Master’s Thesis in Computer Science

Color Accuracy of a Pocket PC

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Abstract

The LCD of the Pocket PC COMPAQ iPAQ H3900 was characterized by standard methods that are normally applied to CRT displays. The primaries were measured, additive properties were checked, and the RGB-to-XYZ transformation and the nonlinear transfer function for each primary color channel were determined.

Different color reproduction methods were compared by psychophysical tests, e.g. by applying the Paired Comparison method.

Preface

I have finished my interesting work for which much efforts and time was spent.

To receive good results would be impossible without my teachers, supervisors, friends and relatives who supported me during all time of my studies.

I want to thank my school teachers Taisia Kursish and Michael Shifman who brought me up, and who showed me the beauty and harmony of formulas. I express my gratitude to Jussi, who supported me in unknown situation, and helped me to settle down into in new research group, and to adapt to new atmosphere.

I also want to thank Eugene. It is pity that we did not have a chance work together. Wish you good health and forces.

And finally my hearty thanks to Hannu, who helped me with the literature and devices. I am honored to met such a professional.

Content:

1. Introduction

Human being has a very good color vision. We can distinguish a wide range of tints, moreover we can see fluorescent colors. On the other hand, existing devices for color reproduction are rather limited in accuracy, and in resolution.

Human gets a visual experience while looking at his/her surrounding. For instance, he/she might like it and wants to have some kind of copy to share his experience with somebody else. It is well known that eyes are the most important sensor of human being, so, we prefer visualized information to express our feelings and thoughts. Techniques to create these pictures range from rock paintings to laser show. In our days we have several ways to store information. The most widespread ways to maintain permanent records of visual information are photos, slides, and various digital media.

Light has the main role in visualisation. In our surroundings light reflects, refracts, diffracts or scatters from an object. The resulting color signal is detected by our eyes or cameras, etc. We can see only reverberate light. Every object for us has a size, color, and luminance from visual point of view. But we have one problem with appearance our work area on the photo – environment of human is a three dimensional space and the picture is only two. However, color and intensity variations in a two dimensional image are enough to create sensations of a three dimensional object recognition because of our abstract thinking. The skeleton of how a person compares original and test images, see in Fig. 1.

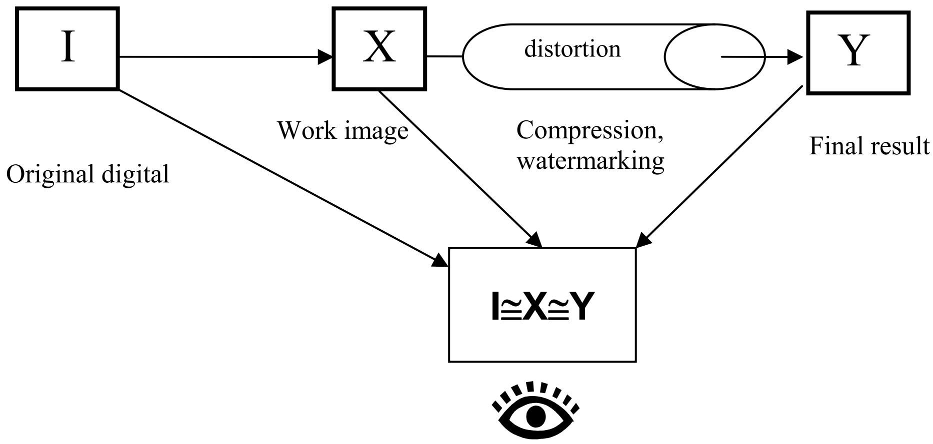


Fig. 1. Scheme how a person compares original and test images.

In this work we suppose that there is an initial picture of a scene which quality satisfies us. Let's call this picture as the original one. This image is supposed to be passed to somebody else. Let us think that also a remote recipient wants to receive this picture with some personal device, for instance a mobile device, computer or any professional scientific system. More over, we want to pass this picture quickly and want to keep the quality of the information contents. Due to all of the digital transmissions transforms and e.g. watermarking, compression, formatting or other transformations (for instance a transformation of the picture from spectral data into RGB format) we loose partially quality of the image. Fig. 2 shows how an image might change until it reaches an observer.

