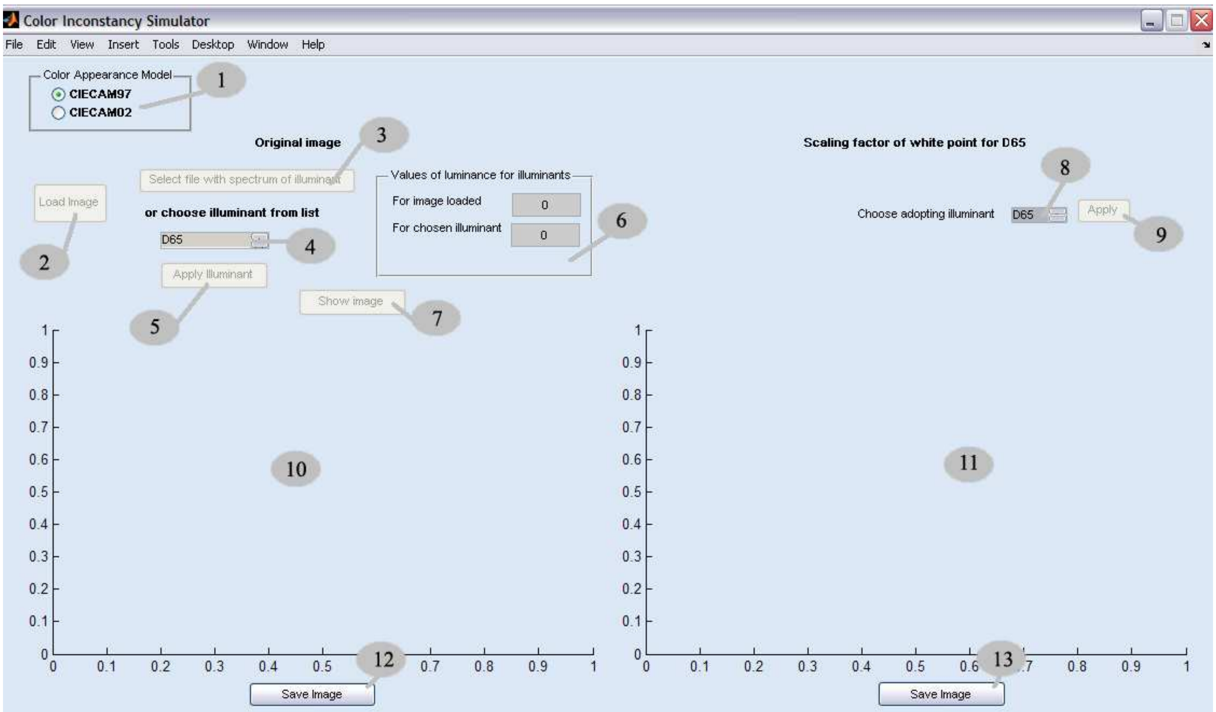


Figure 14: Main window of the software. Uninitialized state.

Number of the element	Description
1	Radiobuttons that performed selection between two modes: CIECAM97s and CIECAM02
2	Button that loads image file (.spb or .tiff)
3	Button that loads file with spectrum of illuminant
4	Listbox with list of standard illuminants
5	Button that confirms selected adapting illuminant

6	Edit field for input values of the luminance for reference image and selected illuminant
7	Button that runs transform
8	Listbox with list of illuminant for obtaining compensated image
9	Button that confirms selected compensating illuminant
10	Axis on which adapted image appears
11	Axis on which compensated image appears
12	Button that allows saving adapted image (as .tiff file)
13	Button that allows saving compensated image (as .tiff file)

Table 3: Description of interface elements.

In general steps for algorithm are as follows:

1: Using radiobuttons #1 we can select required model for color transformation: CIECAM97s or CIECAM02.

2: Using button #2 we load reference image. File with .tiff or .spb extensions are allowed to load as a reference image.

3: Choose method for receiving values of white point for illuminant. We can load file with spectrum of the illuminant (use button #3 for it) or select one of standard illuminants represent in listbox #4. After selection or loading illuminant we should confirm our choice using button #5.

4: After we input values of luminance for illuminant under which reference image was taken and for the adapting illuminant. If value of luminance is equal to 0 or not inputted then it is equal to 100 cd/m² for the computations.

5: When all specifications were chosen we should press button #7 that runs process of the adaptation.

6: After acquiring adapted image we can obtain compensated image (Compensated image is an image that will look under compensating illuminant like image on left axis #10). We can chose compensating illuminant using listbox #8 and confirm our choice using button #9.

7: Using buttons #12 and #13 we can save acquired images as a .tiff file.

On the Fig. 15 represents example of running software.

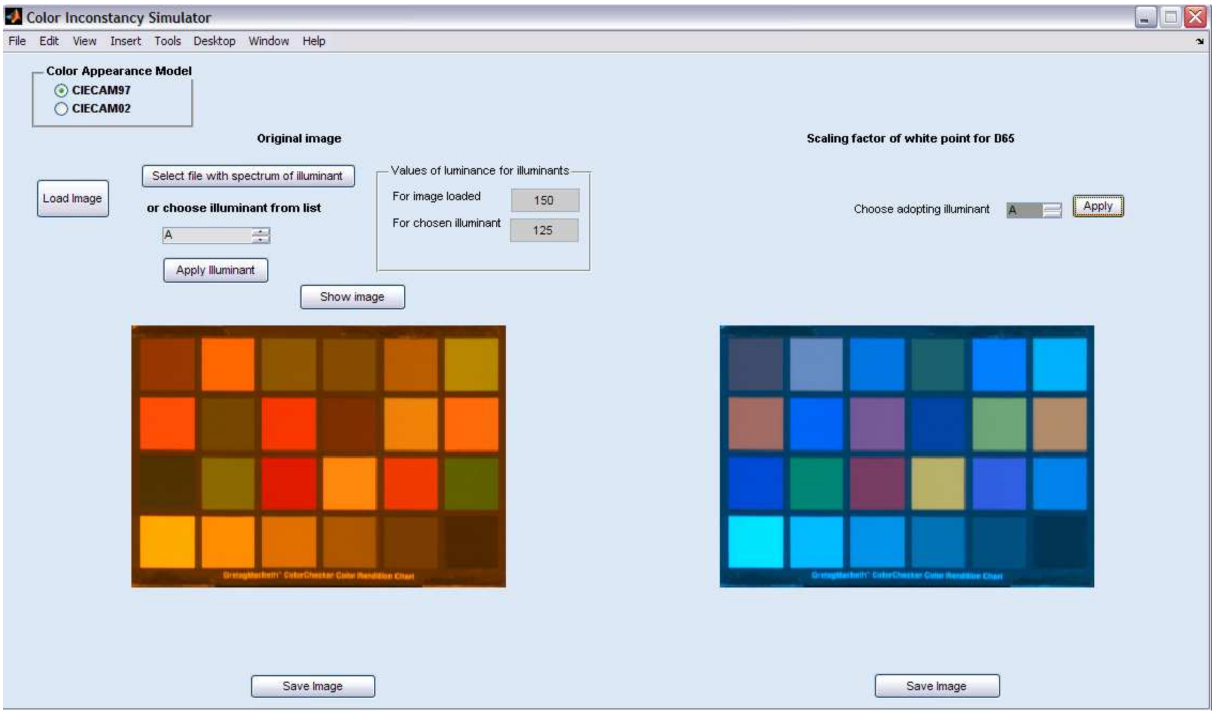


Figure 15: Developed software running in CIECAM97s mode.

For the simulation process can be used follows standard illuminants: D65, D50, A, B, C, F2, F7, F11 and illuminants of the Assessment Cabinet: D75AC, D65AC, D50AC, 840AC, FAC (white points of these illuminants presented in Appendix III, Table 17). Developed software performs simulation of illumination change successfully. Ability to save and load an image files and apply different chromatic adaptation to predicting corresponding color allow to flexibly tune software for various requirements.

4. TEST AND PROCESSING OF THE RESULTS

In chapter 4 we will describe process of the measurements and laboratory equipment that were used. Acquired results will be presented as graphs and images built on values obtained from colorimetric devices.

4.1. Measurements

4.1.1. Laboratory Devices

This section describes laboratory devices that were used for measurements. Practical research has been done in the LIGIV laboratory, Saint-Etienne, France and supervised by Professor Alain Tremeau.

Laboratory equipment:

- ELDIM MURATest Camera;
- MINOLTA Spectroradiometer CS-1000;
- VeriVide DCAC Assessment Cabinet (D75, D65, D50, 840, F illuminants).

ELDIM MURATest Camera:

MURATest Camera (see Figure 16 below) is the device for measuring and analysis of colors from emitting or reflecting target that can be objects, images, display modules, display walls and clusters [29].

Specifications:

- Measurement modes: luminance/CR, color.
- Sensor configuration: peltier cooled CCD (adjustable -5ºC/-20ºC), photopic response, 16-bit A/D converter.
- Luminance units: Selectable cd/m² (nit), fl, normalized or binary format.
- Luminance range: Full scale range 0.05 to 5000 cd/m² (without ND filter), enhanceable to 500 000 cd/m². Maximum sensivity: 0.0001 cd/m².
- Luminance: Measurement time approx. 3s. Accuracy ±0.002 CIE (x, y) on A type illuminant, 0.005 RMS CIE (x, y) on any color stimulus. Short term repeatability ±0.002 on one pixel, ±0.0002 on 100 pixels.

– Dynamic range: 23 000 for single shot, 44 000 for high dynamic measurement mode, 10º for contrast analysis.
– CCD resolution: 1536×1024 (±8º & ±16º), 3072×2048 (±9º), 4872×3248 (±16º).

Figure 16: ELDIM MURATest Camera
(Image taken from [29]).

MINOLTA Spectroradiometer CS-1000:

Spectroradiometer CS-1000 (see Figure 17 below) can measure spectral power distribution, luminance, color and correlated color temperature of display devices including CRTs, flat panel displays, LEDs and light sources, while offering excellent absolute accuracy and short-term repeatability. The CS-1000 can be used as a master instrument in the R&D centers of display devices manufacturers, as well as lighting and lamp companies, to measure the spectral radiance of a light source [30].

Figure 17: MINOLTA Spectroradiometer CS-1000 (Image taken from [30]).

Specifications:

- Spectral range : 380 up to 780 nm +/- 0.3 nm
- Minimal surface : 0.25 mm with macro lens
- Luminance range : 0.01 up to 80 000 cd/m²
- Accuracy : ± 2%   ±1 digit   x : ± 0.0015   y = 0.001
- Polarisation error : less than 5% (400 nm to 700 nm)
- Certified ISO9001 and ISO 14001

VeriVide DCAC Assessment Cabinet:

Assessment Cabinet as you can see in Figure 18 below is the device simulating lightning conditions of 5 illuminants: D75, D65, D50, 840, F. Illuminant is a mathematical representation of real light source (for example north sky daylight) and it represents by spectral distribution of light energy (intensity). The DCAC range has been developed for the visual assessment of color in accordance with British Standards 950:1 directives and International Standards [31].

Specifications:

- Light Sources: 5.
- Viewing Cavity: width 1530 mm, height 545 mm, depth 590 mm.

Figure 18: VeriVide DCAC Assessment Cabinet
(Image taken from [31]).

4.1.2 Process of measurements

Practical research was held in two parts:

- measurements of color inconstancy of the sample in different lightning conditions;
- simulation of change of illuminations using developed software.

The GretagMacbeth ColorChecker Color Rendition Chart with 24 colors (Appendix I, Fig. 54) had been used as sample. Sample of "reference white" have been used for obtaining spectra of illuminants of the Assessment Cabinet.

Process of the measurements consists of following parts:

- First step: Obtained spectrum of all illuminants using MINOLTA Spectroradiometer CS-1000.
- Second step: Put the samples to the Assessment Cabinet. Measured GretagMacbeth ColorChecker with MURATest Camera under all illuminants of cabin. Calculated average XY values for each color.
- Third step: Output image of the samples to monitor. Measured samples on monitor with MURATest camera under all illuminants of the cabin.
- Fourth step: Convert image of the samples using developed software and output to monitor. Measured colors of image of GretagMacbeth ColorChecker obtained after CIECAM conversion under illuminants of the cabin.

After gaining results I compared colors of image obtained from developed software and image reproduced on monitor under corresponding illuminant. Calculated difference between these images allows correction of the transition matrix for the used chromatic adaptation transform.

4.2. Calculated results

4.2.1 Illuminants of the Assessment Cabinet and samples description

For all five illuminants of the VeriVide DCAC Assessment Cabinet were obtained spectral distribution of the light energy for each wavelength from 380 nm to 780 nm. The Assessment Cabinet has 5 types of fluorescent lamps which simulating following illuminants [14]:

– Illuminant D75: Simulates north sky daylight (Fig. 19). Color temperature: 7500 K.
– Illuminant D65: Simulates average north sky daylight (Fig. 20). Color temperature: 6500 K.
– Illuminant D50: Simulates noon sky daylight (Fig. 21). Color temperature: 5000 K.
– Illuminant 840 (TL84): Mathematical representation of commercial, rare earth phosphor, narrow band fluorescent used in Europe and the Pacific Rim (Fig.22). Color temperature: 4100 K. Simulates typical office or store lightning.
– Illuminant F (F12): Simulates sunset light (Fig. 23). Color temperature: 3000 K. Simulates typical store lighting for Sears (USA equivalent of TL83).