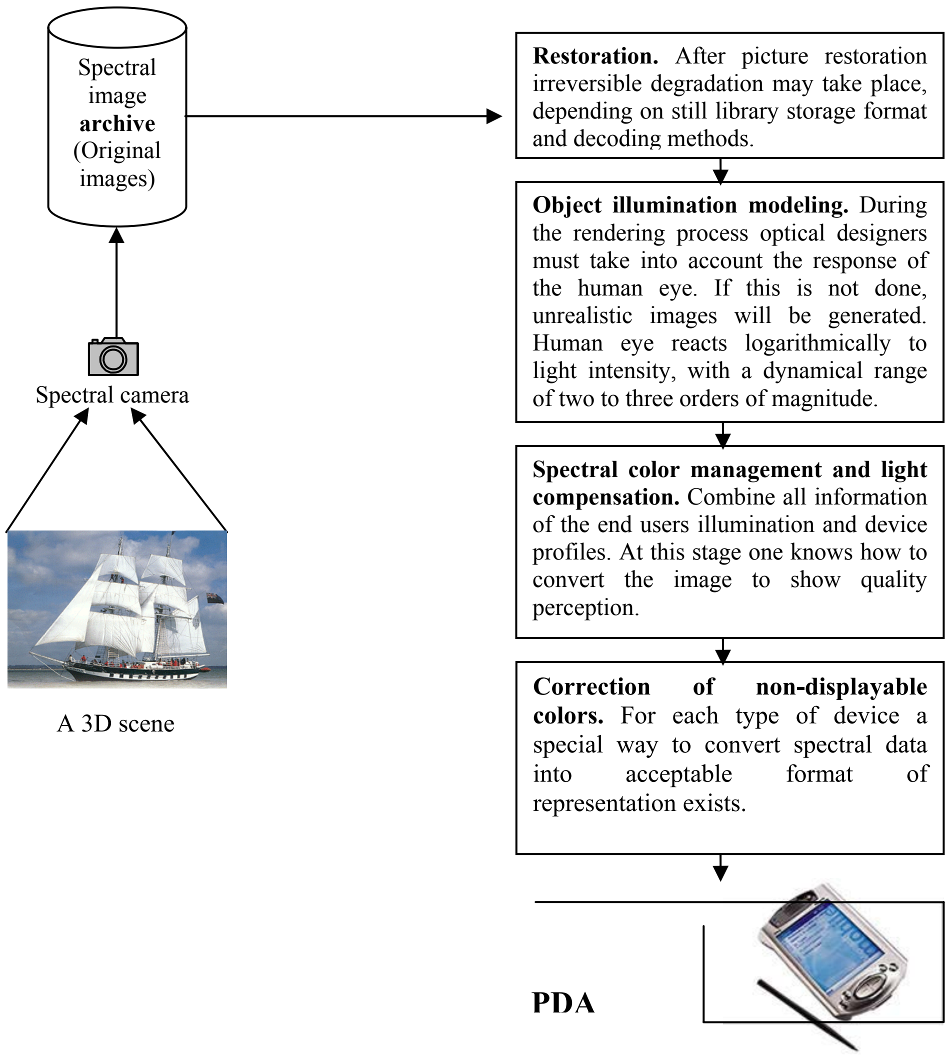
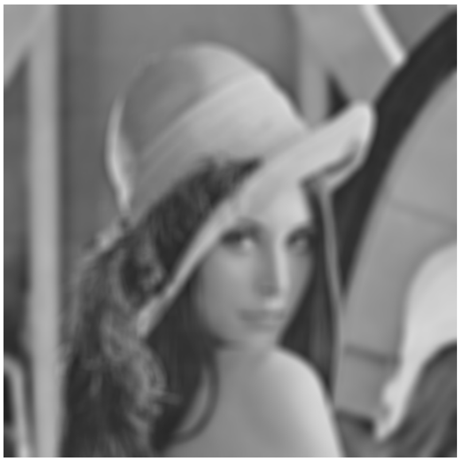


Fig. 2. Steps of the reproducing colors of original sample image process.

One can divide the problem of image degradation into two parts – first, consider color accuracy of the representation of the original image, and secondly consider structural precision (examples of structural image changes are shown in Fig. 3). This work was focused on color accuracy on mobile device.



Original "Lena" Image Blurring

Additive Gaussian Noise Impulsive Salt-Pepper Noise

Fig. 3. Examples of structural image changes [13]**.**

There are two of factors that influence on accurate image reproduction on a mobile device:

- Color image rendering
- Image degradation factors,

Color rendition factors affect accurate rendition of colors due to color reproduction abilities of the device (gamut of colors that can be rendered on the device), and illumination conditions at the moment of visualization of the image. The colors displayable by the device can (and usually do) have different spectral properties than the original colors of the image. Even though the human response on the display colors may be adequate compared to the original ones, the situation may easily change with the change of the lighting condition. The color rendition factors can be considered as global, since they equally affect on all pixels in the image. Of course, the degree of color accuracy can be more noticeable to the user dependent of the color and brightness of the pixels. Indeed, dark pixels exhibit less color shift than the bright ones. Also, human response to color shifts varies for various colors.

Image degradation is usually caused by image encoding/decoding and processing operations. In many cases such operations are due to restrictions of mobile terminals. Such restrictions are e.g.: limited bandwidth leading to use of lossy image compression schemes, limited number of colors leading to image resampling, and copyright protection required to digitally sign or watermark imagery data. Quality factors due to image degradation can be considered as local factors, since degradation processes affect various pixels with varied strength, which is usually dependent of the value of the pixel and its neighborhood.

Colors of an image can be represented accurately enough, after the properties of the output device are known. It will be shown in this thesis that standard sRGB images look bad on the LCD display. This was proved by human tests. The sRGB transformation works in theory but leads to one particular practical problem. The range of displayable colors of a device (color gamut) may not be large enough to accommodate all pixel values of the image. Gamut examples of CRT and PDA will be shown later in this work.

The aims of this work are to study color reproduction abilities of the PDA Pocket PC COMPAQ IPAQ with some traditional CRT techniques. In this work were also made psychophysical tests to evaluate of the proposed PDA characterization techniques.

Let us finally list some artifacts which may appear in images after their processing and briefly explain the reasons for artifacts.

Some Image Artifacts

Fig. 4. From left to right: Blocking effect, Mosaic effect, Blurring effect [13].

Structural image artifacts are:

- *Blocking*. Effect of splitting an image into square blocks (usually 8x8 pixels) with noticeable borders. It happens due to dividing the picture in blocks and after that each block is coded individually (independently of other blocks). Coding use Discrete Cosine Transform (DCT) and quantization of coefficients. Main thing of the DCT is presence of the non-zero errors at the edges of the blocks [9], [13]. Human perceives these errors as sudden change of brightness from a block to another.
- *Mosaic effect*. Mosaic effect looks similar to blocking effect, but here in neighbor blocks image data differs very much. The reason for the mosaic effect in rough quantization after DCT [9].
- *Blurring effect*. If compression ratio is very high it can cause a blurring of the image. This effect is a result of nulling high frequencies of the spectrum. Fine details become degraded or disappear at all from the image. [6]
- *Edging on the edges.*[9] This kind of artifact looks like edging in the area of sharp transition of brightness near the edge. It happens due to big distortions in high frequency part of the spectrum. The step signal contains a lot of spectral components which amplitude decrease in inverse proportion to their number. Its change can break

the monotony of function near the edge. Viewer sees it like rippling of brightness.

- *Jaggedness.* Appears for instance in the JPEG format pictures. This artifact is a result of incorrect restoration of the edges inside blocks of the image. A simple example is a line. Which is supposed to be parallel to one of the borders of the blocks. Artifact looks like a sharp turn of the line during passage a boundary between blocks. It starts to form a step with respect to the border instead to be parallel. Usually one sees such troubles in big scales of restored pictures [9].