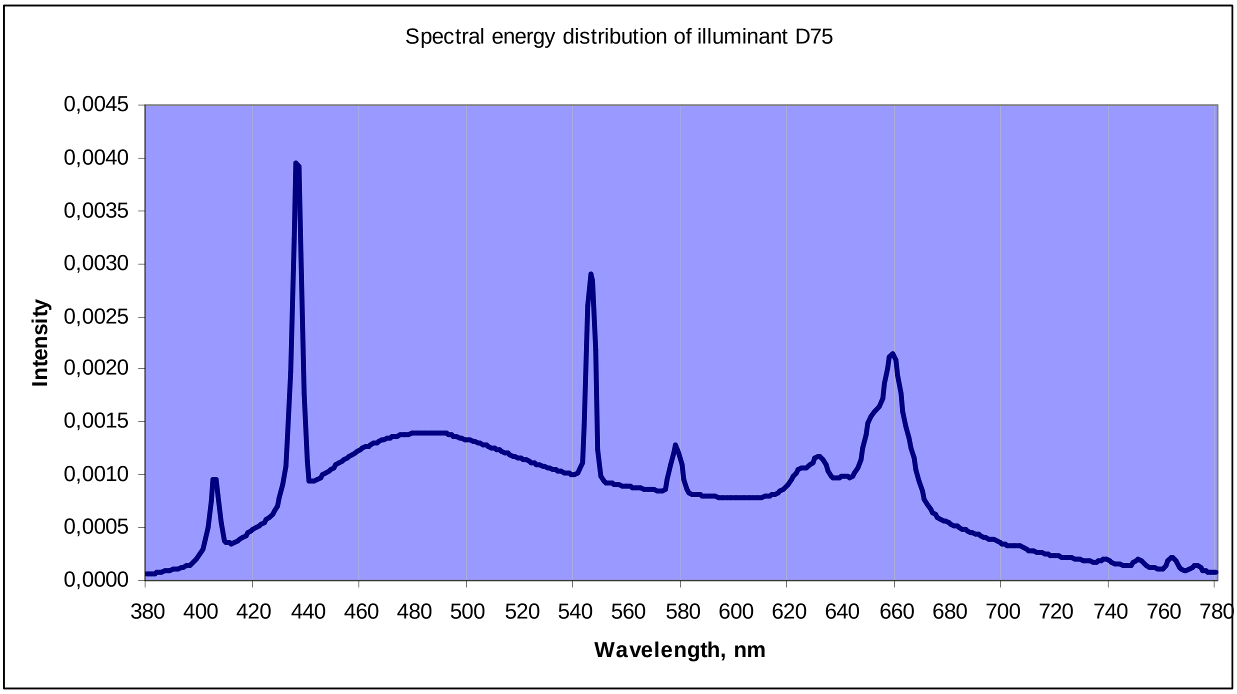


Figure 19: Spectral energy distribution of illuminant D75 of the Assessment Cabinet that simulates north sky daylight.

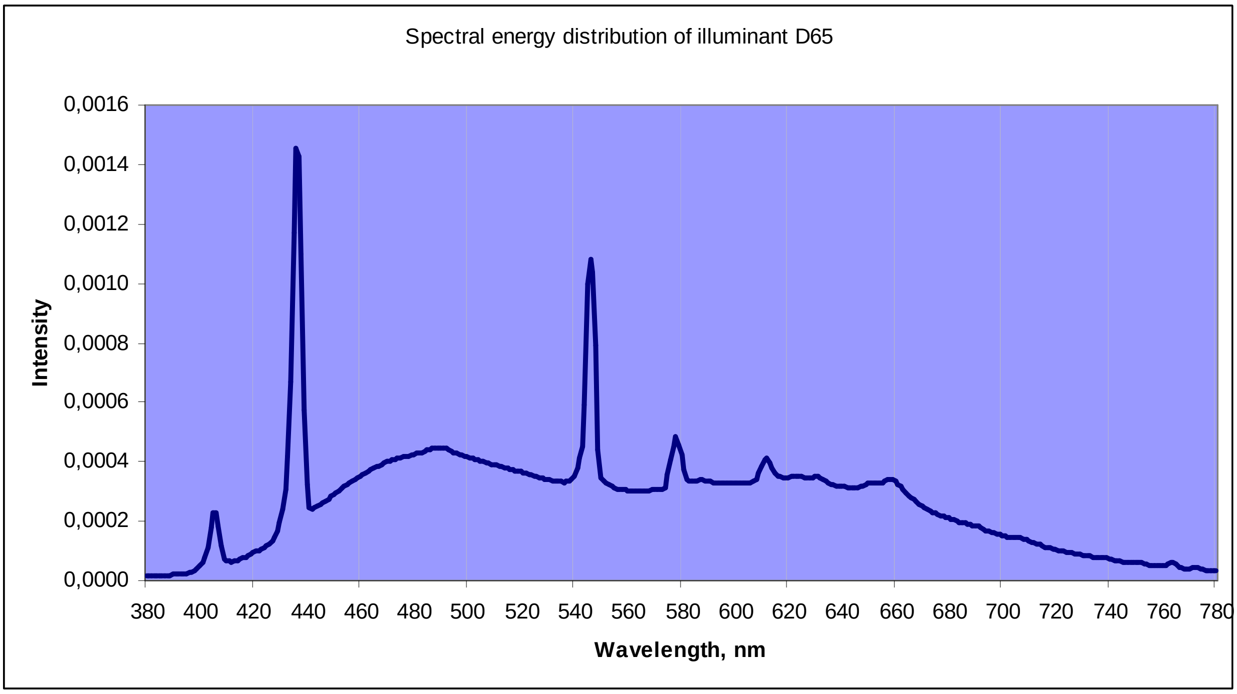


Figure 20: Spectral energy distribution of illuminant D65 of the Assessment Cabinet that simulates average north sky daylight.

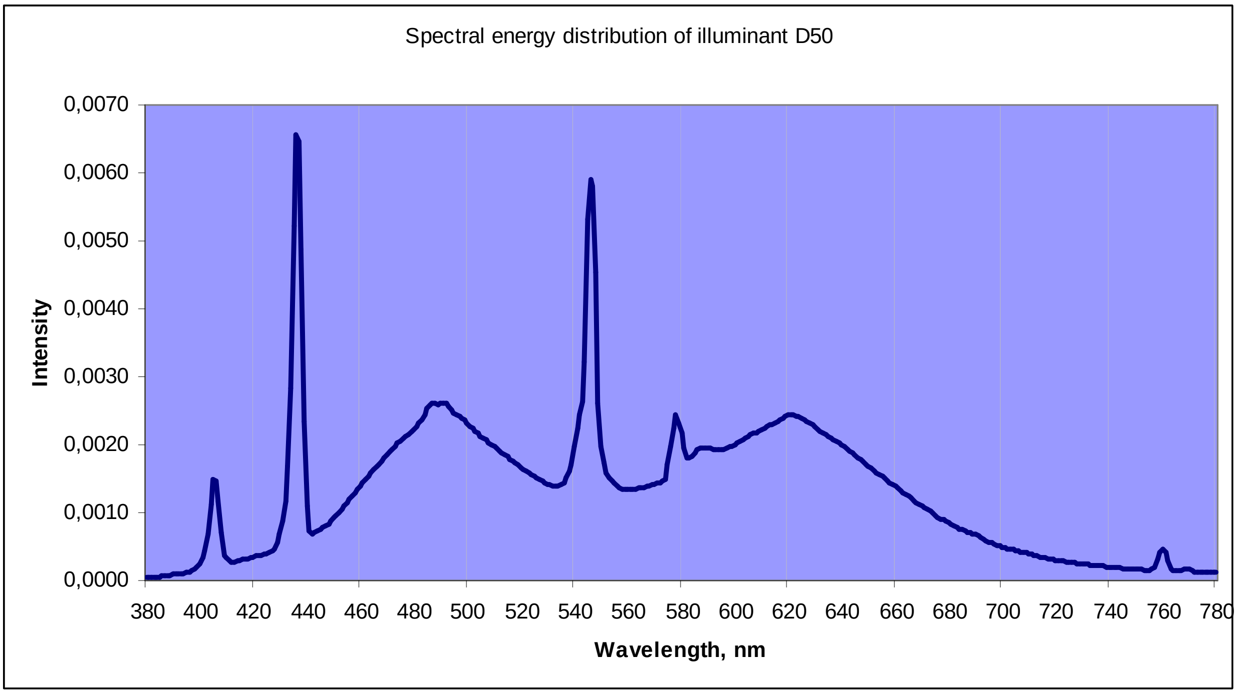


Figure 21: Spectral energy distribution of illuminant D50 of the Assessment Cabinet that simulates noon sky daylight.

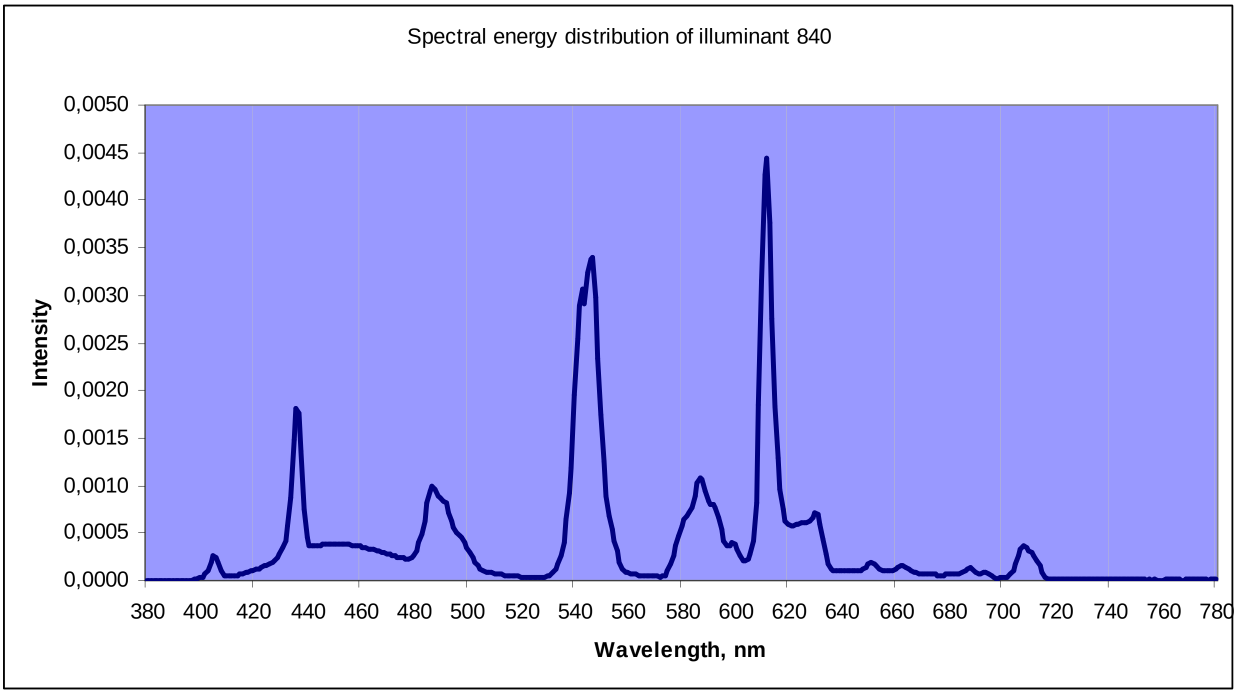


Figure 22: Spectral energy distribution of illuminant 840 of the Assessment Cabinet that simulates typical office or store lightning.