Now the following aspects of Human Visual System need to be taken into account:

- *Brightness*

- *Spatial frequency sensitivity* – human eye is less sensitive to artifacts in areas of high activity. The activity can be measured by the total energy of spatial frequencies, which can be calculated by the windowed Fourier transform.

Typical color changes (Blurring of colors) are caused by the same reasons as the Edging. But it appears in regions near the sudden change of brightness [9].

2. Human Perception

Human sees not by eyes but via eyes. The visual information is transferred after retinal preprocessing through the optic nerve to certain areas of brain where one creates the color sensation. Our visual system is composed of many different kinds of organs and structures. Presence of two eyes allows us to let our sight be stereoscopic (we can see our surrounding world as 3-dimentional). Retinal data of the left and right eye are partly crossed before delivered further in visual system. Then brain combines both parts into one image [20]. Because each eye takes its own portion of view, human can loose his binocular vision if eyes stop to move simultaneously (this means that human will see two pictures at the same time and does not perceive 3D effects, or image will be seen double).

Question of color is also very interesting. People are interested in this issue for a long time. Since an attempt in 1810 for a three-dimensional “the color globe” description of colors by the painter Philipp Otto, various systems of color have been introduced, (see Fig. 5). Due to all changes in color theory the terminology of theory has been under continues developing [14]. The most standard are those notations which describe hue of the color (blue, green etc.) and terms as “light”, “dark”, “warm”. Such words as “warm” and “cold” help to specify a tint of color. On the other hand, it is necessary to pay attention to the surface from which the discussed light irradiates. Usually people use words “glossy” and “matt”.

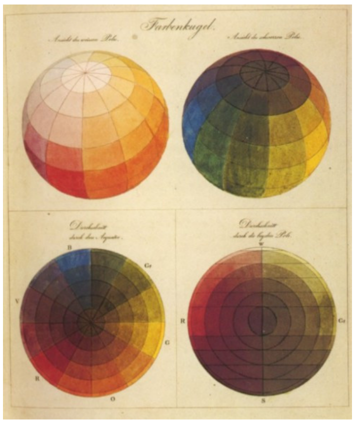


Fig. 5. Philipp Otto Runge globe model of colour, 1810 [14].

There are several reasons why the perception of light and its physical characteristics do not correlate. This problem is a subject of Metamerism. *Metameric* color stimulis are color stimulis with the same tristimulus values but different spectral radiant power distributions [45]. The spectral difference can become visible only if we change illumination. For instance, vegetables may have one kind of color under natural illumination, and they can appreciably change their view under artificial illumination.

2.1. Reasons for Color

Since the subject of my interest is color, it would be interesting to know reasons that cause it. For instance, what can be reason for the gemstones on Fig. 6 to be "blue"?

Fig. 6. Six gemstones, six causes of color
Clockwise from top left:
(1) Maxixe-type beryl, radiation-induced color center. (2) Round blue spinel, ligand-field color from a cobalt impurity. (3) Spinel "doublet, "colorless spinel containing a layer of organic dye. (4) Oval lapis lazuli, S_3^- anion-anion charge transfer. (5) blue sapphire, Fe-Ti intervalence charge transfer. (6) Oval shattuckite, cobalt compound. Scale: the largest stone is 2 cm across. [35]

As mentioned above human eyes handle transformed light of the illuminant. The original spectrum of the illuminant is transformed to the color signal through scattering, refraction, diffraction and interference, and there are several other reasons also. In reference [35] there are 5 main mechanisms for color signal production, but in fact there are three basic ways of processing light – absorption, reflection and transmission [34].

Geometrical and physical optic effects produce colors due to dispersive refraction (rainbow, prisms). As Isaac Newton discovered the nature of color and found out, that visible light consists of several main visible primary components. He found out that light can be dispersed by a prism or grating into a spectrum. Dispersion is known as dispersive refraction also. Then there was detected such phenomena as absorption of the visible spectrum of light, so, eyes do detect only that part of energy which has reached our eyes. Independent on how the color signal is produced, the color appearance depends on the spectral power distribution of the color signal. For instance, color red arises when all wavelengths are other absorbed but red part of the spectrum is reflected from the object. In sketch it looks like on Fig. 7.

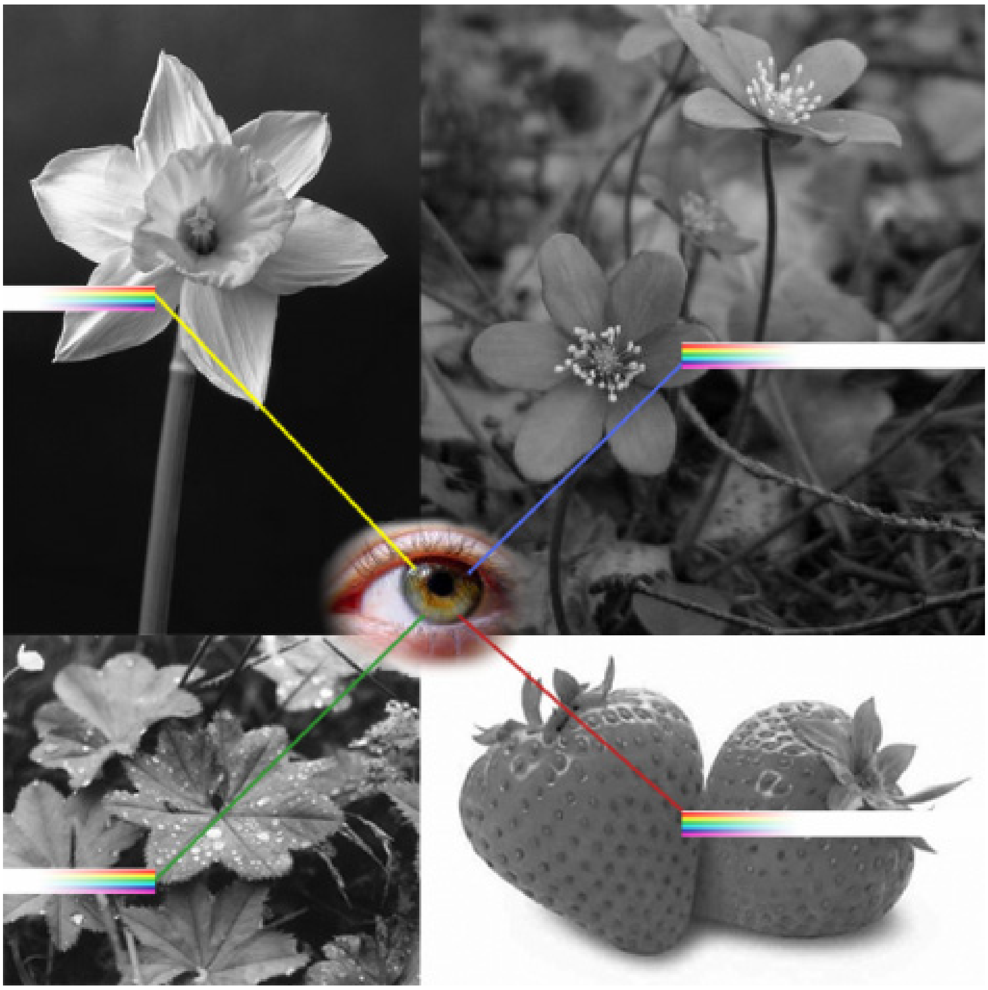


Fig. 7. Simple model of color appearing via reflection.