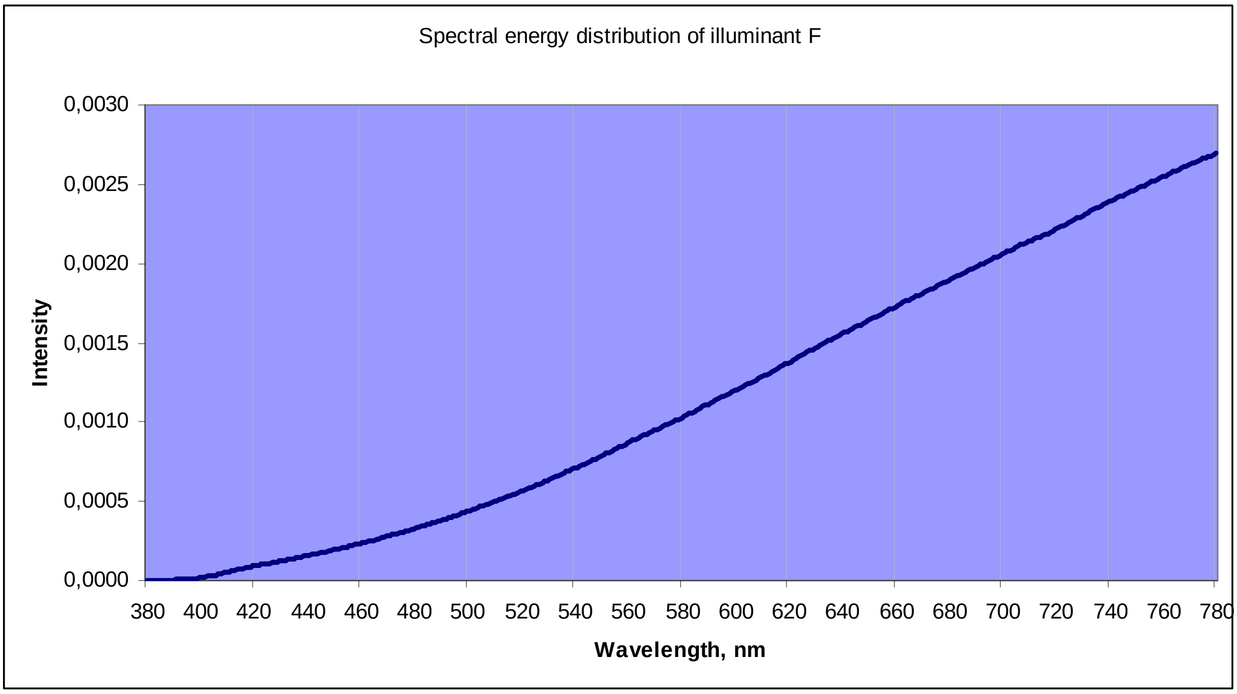
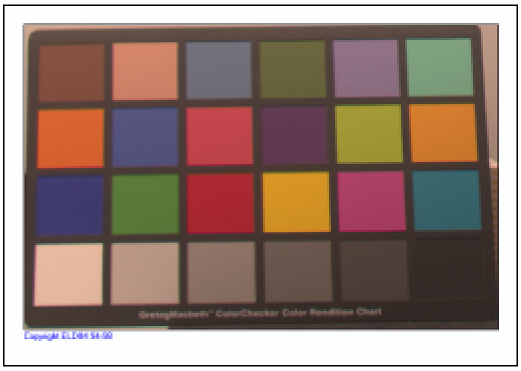


Figure 23: Spectral energy distribution of illuminant F of the Assessment Cabinet that simulates light of sunset.

After acquiring those spectra I obtained average CIE tristimulus values X and Y and magnitude of luminance for each of 24 colors of GretagMacbeth ColorChecker under illuminants of the Assessment Cabinet. Data of colors are represented in Appendix I, Table 5 and on Fig. 24–33 below. All data represented on images were obtained using ELDIM Software for the MURATest Camera.



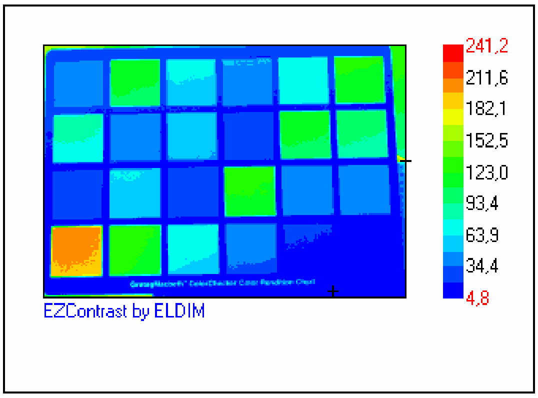


Figure 24 **Figure 25**

Representation of color (Fig. 24) and luminance (Fig. 25) information for illuminant D75 of the Assessment Cabinet.

GretagMacbeth ColorChecker was put into Assessment Cabinet under D75 illuminant and tristimulus values for each color was taken. As we can see in Fig. 24 sample under D75 looks like under light of early morning—all colors are bright and the white color (most luminous) has luminance approximately 240 cd/m². This illuminant is most luminous between the other ones available in the Assessment Cabinet.

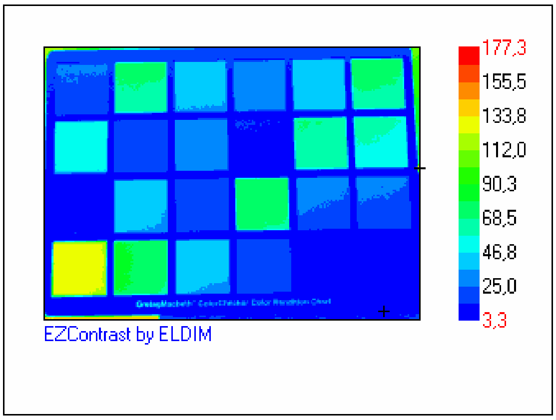


Figure 26 **Figure 27**

Representation of color (Fig. 26) and luminance (Fig. 27) information for illuminant D65 of the Assessment Cabinet.

Sample under D65 illuminant looks less bright and colors are less saturated then previous sample. Luminance of the white color is approximately equal to 140 cd/m².

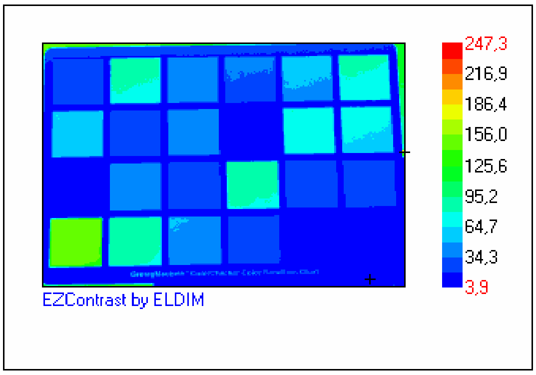


Figure 28 **Figure 29**

Representation of color (Fig. 28) and luminance (Fig. 29) information for illuminant D50 of the Assessment Cabinet.

Light of the D50 illuminant looks more “yellow” than previous ones and colors of the sample are less saturated. Luminance of the white color is 100 cd/m².

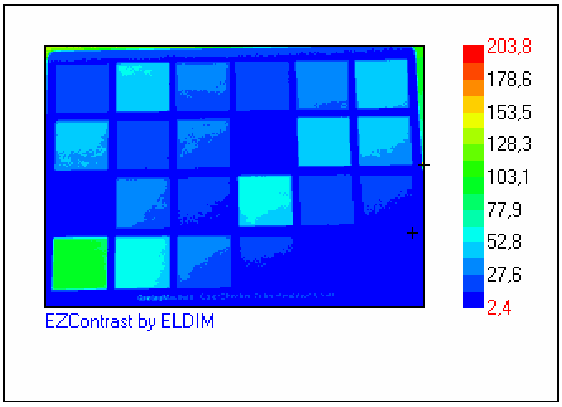


Figure 30 **Figure 31**

Representation of color (Fig. 30) and luminance (Fig. 31) information for illuminant 840 of the Assessment Cabinet.

Under 840 illuminant sample looks like illuminated by the lamp. Colors are less saturated and look warmer then under daylight-simulating illuminants. White color has luminance approximately equal to 90 cd/m².

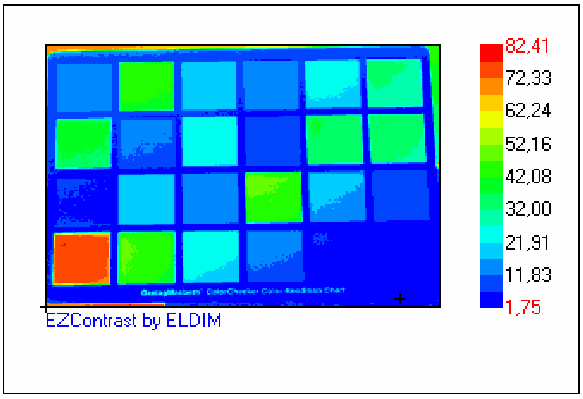


Figure 32 **Figure 33**

Representation of color (Fig. 32) and luminance (Fig. 33) information for illuminant F of the Assessment Cabinet.

Illuminant F is most "warm" illuminant (spectral energy distribution of this illuminant monotonically increase from short waves to long waves), so all colors look more "orange". White color has smallest luminance approximately equal to 80 cd/m^2.

As we can see on Figure 24—33 above image of the GretagMacbeth ColorChecker under all illuminants of the Assessment Cabinet and CIE tristimulus values for each color were obtained.

On next stage of the experiment I reproduced obtained images on a LCD monitor placed in the Assessment Cabinet and measured colors of images under all available illuminants of the cabinet. Graphical representation of the acquired data presented below in Table 4. Hence I have reference images for correction of color adaptation in developed software.

	D75	D65	D50	840	F
D75					
D65					
D50					
840					
F					

Table 4: Images of the GretagMacbeth ColorChecker reproduced on LCD monitor placed in DCAC under illuminants.

Developed software works with images in .tiff (Tagged Image File Format) and .spb (Spectral Binary Data) formats. I took spectral image of the GretagMacbeth ColorChecker sample under D65 illuminant and used this image like reference for color adaptation. Reference tristimulus values of each color GretagMacbeth ColorChecker sample represent in Appendix II, Table 6. Simulating change of illumination was done using Chromatic Adaptation Transform for two Color Appearance Models: CIECAM97s and CIECAM02.

4.2.2. Results of usage CIECAM97s

Chromatic adaptation transform using for CIECAM97s is a modified von Kries transformation (performed on a type chromaticity coordinates) with exponential nonlinearity added to the short-wavelength-sensitive channel. [8, 256] Input data to this model are:

- luminance of the reference illuminant (illuminant under which taken reference image);
- luminance of the adaptive illuminant;
- tristimulus values XYZ of the reference image (taken from image file);
- reference white point (taken from illuminant's characteristics).

Variable F is taken equal to 1.0 for average viewing condition. Variable D specifies degree of adaptation (from 0 – without adaptation to 1 – full adaptation). As transition matrix for transformation was used matrix M specified in Eq. 27.

$$M = \begin{pmatrix} 0.7982 & 0.3389 & -0.1371 \\ -0.5918 & 1.5512 & 0.0406 \\ 0.0008 & 0.0239 & 0.9753 \end{pmatrix} \qquad (27)$$

Obtained results represented on Figure 34–38 below. These images were reconstructed from values taken by MURATest Camera from LCD monitor thus white color looks like rose-colored. Tristimulus values of each color of the sample presented in Appendix II, Tables 7—11.

Figure 34 b

Figure 34 c

Figure 34 a

Sample under D75 illuminant of the Assessment Cabinet reproduced on the screen (a), after CIECAM97s transform under D65 illuminant (b) and under D75 illuminant (c).

Figure 35 a

Figure 35 b

Sample under D65 illuminant of the Assessment Cabinet reproduced on the screen (a), after CIECAM97s transform under D65 illuminant (b).

Figure 36 a

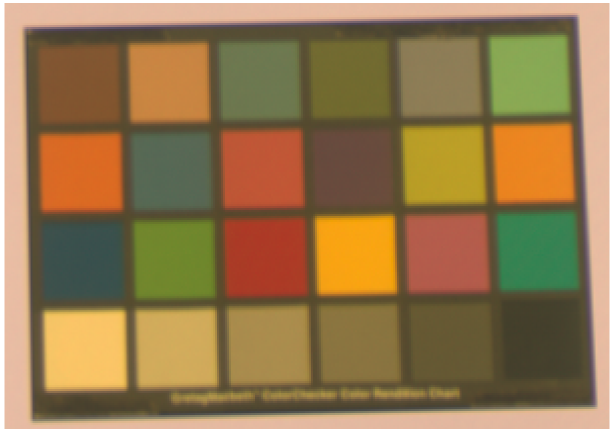


Figure 36 b

Figure 36 b

Sample under D50 illuminant of the Assessment Cabinet reproduced on the screen (a), after CIECAM97s transform under D65 illuminant (b) and under D50 illuminant (c).

Figure 37 a

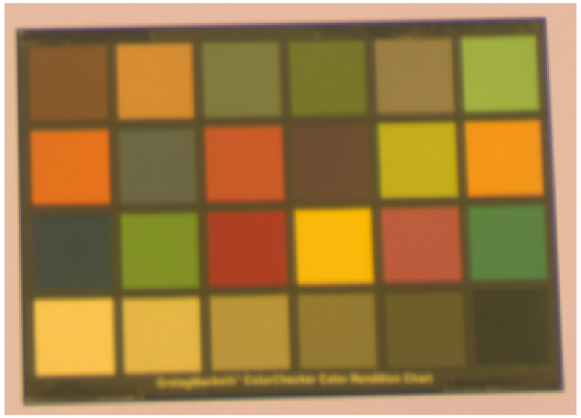


Figure 37 b

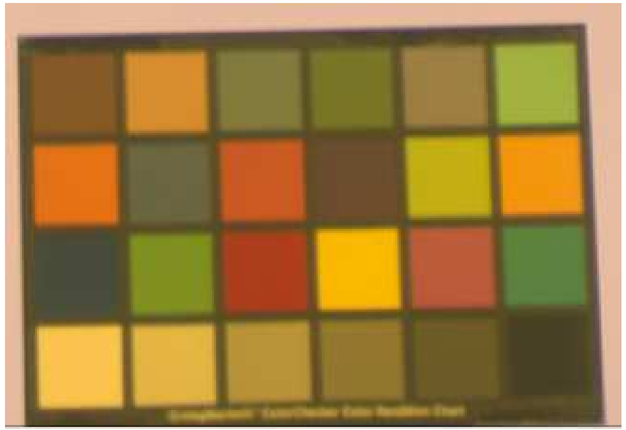


Figure 37 c

Sample under 840 illuminant of the Assessment Cabinet reproduced on the screen (a), after CIECAM97s transform under D65 illuminant (b) and under 840 illuminant (c).