There are number of physical and chemical causes of color. A simple list contains just 15 examples from Kurt Nassau [35],[26]:

- Vibrations and simple excitations
  1. Incandescence (Hot objects, the Sun, flames, filament lamps, carbon arcs, limelight)
  2. Gas excitations (Vapor lamps, neon signs, auroras)
  3. Vibrations and rotations (Blue water and ice)
- Transitions involving ligand field effects
  8. Transition metal compounds
  9. Transition metal impurities
- Transition between molecular orbitals
  6. Transition metal impurities
  7. Charge transfer (Blue Sapphire, Lapis Lazuli)
- Transitions involving energy bands
  8. Metals (Copper, Silver, Gold)
  9. Pure Semiconductors (Silicon)
  10. Doped Semiconductors (Blue and yellow diamonds)
  11. Color centers (Amethyst, desert “amethyst” glass)
- Geometrical and physical optics
  12. Dispersive refraction, polarization (Rainbow, “fire” in gemstones)
  13. Scattering (Red sunset, blue Moon, moonstone, blue eyes, skin, biological colors but not all)
  14. Interference without diffraction (Oil slick on water)
  15. Diffraction (Aureole, Opal, some liquid crystals biological colors)

One need to point out that this list is just an example and other reasons exist too. Since there are a lot of possibilities to simulate same *stimuli* of color, two types of perceived colors exist:

- *Unrelated color* perceived to belong to an area seen independently in the surrounding. This kind of illumination interacts with eyes directly.

- *Related color* perceived to belong to an area seen in relation to an other area of colors. Colored light is produced by the interaction of different light sources in the material [2].

2.2. Source of Radiant Energy

All bodies surrounding us are radiate electromagnetic radiation because of nonzero absolute temperature. When we speak about *light*, we mean the visible range of electromagnetic radiation, 380-780$_{nm}$. S*pectral power distribution (SPD)* is related to color of light. SPD is given in terms of quantity per unit wavelength. The wavelength λ and frequency ν are related to each other by formula:

$$\lambda = c\nu^{-1}$$

Frequency is a fundamental parameter of radiant energy. λ is measured in *nanometers (nm)*.

In fact range of the radiation spectrum is very wide. Part of this range that can be recognized by humans on the contrary, is narrow – from 380 nm till 780 nm.

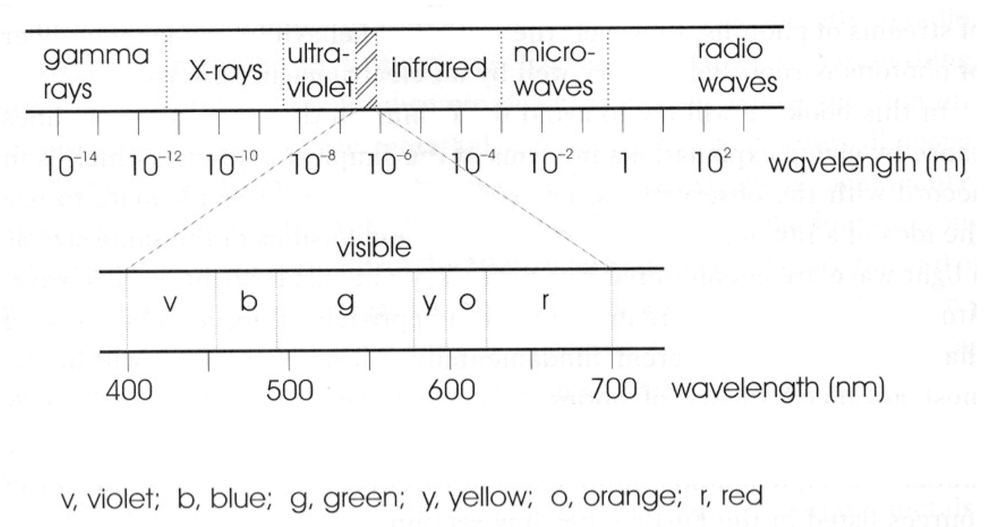


Fig. 8. The electromagnetic spectrum. [40]