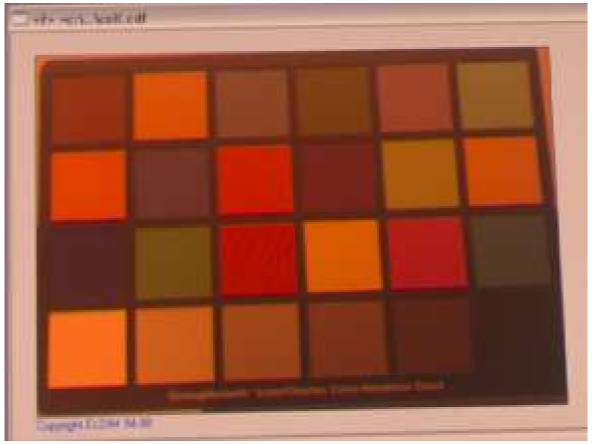


Figure 38 a

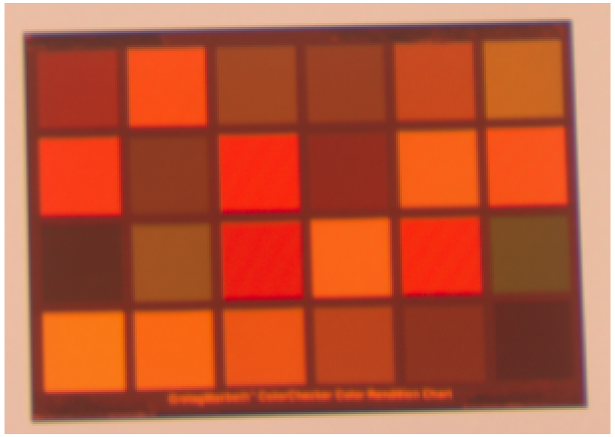


Figure 38 b

Figure 38 c

Sample under F illuminant of the Assessment Cabinet reproduced on the screen (a), after CIECAM97s transform under D65 illuminant (b) and under F illuminant (c).

As we can see from images above there is some difference between reference image and images obtained after chromatic adaptation. Reference and obtained tristimulus values of each color of the sample under different illuminants are presented on Fig. 39—43 below

.

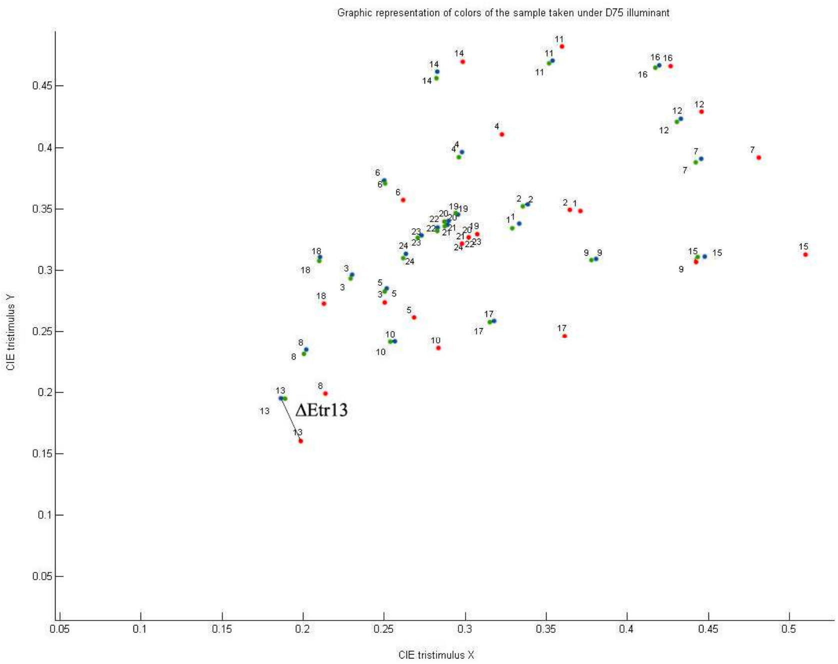


Figure 39: Graphical representation of tristimulus values for reference sample under D75 illuminant (marked as red points) and sample after CIECAM transformation under D75 (marked as green points) and D65 illuminants (marked as blue points). Difference between values for each point is magnitude of the error ΔE_{tr} .

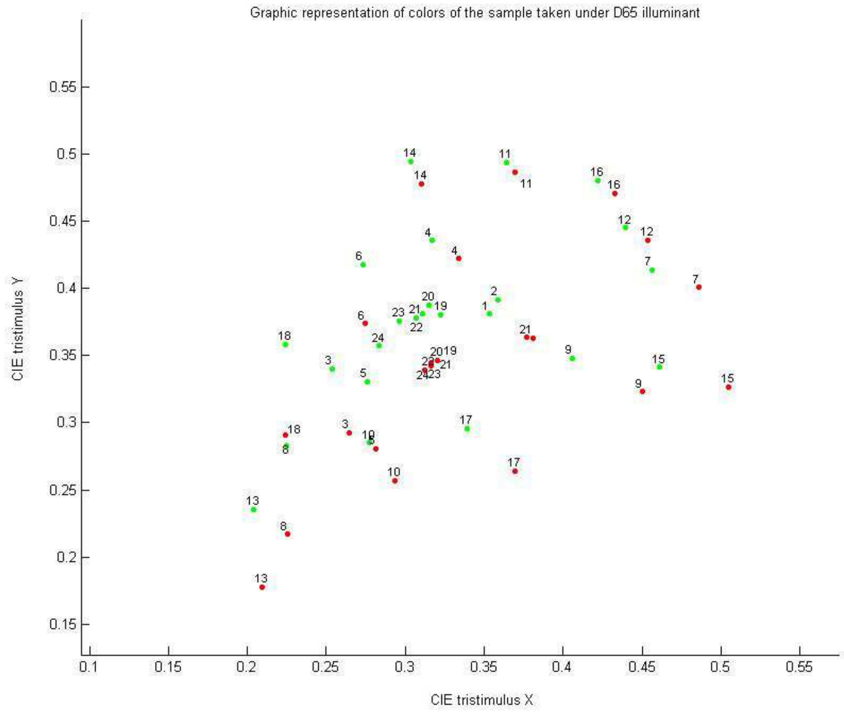


Figure 40: Graphical representation of tristimulus values for reference sample under D65 illuminant (marked as red points) and sample after CIECAM transformation under D65 illuminants (marked as green points).

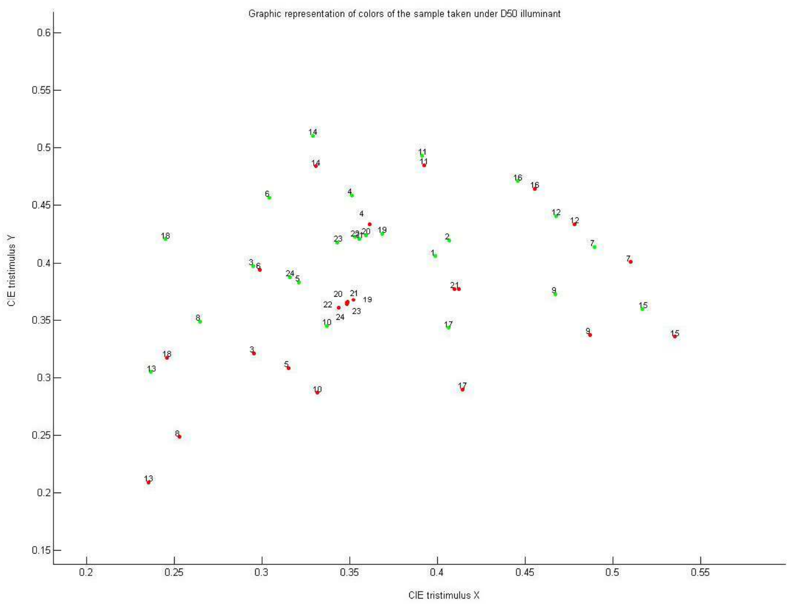


Figure 41: Graphical representation of tristimulus values for reference sample under D50 illuminant (marked as red points) and sample after CIECAM transformation under D50 (marked as green points) and D65 illuminants (marked as blue points).

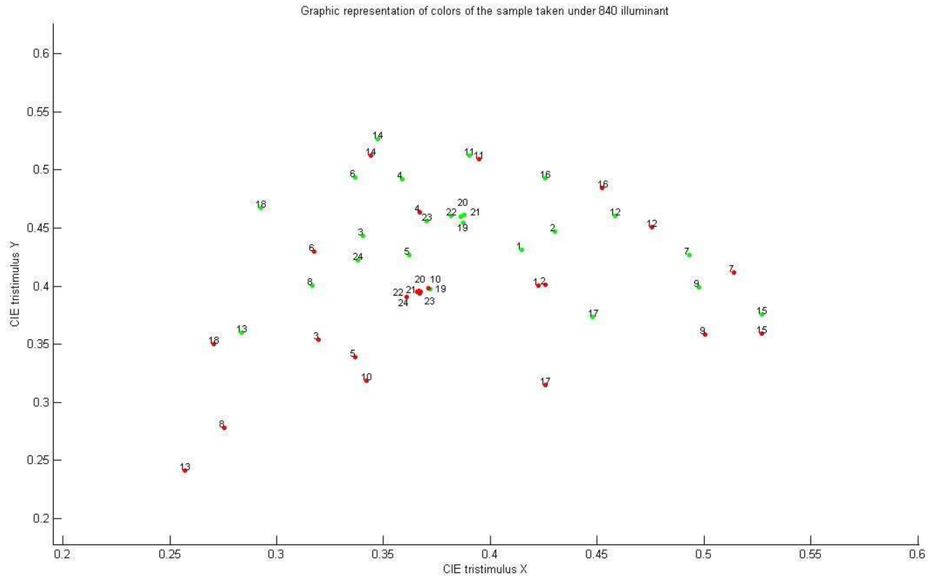


Figure 42: Graphical representation of tristimulus values for reference sample under 840 illuminant (marked as red points) and sample after CIECAM transformation under 840 (marked as green points) and D65 illuminants (marked as blue points).

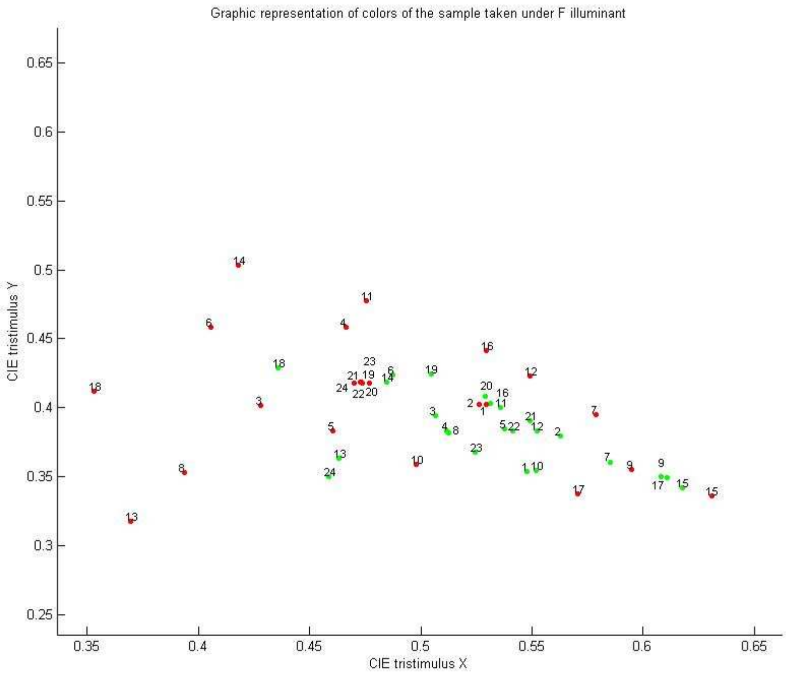


Figure 43: Graphical representation of tristimulus values for reference sample under F illuminant (marked as red points) and sample after CIECAM transformation under F (marked as green points) and D65 illuminants (marked as blue points).

Calculated ΔE_{tr} for each color of the sample allows adjusting matrix M used for transformation. After all calculation I have corrected matrix M for CIECAM97s:

$$M = \begin{bmatrix} 3.24071 & -0969258 & 0.0556352 \\ -1.53726 & 1.87599 & -0.203996 \\ -0.498571 & 0.0415557 & 1.05707 \end{bmatrix} \quad (28)$$

4.2.3. Results of usage CIECAM02

CIECAM02 color appearance model is the improvement of the CIECAM97s color appearance model and based on linear von-Kries type chromatic adaptation transform. Principal difference between these two models lies in conversion from CIE tristimulus values to corresponding RGB values. For CIECAM02 is used optimized transform matrix M (Eq. 29) and factor D–degree of adaptation—is computed according to Eq. 30.

$$M = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix} \quad (29)$$

$$D = F * \left(1 - (1/3.6) * \varepsilon^{(-(L_a+42)/92)}\right), \quad (30)$$

where L_a—luminance of the adapting illuminant, F—value of viewing conditions (F=1 for average surround, F=0.9 for dim surround and F=0.8 for dark surround).

Input data for CIECAM02:

– luminance of the surround (dark, average, dim):
– luminance of the adaptive illuminant;

– tristimulus values XYZ of the reference image (taken from image file);
– reference white point (taken from illuminant's characteristics).

After chromatic adaptation were obtained tristimulus values for each of the colors of the sample under different illuminants as illustrated in Appendix II, Tables 12—16 and graphical representation (Fig. 44—48 below). As we can see on images after CIECAM02 transform we obtained colors more "bluish-green" than they should be. Yellow looks like green color and red seems like blue. For the precise difference evaluation between reference and image after transform were used tristimulus values of each color; graphical representation of the results are illustrated on Figure 49—53. Colors obtained after CIECAM02 transform have a significant difference with reference values; it shows that algorithm works incorrectly for the sample in conditions of the experiment. After all corrections for CIECAM02 mode and considering necessity of post-adaptation nonlinear compression has been used matrix M according to Eq. 31 and obtained RGB responses were converted from MCAT02 representation to Hunt-Pointer-Estevez values (Eq. 32) that are more closely represent cone responsivities of human vision system.

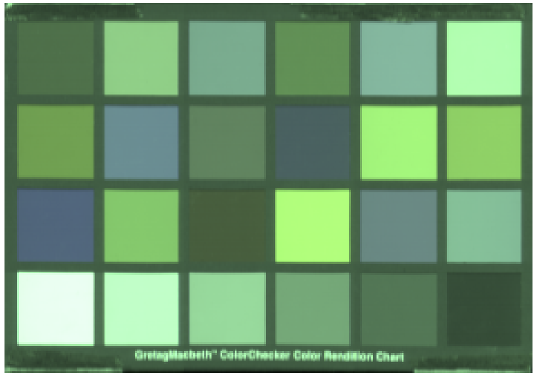
$$M_{CAT02}^{-1} = \begin{bmatrix} 1.096124 & -0.278869 & 0.182745 \\ 0.454369 & 0.473533 & 0.072098 \\ -0.009628 & -0.005698 & 1.015326 \end{bmatrix} \qquad (31)$$

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = M_{HPE} M_{CAT02}^{-1} \begin{bmatrix} R_C \\ G_C \\ B_C \end{bmatrix}, \qquad (32)$$

where R_C, G_C, B_C present inner CAT02 RGB system and M_{HPE} is determined as:

$$M_{HPE} = \begin{bmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00000 & 0.00000 & 1.00000 \end{bmatrix}. \quad (33)$$

.



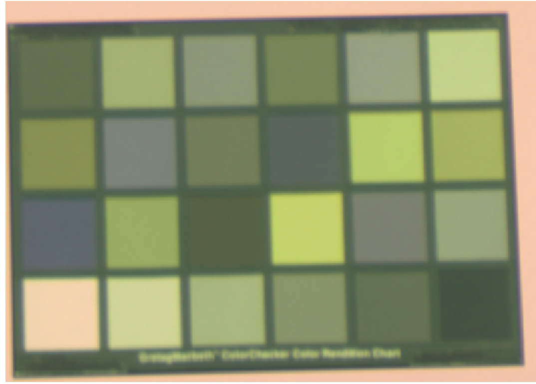
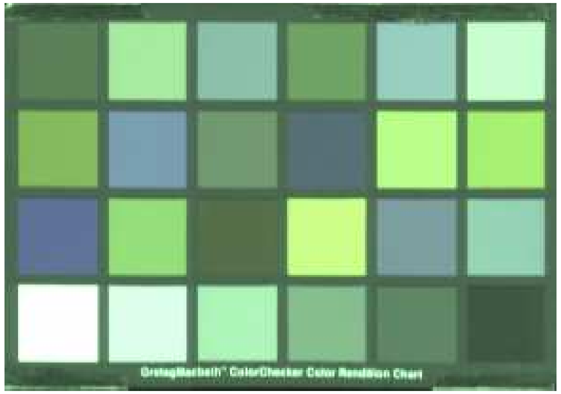


Figure 44 a **Figure 44 b** **Figure 44 c**

Sample under D75 illuminant of the Assessment Cabinet reproduced on the screen (a), after CIECAM02 transform under D65 illuminant with color correction (b) and without correction (c).



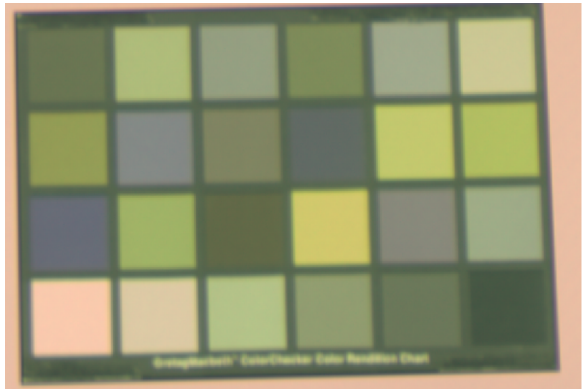
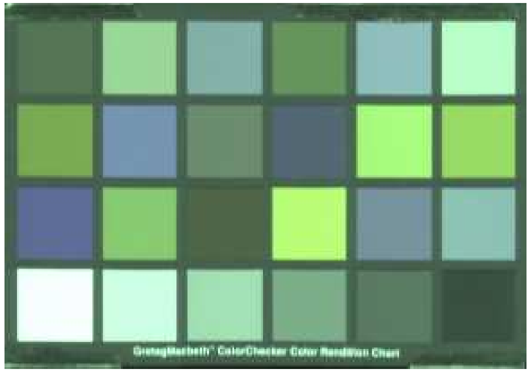


Figure 45 a **Figure 45 b** **Figure 45 c**

Sample under D65 illuminant of the Assessment Cabinet reproduced on the screen (a), after CIECAM02 transform under D65 illuminant with color correction (b) and without correction (c).



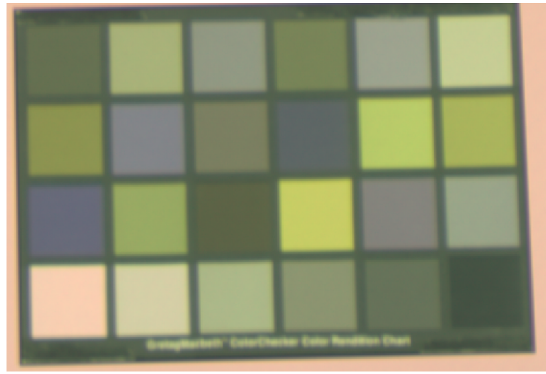
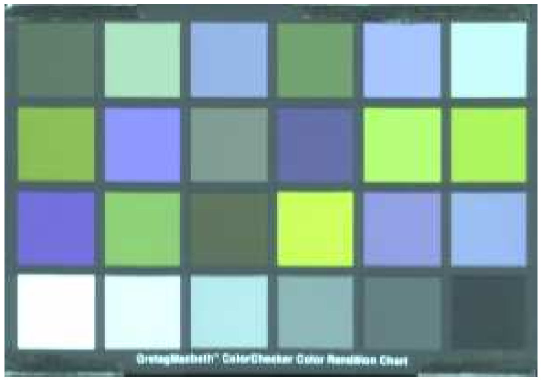


Figure 46 a

Figure 46 b

Figure 46 c

Sample under D50 illuminant of the Assessment Cabinet reproduced on the screen (a), after CIECAM02 transform under D65 illuminant with color correction (b) and without correction (c).



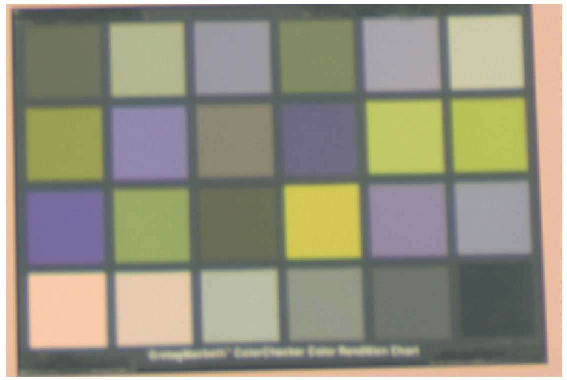


Figure 47 a

Figure 47 b

Figure 47 c

Sample under 840 illuminant of the Assessment Cabinet reproduced on the screen (a), after CIECAM02 transform under D65 illuminant with color correction (b) and without correction (c).

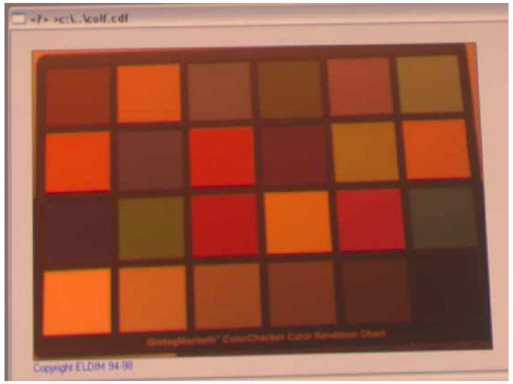


Figure 48 a

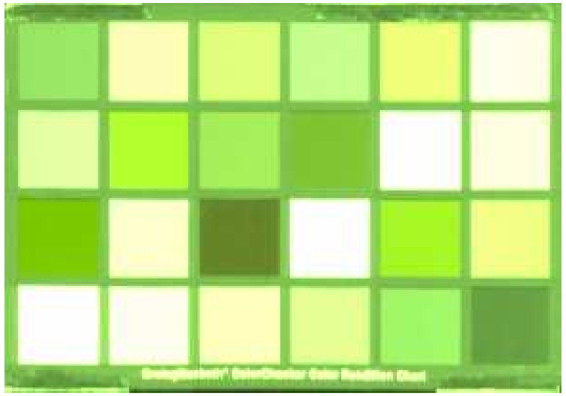


Figure 48 b

Figure 48 c

Sample under F illuminant of the Assessment Cabinet reproduced on the screen (a), after CIECAM02 transform under D65 illuminant with color correction (b) and without correction (c).

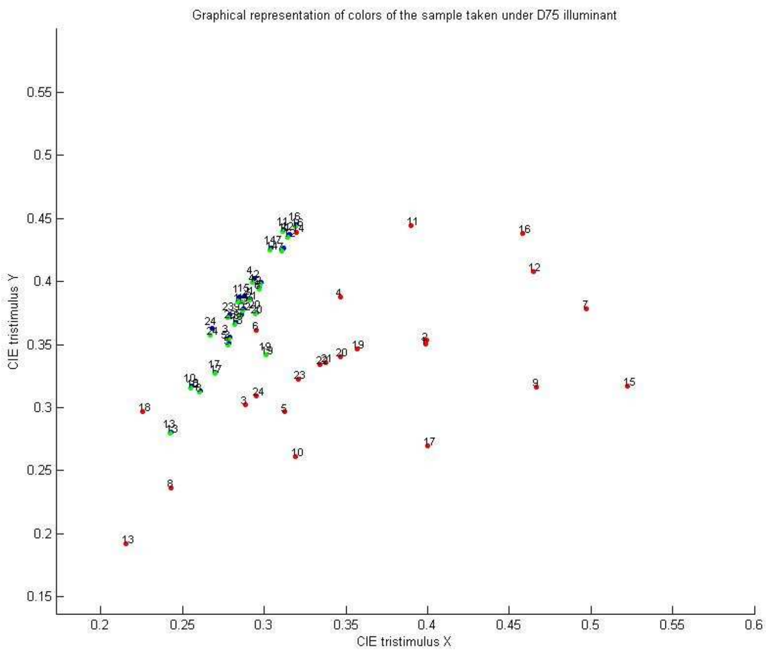


Figure 49: Graphical representation of tristimulus values for reference sample under D75 illuminant (marked as red points) and sample after CIECAM transformation under D75 (marked as green points) and D65 illuminants (marked as blue points).