Since SPD is a continuous function of wavelength and depends on nature of the sample and its temperature, only *Black Body Radiator* explains the whole truth. The dependence of the spectral density of the *radiance energy* over unit wavelength interval emitted by black body (in the constant temperature) is described by Planck's formula:

$$u_{e\lambda} = 8\pi hc\lambda^{-5}\left(e^{\frac{hc}{kT\lambda}} - 1\right)^{-1}$$

where
c = 2.997 924 58 * 10^8 $m \cdot s^{-1}$ is Velocity of light
h = 6.626 176 * 10^{-34} $J \cdot s$ is Planck constant
k = 1.380 662 * 10^{-34} $J \cdot K^{-1}$ is Boltzmann constant

The spectral *radiant exitance* of a black body at temperature T per unit wavelength interval is defined by [3] :

$$M_e = \frac{c}{4} u_{e\lambda} \quad (1)$$

Since CRT monitors are Lambertian radiators within typical viewing angles, the *spectral radiance* is [3]:

$$L_{e\lambda} = \frac{1}{\pi\omega_0} M_{e\lambda} \quad (2)$$

$\omega_0 = S / r^2$, is a solid angle of magnitude one steradian; S is a part of the surface of the sphere limited by solid angle ω_0, r which is a radius of the sphere.

Kirchhgoff's law: the ratio of the radiant power emitted by the matte surface of a thermal radiator to the absorbance of the surface is the same for all thermal radiators at the same temperature. If such a surface receives the radiant power P_λ, the proportion $\alpha(\lambda)P_\lambda$ is absorbed and converted into heat and the rest $\rho(\lambda)P_\lambda$ is reflected diffusely. $\rho(\lambda)$ is called *reflectance* and related with $\alpha(\lambda)$ as follows:

$$\rho(\lambda) = 1 - \alpha(\lambda)$$

For the black body $\rho(\lambda) = 0$ and $\alpha(\lambda) = 1$ at all wavelengths [45].

Absolute thermal radiator does not exist in practice. For radiometric and colorimetric purposes CIE has defined standard lighting sources e.g. A, B, C, and various D-sources. Most important commercial light sources include:

1. Incandescent lamps
2. Tungsten – Halogen lamps
3. Filtered tungsten filament lamps
4. Electric discharge lamp
5. Carbon arc lamps
6. Fluorescent lamps
7. High – pressure Xenon arc lamps [45]
8. LEDs

Relative spectral distribution gives the spectral concentration of a source in arbitrary radiometric units. A normal convention is to normalize relative spectral distribution to have unit power at wavelength λ = 560$_{mn}$.