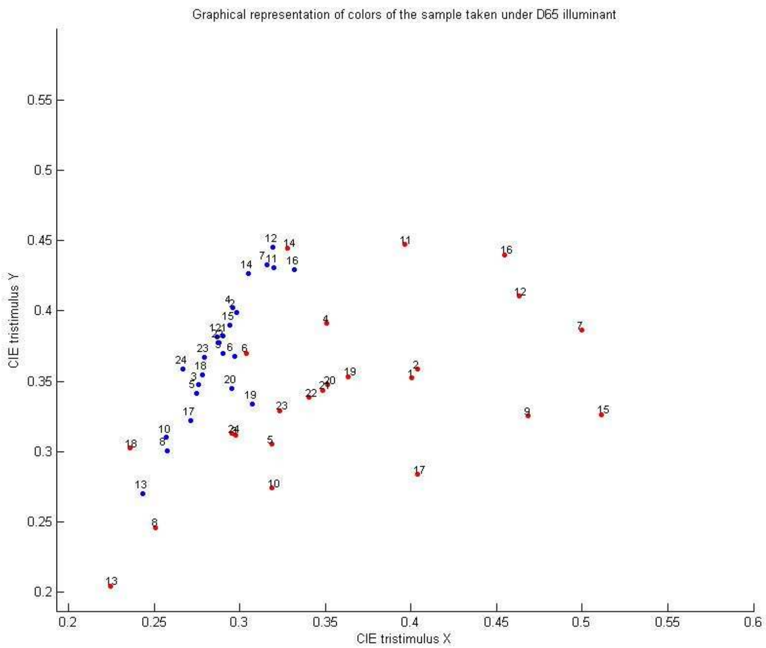


Figure 50: Graphical representation of tristimulus values for reference sample under D65 illuminant (marked as red points) and sample after CIECAM transformation under D65 illuminants (marked as blue points).

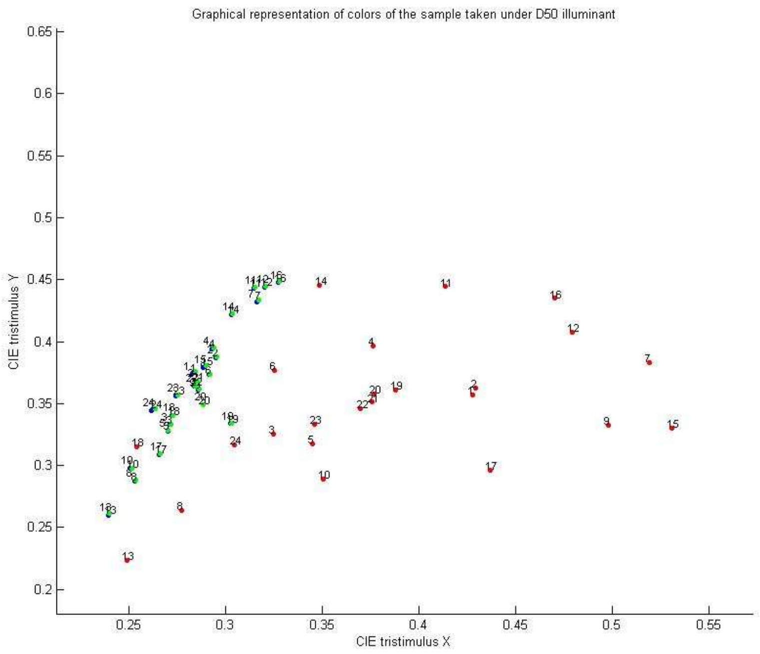


Figure 51: Graphical representation of tristimulus values for reference sample under D50 illuminant (marked as red points) and sample after CIECAM transformation under D50 (marked as green points) and D65 illuminants (marked as blue points).

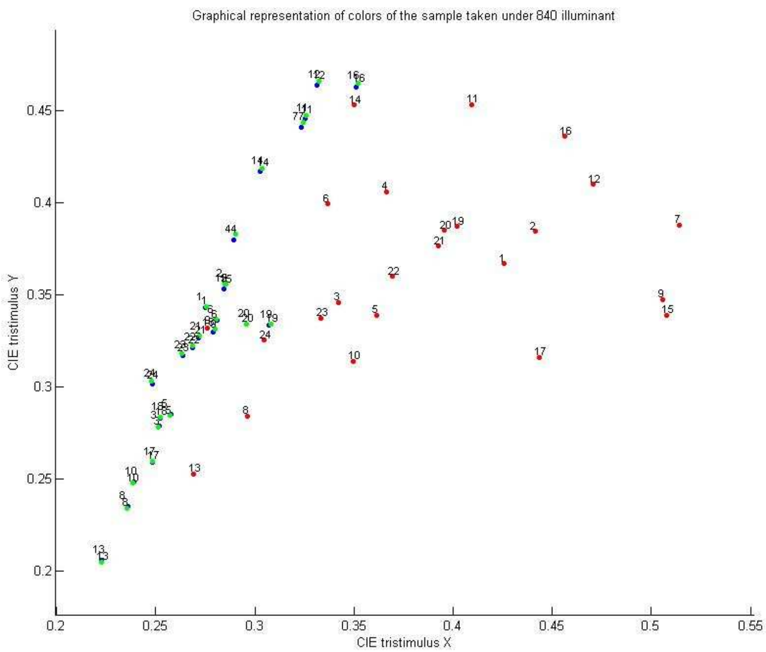


Figure 52: Graphical representation of tristimulus values for reference sample under 840 illuminant (marked as red points) and sample after CIECAM transformation under 840 (marked as green points) and D65 illuminants (marked as blue points).

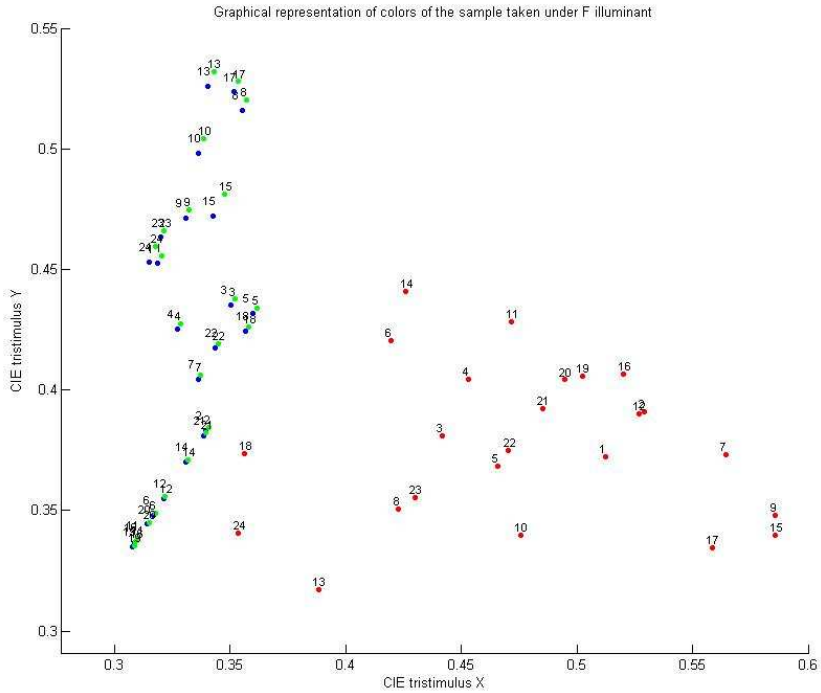


Figure 53: Graphical representation of tristimulus values for reference sample under F illuminant (marked as red points) and sample after CIECAM transformation under F (marked as green points) and D65 illuminants (marked as blue points).

4.3. Experiment results

Two color appearance models were investigated in context of the experiment: CIECAM97s and CIECAM02. Algorithm of the chromatic adaptation transform was used for CIECAM97s model and gave us successful results; images created by developed software are similar to reference. Hence CIECAM97s mode can be used for simulating effect of illumination changes and allow predict color inconstancy—how colors of the sample will change under different illuminants.

But algorithm of CIECAM02 chromatic adaptation transform was failed and gave us incorrect results. The reason of this error is incomplete procedure of color appearance model in the software. Developed software implements only chromatic adaptation transform depending on color of reference image and illuminants without calculations viewing condition-dependent components which allow build correct cone responsivities of human vision system. Without correction that depends on characteristics of human eye system used algorithm of the color appearance is incomplete and obtained image look different from reference for observer.

5. CONCLUSIONS

In this thesis a topic of color inconstancy was considered. Review of most important issues of the subject was done and a lot of theoretical concepts in color theory were discussed. Also practical research that approved the theory was executed. The software for simulation change of illumination was developed and tested. In this chapter we briefly review the main results obtained by practical researches and discuss possible future development of this topic.

The following results were obtained due experimental part of the research:

- Process of the simulation implemented by the chromatic adaptation transform from CIECAM97s model was performed successfully. Tests with range of image set were done and gave us correct results. Difference between the control values of reference colors (obtained by colorimetric devices) and adapted colors (created by developed software) not over the possible error value.
- Due simulation with chromatic adaptation transform from CIECAM02 acquired results were not accurate and gave us incorrect adapted image. Reason of the error is over-adaptation of the CAT02 to the cone response of human vision. After acquiring post-adaptation cone response we can not obtain tristimulus values of the corresponding colors directly but can use these values to create opponent color response and calculate correlates of color appearance.

Hence future development of the research can be dedicated to the task of obtaining adopted colors closer to response of the human vision system. In addition to chromatic adaptation, full adaptation model including post-adaptation transform can be implemented, allowing better simulation.

Nowadays new version of CIE color appearance model is developed (iCAM). Perhaps implementation of the new model allows achieving more flexible adaptation model that will consider state of surround conditions carefully and create simpler algorithm of the simulation change of environment conditions not only illumination but many others.

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APPENDIX I

GretagMacbeth ColorChecker Data

The GretagMacbeth ColorChecker "Color Rendition Chart" is a chart that measures approximately 13 inches by 9 inches (330 mm by 230 mm). It contains 24 colored patches arranged in a 6 by 4 array.

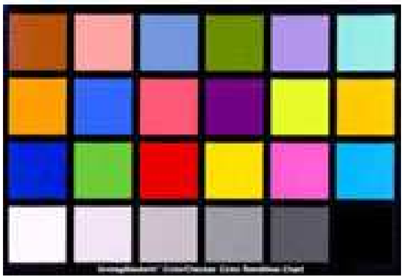

Figure 54: GretagMacbeth ColorChecker (Image taken from [32]).

The chart is described in this paper: McCamy, C.S., Marcus, H., and Davidson, J.G., "A Color Rendition Chart," Journal of Applied Photographic Engineering 11(3) (Summer issue, 1976), 95-99.

Index	Name of color	CIE x	CIE y	CIE Y	Hue	Value	Chroma	ISCC NBS Name
1	dark skin	0.4	0.35	10.1	3 YR	3.7	3.2	moderate brown
2	light skin	0.377	0.345	35.8	2.2 YR	6.47	4.1	light reddish brown
3	blue sky	0.247	0.251	19.3	4.3 PB	4.95	5.5	moderate blue
4	foliage	0.337	0.422	13.3	6.7 GY	4.2	4.1	moderate olive green
5	blue flower	0.265	0.24	24.3	9.7 PB	5.47	6.7	light violet
6	bluish green	0.261	0.343	43.1	2.5 BG	7	6	light bluish green
7	orange	0.506	0.407	30.1	5 YR	6	11	strong orange
8	purplish	0.211	0.175	12	7.5 PB	4	10.7	strong purplish

	blue							blue
9	moderate red	0.453	0.306	19.8	2.5 R	5	10	moderate red
10	purple	0.285	0.202	6.6	5:00 PM	3	7	deep purple
11	yellow green	0.38	0.489	44.3	5 GY	7.1	9.1	strong yellow green
12	orange yellow	0.473	0.438	43.1	10 YR	7	10.5	strong orange yellow
13	blue	0.187	0.129	6.1	7.5 PB	2.9	12.7	vivid purplish blue
14	green	0.305	0.478	23.4	0.25 G	5.4	8.65	strong yellowish green
15	red	0.539	0.313	12	5 R	4	12	strong red
16	yellow	0.448	0.47	59.1	5 Y	8	11.1	vivid yellow
17	magenta	0.364	0.233	19.8	2.5 RP	5	12	strong reddish purple
18	cyan	0.196	0.252	19.8	5 B	5	8	strong greenish blue
19	white	0.31	0.316	90	N	9.5	0	white
20	neutral 8	0.31	0.316	59.1	N	8	0	light gray
21	neutral 6.5	0.31	0.316	36.2	N	6.5	0	light medium gray
22	neutral 5	0.31	0.316	19.8	N	5	0	medium gray
23	neutral 3.5	0.31	0.316	9	N	3.5	0	dark gray
24	black	0.31	0.316	3.1	N	2	0	black

Table 5: Color data of the GretagMacbeth ColorChecker.

Data represent in table calculated by Charles Poynton, Color technology, 2005: (http://www.poynton.com/notes/color/GretagMacbeth-ColorChecker.html).

APPENDIX II

Index of color	**Color**	X (D75)	Y (D75)	X (D65)	Y (D65)	X (D50)	Y (D50)	X (840)	Y (840)	X (F)	Y (F)
1	moderate brown	0,3712	0,3486	0,3808	0,3632	0,4123	0,3774	0,4224	0,4004	0,5293	0,4026
2	light reddish brown	0,3646	0,3489	0,3767	0,3636	0,4096	0,3775	0,4257	0,4009	0,5264	0,4025
3	moderate blue	0,2505	0,2738	0,2645	0,2926	0,2952	0,3210	0,3195	0,3538	0,4280	0,4018
4	moderate olive green	0,3226	0,4112	0,3336	0,4221	0,3614	0,4334	0,3671	0,4636	0,4663	0,4581
5	light violet	0,2683	0,2614	0,2814	0,2806	0,3151	0,3081	0,3368	0,3388	0,4605	0,3834
6	light bluish green	0,2614	0,3572	0,2747	0,3738	0,2988	0,3939	0,3176	0,4296	0,4056	0,4581
7	strong orange	0,4805	0,3919	0,4863	0,4008	0,5102	0,4008	0,5141	0,4120	0,5789	0,3953
8	strong purplish blue	0,2137	0,1994	0,2252	0,2170	0,2527	0,2485	0,2753	0,2782	0,3935	0,3534

9	moderate red	0,4418	0,3080	0,4501	0,3232	0,4871	0,3372	0,5004	0,3580	0,5948	0,3550
10	deep purple	0,2833	0,2364	0,2933	0,2570	0,3314	0,2869	0,3420	0,3182	0,4979	0,3593
11	strong yellow green	0,3597	0,4823	0,3697	0,4867	0,3922	0,4850	0,3948	0,5093	0,4755	0,4775
12	strong orange yellow	0,4460	0,4291	0,4539	0,4360	0,4782	0,4338	0,4757	0,4504	0,5492	0,4231
13	vivid purplish blue	0,1983	0,1615	0,2090	0,1778	0,2352	0,2093	0,2572	0,2409	0,3697	0,3179
14	strong yellowish green	0,2981	0,4703	0,3101	0,4777	0,3304	0,4840	0,3441	0,5123	0,4179	0,5032
15	strong red	0,5104	0,3130	0,5048	0,3265	0,5354	0,3355	0,5270	0,3594	0,6307	0,3359
16	vivid yellow	0,4266	0,4670	0,4327	0,4707	0,4554	0,4643	0,4525	0,4848	0,5296	0,4418
17	strong reddish purple	0,3614	0,2464	0,3698	0,2642	0,4141	0,2897	0,4257	0,3149	0,5707	0,3375
18	strong greenish	0,2128	0,2730	0,2243	0,2910	0,2457	0,3174	0,2707	0,3498	0,3530	0,4123

	blue										
19	white	0,3071	0,3300	0,3207	0,3465	0,3521	0,3675	0,3709	0,3980	0,4768	0,4182
20	light gray	0,3028	0,3268	0,3166	0,3437	0,3485	0,3653	0,3672	0,3955	0,4734	0,4184
21	light medium gray	0,3019	0,3253	0,3161	0,3424	0,3481	0,3640	0,3669	0,3936	0,4735	0,4176
22	medium gray	0,3020	0,3275	0,3163	0,3447	0,3488	0,3658	0,3667	0,3959	0,4728	0,4187
23	dark gray	0,3017	0,3266	0,3162	0,3437	0,3482	0,3654	0,3656	0,3952	0,4728	0,4184
24	black	0,2979	0,3218	0,3120	0,3388	0,3437	0,3608	0,3609	0,3906	0,4700	0,4178

Table 6: Reference tristimulus values of each color GretagMacbeth ColorChecker sample.

Index of color	Color	X (D75 under D65)	Y (D75 under D65)	X (D75 under D75)	Y (D75 under D75)
1	moderate brown	0,3329	0,3376	0,3298	0,3347
2	light reddish brown	0,3373	0,3535	0,3362	0,3522
3	moderate blue	0,2297	0,2953	0,2295	0,2943
4	moderate olive green	0,2979	0,3960	0,2960	0,3922
5	light violet	0,2506	0,2837	0,2501	0,2830
6	light bluish green	0,2488	0,3731	0,2486	0,3720
7	strong orange	0,4456	0,3906	0,4424	0,3883
8	strong purplish blue	0,2018	0,2344	0,2021	0,2343
9	moderate red	0,3804	0,3093	0,3778	0,3080
10	deep purple	0,2553	0,2414	0,2544	0,2407
11	strong yellow green	0,3535	0,4705	0,3520	0,4680
12	strong orange yellow	0,4326	0,4236	0,4302	0,4216
13	vivid purplish blue	0,1876	0,1954	0,1882	0,1957
14	strong yellowish green	0,2826	0,4617	0,2816	0,4575
15	strong red	0,4476	0,3115	0,4422	0,3095
16	vivid yellow	0,4190	0,4671	0,4175	0,4651
17	strong reddish purple	0,3165	0,2582	0,3153	0,2577
18	strong greenish blue	0,2100	0,3094	0,2099	0,3080
19	white	0,2945	0,3455	0,2942	0,3449
20	light gray	0,2881	0,3400	0,2877	0,3393
21	light medium gray	0,2879	0,3370	0,2873	0,3360
22	medium gray	0,2824	0,3354	0,2814	0,3338
23	dark gray	0,2719	0,3284	0,2709	0,3260
24	black	0,2635	0,3135	0,2620	0,3103

Table 7: Tristimulus values of color of the sample obtained under D75 illuminant and reproduced after CIECAM97s transformation under D65 and D75 illuminants.

Index of color	**Color**	X (D65 under D65)	Y (D65 under D65)
1	moderate brown	0,3533	0,3808
2	light reddish brown	0,3590	0,3915
3	moderate blue	0,2538	0,3403
4	moderate olive green	0,3168	0,4354
5	light violet	0,2758	0,3306
6	light bluish green	0,2733	0,4179
7	strong orange	0,4562	0,4139
8	strong purplish blue	0,2251	0,2833
9	moderate red	0,4060	0,3481
10	deep purple	0,2772	0,2849
11	strong yellow green	0,3640	0,4939
12	strong orange yellow	0,4397	0,4449
13	vivid purplish blue	0,2037	0,2356
14	strong yellowish green	0,3034	0,4946
15	strong red	0,4608	0,3414
16	vivid yellow	0,4218	0,4804
17	strong reddish purple	0,3394	0,2956
18	strong greenish blue	0,2241	0,3583
19	white	0,3227	0,3804
20	light gray	0,3148	0,3875
21	light medium gray	0,3112	0,3808
22	medium gray	0,3072	0,3783
23	dark gray	0,2959	0,3757
24	black	0,2831	0,3572

Table 8: Tristimulus values of color of the sample obtained under D65 illuminant and reproduced after CIECAM97s transformation under D65 illuminant.

Index of color	Color	X (D50 under D65)	Y (D50 under D65)	X (D50 under D50)	Y (D50 under D50)
1	moderate brown	0,3947	0,4029	0,3986	0,4059
2	light reddish brown	0,4052	0,4186	0,4066	0,4197
3	moderate blue	0,2934	0,3957	0,2947	0,3973
4	moderate olive green	0,3486	0,4559	0,3511	0,4588
5	light violet	0,3199	0,3820	0,3211	0,3831
6	light bluish green	0,3034	0,4560	0,3041	0,4570
7	strong orange	0,4874	0,4130	0,4894	0,4141
8	strong purplish blue	0,2632	0,3474	0,2646	0,3486
9	moderate red	0,4647	0,3720	0,4674	0,3731
10	deep purple	0,3336	0,3430	0,3367	0,3450
11	strong yellow green	0,3902	0,4919	0,3913	0,4933
12	strong orange yellow	0,4664	0,4400	0,4675	0,4409
13	vivid purplish blue	0,2348	0,3033	0,2366	0,3048
14	strong yellowish green	0,3276	0,5083	0,3289	0,5106
15	strong red	0,5127	0,3581	0,5170	0,3595
16	vivid yellow	0,4446	0,4704	0,4457	0,4712
17	strong reddish purple	0,4044	0,3424	0,4063	0,3432
18	strong greenish blue	0,2439	0,4190	0,2449	0,4207
19	white	0,3680	0,4250	0,3685	0,4254
20	light gray	0,3586	0,4237	0,3592	0,4242
21	light medium gray	0,3545	0,4201	0,3555	0,4210
22	medium gray	0,3512	0,4210	0,3528	0,4226
23	dark gray	0,3405	0,4153	0,3429	0,4176
24	black	0,3118	0,3837	0,3159	0,3875

Table 9: Tristimulus values of color of the sample obtained under D50 illuminant and reproduced after CIECAM97s transformation under D65 and D50 illuminants.

Index of color	**Color**	X (840 under D65)	Y (840 under D65)	X (840 under 840)	Y (840 under 840)
1	moderate brown	0,4059	0,4228	0,4149	0,4315
2	light reddish brown	0,4268	0,4431	0,4303	0,4473
3	moderate blue	0,3378	0,4366	0,3404	0,4434
4	moderate olive green	0,3553	0,4821	0,3589	0,4917
5	light violet	0,3596	0,4221	0,3620	0,4265
6	light bluish green	0,3358	0,4895	0,3368	0,4936
7	strong orange	0,4872	0,4242	0,4933	0,4269
8	strong purplish blue	0,3147	0,3952	0,3167	0,4006
9	moderate red	0,4889	0,3950	0,4975	0,3991
10	deep purple	0,3643	0,3888	0,3719	0,3973
11	strong yellow green	0,3882	0,5079	0,3902	0,5121
12	strong orange yellow	0,4548	0,4580	0,4584	0,4608
13	vivid purplish blue	0,2834	0,3552	0,2835	0,3598
14	strong yellowish green	0,3445	0,5192	0,3472	0,5262
15	strong red	0,5133	0,3711	0,5270	0,3754
16	vivid yellow	0,4237	0,4898	0,4256	0,4928
17	strong reddish purple	0,4420	0,3714	0,4480	0,3735
18	strong greenish blue	0,2919	0,4609	0,2925	0,4675
19	white	0,3853	0,4518	0,3872	0,4541
20	light gray	0,3858	0,4585	0,3876	0,4611
21	light medium gray	0,3838	0,4559	0,3863	0,4597
22	medium gray	0,3784	0,4550	0,3816	0,4605
23	dark gray	0,3648	0,4462	0,3703	0,4557
24	black	0,3306	0,4084	0,3379	0,4220

Table 10: Tristimulus values of color of the sample obtained under 840 illuminant and reproduced after CIECAM97s transformation under D65 and 840 illuminants.

Index of color	**Color**	X (F under D65)	Y (Funder D65)	X (F under F)	Y (F under F)
1	moderate brown	0,5252	0,3501	0,5477	0,3539
2	light reddish brown	0,5517	0,3772	0,5626	0,3797
3	moderate blue	0,4878	0,3875	0,5064	0,3940
4	moderate olive green	0,4908	0,3770	0,5116	0,3834
5	light violet	0,5241	0,3807	0,5377	0,3847
6	light bluish green	0,4790	0,4191	0,4876	0,4235
7	strong orange	0,5735	0,3590	0,5851	0,3608
8	strong purplish blue	0,4876	0,3748	0,5124	0,3821
9	moderate red	0,5969	0,3473	0,6107	0,3491
10	deep purple	0,5222	0,3491	0,5519	0,3544
11	strong yellow green	0,5280	0,3973	0,5360	0,4002
12	strong orange yellow	0,5434	0,3807	0,5522	0,3832
13	vivid purplish blue	0,4311	0,3539	0,4634	0,3635
14	strong yellowish green	0,4702	0,4119	0,4846	0,4188
15	strong red	0,6026	0,3405	0,6176	0,3423
16	vivid yellow	0,5237	0,4003	0,5313	0,4032
17	strong reddish purple	0,5960	0,3487	0,6082	0,3505
18	strong greenish blue	0,4208	0,4185	0,4359	0,4289
19	white	0,4982	0,4216	0,5047	0,4245
20	light gray	0,5214	0,4049	0,5292	0,4081
21	light medium gray	0,5397	0,3880	0,5493	0,3909
22	medium gray	0,5268	0,3794	0,5413	0,3836
23	dark gray	0,5009	0,3620	0,5244	0,3680
24	black	0,4319	0,3432	0,4587	0,3504

Table 11: Tristimulus values of color of the sample obtained under F illuminant and reproduced after CIECAM97s transformation under D65 and F illuminants.

Index of color	Color	X (D75 under D65)	Y (D75 under D65)	X (D75 under D75)	Y (D75 under D75)
1	moderate brown	0,2852	0,3877	0,2838	0,384
2	light reddish brown	0,2981	0,3996	0,2974	0,3979
3	moderate blue	0,2787	0,3559	0,2781	0,3544
4	moderate olive green	0,2937	0,4023	0,2927	0,3993
5	light violet	0,2781	0,3512	0,2777	0,35
6	light bluish green	0,2971	0,3952	0,2968	0,3942
7	strong orange	0,3118	0,4268	0,3108	0,4242
8	strong purplish blue	0,261	0,3134	0,2606	0,3124
9	moderate red	0,2862	0,374	0,2852	0,3718
10	deep purple	0,2554	0,3171	0,255	0,3154
11	strong yellow green	0,3121	0,4411	0,3116	0,4396
12	strong orange yellow	0,3153	0,4374	0,3146	0,4354
13	vivid purplish blue	0,2427	0,2808	0,2426	0,2799
14	strong yellowish green	0,3044	0,4267	0,3037	0,4248
15	strong red	0,2881	0,3886	0,2864	0,3838
16	vivid yellow	0,3196	0,4451	0,3192	0,4437
17	strong reddish purple	0,2702	0,3282	0,2698	0,3269
18	strong greenish blue	0,2823	0,3672	0,2819	0,3659
19	white	0,3013	0,3422	0,3009	0,3417
20	light gray	0,2949	0,3756	0,2944	0,3748
21	light medium gray	0,2914	0,3864	0,2909	0,3851
22	medium gray	0,2874	0,3786	0,2869	0,3767
23	dark gray	0,2788	0,3738	0,2778	0,3711
24	black	0,2681	0,3625	0,267	0,3576

Table 12: Tristimulus values of color of the sample obtained under D75 illuminant and reproduced after CIECAM02 transformation under D65 and D75 illuminants.

Index of color	**Color**	X (D65 under D65)	Y (D65 under D65)
1	moderate brown	0,2868	0,3819
2	light reddish brown	0,2981	0,3992
3	moderate blue	0,2758	0,3474
4	moderate olive green	0,2956	0,4022
5	light violet	0,2747	0,3417
6	light bluish green	0,2969	0,3678
7	strong orange	0,316	0,4329
8	strong purplish blue	0,2576	0,3008
9	moderate red	0,29	0,37
10	deep purple	0,2567	0,3102
11	strong yellow green	0,32	0,4311
12	strong orange yellow	0,3194	0,4453
13	vivid purplish blue	0,2434	0,2705
14	strong yellowish green	0,3052	0,4269
15	strong red	0,2942	0,39
16	vivid yellow	0,3316	0,4296
17	strong reddish purple	0,271	0,3222
18	strong greenish blue	0,278	0,3548
19	white	0,3075	0,334
20	light gray	0,2951	0,3452
21	light medium gray	0,29	0,3822
22	medium gray	0,2881	0,3774
23	dark gray	0,2793	0,3674
24	black	0,2665	0,3589

Table 13: Tristimulus values of color of the sample obtained under D65 illuminant and reproduced after CIECAM02 transformation under D65 illuminant.

Index of color	**Color**	X (D50 under D65)	Y (D50 under D65)	X (D50 under D50)	Y (D50 under D50)
1	moderate brown	0,283	0,3741	0,2845	0,3756
2	light reddish brown	0,2949	0,3874	0,2955	0,3879
3	moderate blue	0,2713	0,3332	0,2718	0,3334
4	moderate olive green	0,2928	0,3941	0,2938	0,3951
5	light violet	0,2701	0,3281	0,2705	0,3284
6	light bluish green	0,2917	0,3737	0,2919	0,3737
7	strong orange	0,3162	0,4324	0,3175	0,4338
8	strong purplish blue	0,253	0,2878	0,2536	0,288
9	moderate red	0,2857	0,3609	0,2865	0,3616
10	deep purple	0,2506	0,2977	0,2516	0,2978
11	strong yellow green	0,3149	0,4433	0,3153	0,4439
12	strong orange yellow	0,3205	0,4442	0,321	0,4447
13	vivid purplish blue	0,2394	0,2601	0,2402	0,2611
14	strong yellowish green	0,3029	0,4219	0,3038	0,4226
15	strong red	0,2884	0,3791	0,29	0,3808
16	vivid yellow	0,3276	0,4478	0,3279	0,4483
17	strong reddish purple	0,2655	0,3092	0,2661	0,3094
18	strong greenish blue	0,2724	0,3405	0,2727	0,3407
19	white	0,3026	0,3339	0,3032	0,3342
20	light gray	0,2883	0,3492	0,2887	0,3494
21	light medium gray	0,285	0,3684	0,2854	0,3683
22	medium gray	0,2838	0,3642	0,2843	0,3645
23	dark gray	0,2743	0,3564	0,2751	0,3569
24	black	0,2618	0,3447	0,2636	0,3463

Table 14: Tristimulus values of color of the sample obtained under D50 illuminant and reproduced after CIECAM02 transformation under D65 and D50 illuminants.

Index of color	**Color**	X (840 under D65)	Y (840 under D65)	X (840 under 840)	Y (840 under 840)
1	moderate brown	0,2752	0,3432	0,2754	0,3439
2	light reddish brown	0,2851	0,3558	0,2854	0,3561
3	moderate blue	0,2518	0,2789	0,2512	0,2784
4	moderate olive green	0,2895	0,3799	0,2903	0,383
5	light violet	0,2575	0,2851	0,257	0,2846
6	light bluish green	0,2807	0,3362	0,2806	0,3367
7	strong orange	0,3236	0,441	0,3245	0,444
8	strong purplish blue	0,236	0,2351	0,2354	0,2342
9	moderate red	0,2791	0,3302	0,2799	0,3314
10	deep purple	0,2389	0,2484	0,2382	0,2478
11	strong yellow green	0,3253	0,4458	0,3259	0,4477
12	strong orange yellow	0,3313	0,4639	0,3321	0,4663
13	vivid purplish blue	0,2228	0,2059	0,2225	0,205
14	strong yellowish green	0,3025	0,4173	0,3036	0,419
15	strong red	0,2842	0,3533	0,2848	0,3558
16	vivid yellow	0,351	0,4632	0,3521	0,465
17	strong reddish purple	0,2482	0,2593	0,2483	0,2597
18	strong greenish blue	0,2525	0,2833	0,2525	0,2837
19	white	0,3072	0,3338	0,3079	0,3345
20	light gray	0,2958	0,334	0,296	0,3344
21	light medium gray	0,2717	0,327	0,2719	0,3279
22	medium gray	0,2684	0,3214	0,2684	0,3225
23	dark gray	0,2635	0,3171	0,2633	0,3185
24	black	0,2485	0,3016	0,2477	0,3035

Table 15: Tristimulus values of color of the sample obtained under 840 illuminant and reproduced after CIECAM02 transformation under D65 and 840 illuminants.

Index of color	**Color**	X (F under D65)	Y (Funder D65)	X (F under F)	Y (F under F)
1	moderate brown	0,3186	0,4524	0,3202	0,4557
2	light reddish brown	0,3394	0,3832	0,3407	0,3844
3	moderate blue	0,3502	0,4352	0,3519	0,4376
4	moderate olive green	0,327	0,4254	0,3284	0,4276
5	light violet	0,3599	0,4318	0,3616	0,434
6	light bluish green	0,3168	0,348	0,3175	0,3488
7	strong orange	0,3361	0,4045	0,3372	0,4061
8	strong purplish blue	0,3551	0,516	0,357	0,5203
9	moderate red	0,3308	0,4711	0,3323	0,4749
10	deep purple	0,336	0,4981	0,3386	0,5041
11	strong yellow green	0,3093	0,3377	0,3099	0,3383
12	strong orange yellow	0,3212	0,3548	0,3219	0,3557
13	vivid purplish blue	0,3402	0,5258	0,3429	0,5322
14	strong yellowish green	0,3308	0,3703	0,3318	0,3711
15	strong red	0,3426	0,4723	0,3475	0,4812
16	vivid yellow	0,3085	0,3366	0,3091	0,3372
17	strong reddish purple	0,3516	0,5236	0,3534	0,5279
18	strong greenish blue	0,3568	0,4244	0,358	0,4261
19	white	0,3079	0,335	0,3084	0,3355
20	light gray	0,3142	0,3443	0,3147	0,3449
21	light medium gray	0,3386	0,381	0,3396	0,3822
22	medium gray	0,3436	0,4176	0,3447	0,4193
23	dark gray	0,3201	0,4632	0,3214	0,4662
24	black	0,315	0,4532	0,3177	0,4595

Table 16: Tristimulus values of color of the sample obtained under F illuminant and reproduced after CIECAM02 transformation under D65 and F illuminants.

Index of color	**Color**	X (D75)	Y (D75)	X (D65)	Y (D65)	X (D50)	Y (D50)	X (840)	Y (840)	X (F)	Y (F)
1	moderate brown	0,3986	0,3501	0,4006	0,3525	0,4276	0,3574	0,4256	0,3670	0,5122	0,3722
2	light reddish brown	0,3992	0,3532	0,4035	0,3587	0,4294	0,3626	0,4413	0,3847	0,5290	0,3909
3	moderate blue	0,2884	0,3021	0,2973	0,3114	0,3248	0,3258	0,3424	0,3459	0,4416	0,3811
4	moderate olive green	0,3464	0,3880	0,3509	0,3913	0,3765	0,3966	0,3666	0,4062	0,4529	0,4044
5	light violet	0,3126	0,2965	0,3186	0,3056	0,3448	0,3178	0,3613	0,3391	0,4656	0,3683
6	light bluish green	0,2951	0,3612	0,3037	0,3701	0,3254	0,3768	0,3370	0,3996	0,4194	0,4203
7	strong orange	0,4974	0,3784	0,4997	0,3864	0,5191	0,3829	0,5140	0,3880	0,5643	0,3732
8	strong purplish blue	0,2430	0,2363	0,2508	0,2462	0,2773	0,2639	0,2962	0,2844	0,4229	0,3506
9	moderate red	0,4665	0,3164	0,4684	0,3255	0,4981	0,3329	0,5058	0,3475	0,5857	0,3480
10	deep purple	0,3192	0,2611	0,3189	0,2741	0,3505	0,2890	0,3495	0,3140	0,4756	0,3396
11	strong yellow green	0,3898	0,4444	0,3962	0,4474	0,4138	0,4444	0,4092	0,4536	0,4718	0,4284
12	strong orange yellow	0,4646	0,4078	0,4630	0,4105	0,4794	0,4074	0,4709	0,4102	0,5268	0,3902
13	vivid purplish blue	0,2153	0,1924	0,2243	0,2047	0,2492	0,2234	0,2689	0,2530	0,3882	0,3172

14	strong yellowish green	0,3197	0,4389	0,3279	0,4449	0,3488	0,4456	0,3501	0,4533	0,4261	0,4409
15	strong red	0,5224	0,3170	0,5112	0,3265	0,5307	0,3300	0,5079	0,3392	0,5858	0,3396
16	vivid yellow	0,4583	0,4381	0,4547	0,4399	0,4704	0,4349	0,4564	0,4363	0,5201	0,4064
17	strong reddish purple	0,4000	0,2701	0,4038	0,2838	0,4368	0,2964	0,4437	0,3161	0,5584	0,3347
18	strong greenish blue	0,2257	0,2972	0,2356	0,3025	0,2540	0,3150	0,2761	0,3322	0,3563	0,3735
19	white	0,3567	0,3469	0,3635	0,3535	0,3877	0,3610	0,4018	0,3873	0,5022	0,4056
20	light gray	0,3464	0,3403	0,3515	0,3478	0,3767	0,3579	0,3958	0,3851	0,4946	0,4042
21	light medium gray	0,3375	0,3356	0,3484	0,3439	0,3756	0,3512	0,3925	0,3766	0,4851	0,3921
22	medium gray	0,3341	0,3343	0,3405	0,3387	0,3700	0,3459	0,3694	0,3601	0,4704	0,3750
23	dark gray	0,3208	0,3227	0,3234	0,3292	0,3458	0,3331	0,3331	0,3374	0,4299	0,3552
24	black	0,2952	0,3096	0,2954	0,3128	0,3048	0,3167	0,3045	0,3255	0,3535	0,3408

Table 17: Reference tristimulus values of each color GretagMacbeth ColorChecker sample reproduced on the LCD monitor.

APPENDIX III

Name	CIE 1931		CIE 1964		CCT	Hue	Note
	x	y	x_{10}	y_{10}			
E	1/3	1/3	1/3	1/3	5400		Equal energy
D50	0.34567	0.35850	0.34773	0.35952	5003		
D55	0.33242	0.34743	0.33411	0.34877	5503		
D65	0.31271	0.32902	0.31382	0.33100	6504		Television, sRGB color space
D75	0.29902	0.31485	0.29968	0.31740	7504		
A	0.44757	0.40745	0.45117	0.40594	2856		Incandescent tungsten
B	0.34842	0.35161	0.3498	0.3527	4874		Obsolete, direct sunlight at noon
C	0.31006	0.31616	0.31039	0.31905	6774		Obsolete, north sky daylight
9300	0.28480	0.29320			9300		High-efficiency blue phosphor monitors
F2	0.37207	0.37512	0.37928	0.36723	4200		Cool White Fluorescent (CWF)
F7	0.31285	0.32918	0.31565	0.32951	6500		Broad-Band Daylight Fluorescent
F11	0.38054	0.37691	0.38543	0.37110	4000		Narrow Band White Fluorescent

Table 18: White points for different illuminants (Data taken from [4]).