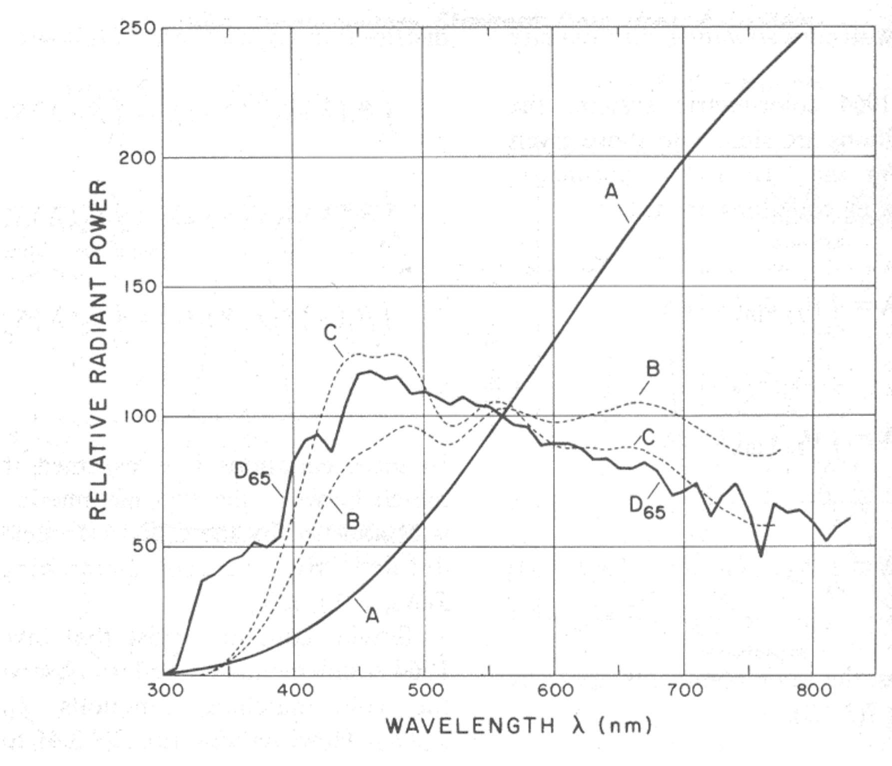


Fig. 9. Relative spectral radiant power distribution of CIE illuminants A, B, C, D_{65} [45].

2.3. Structure of Eye

Before the electric signal calls one's sensation of color it undergoes certain transformations in eyes. Light can be produced by emission from an object (sun or any artificial source of light) as well as by reflection from a surface. Most of us have the same visual system. Its capabilities are admirable. Human eye can distinguish about ten million color tints. All the hues are appearing due to the photoreceptors' sensitivities. A sensation produced by uneven stimulation of cone cells is called as chromatic color. If responses at these cells are equal we can see white, black and different grays. It means we sense (or better to say that we see) achromatic colors [34], [45], [2], [11].

Human eye it is a complicated system. The initial processing and transmitting the information caused by electromagnetic radiation in the visible part of spectrum takes place at retinal level. A schematic diagram of human eye is shown in image below.

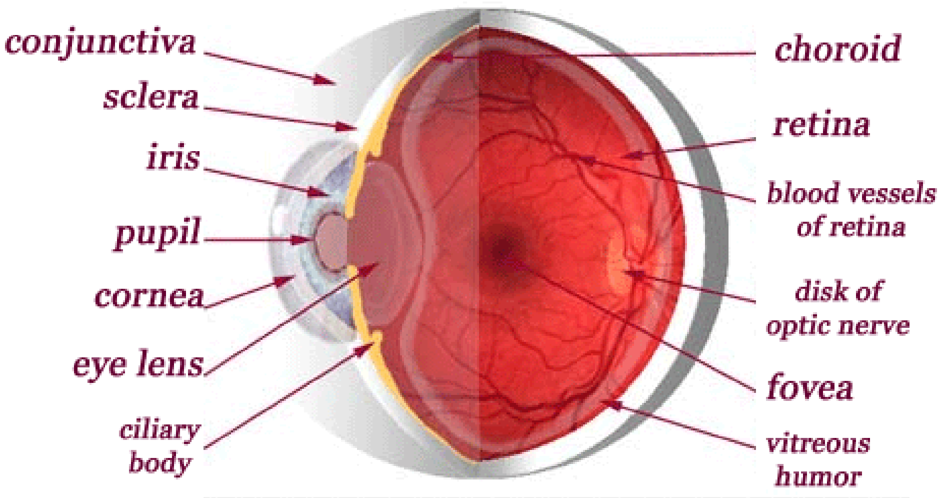


Fig. 10. Structure of eye [44].

The eye forms an optical system. Rays of light first get into the eye through the cornea.

Cornea in optic terms is a very strong converging lens. It focuses light towards retina. The focal power of cornea makes 40 diopters from total 60 diopters of the refracting force of the eye [20].

Sclera is an opaque external eye's cover, which does not take part in refracting light inside the eye. That is why we will exclude the detailed consideration of sclera.

Conjunctiva is a mucous membrane that lines the inner surfaces of the eyelids and folds back to cover the front surface of the eyeball, except for the central clear portion of the outer eye (the cornea). The entire conjunctiva is transparent [12].

Pupil of the eye is a round hole in the iris. It regulates the quantity of the light on the retina. This feature is very important since we adapt to different levels of illumination. Also pupil screen lateral rays of light which could otherwise cause the distortion of vision.

After cornea light is refracted by crystalline lens.

Crystalline lens is also a lens like cornea, but its main advantage is the capability of changing its form. This phenomenon is called accommodation. Thus crystalline lens controls the focusing and thus image forming properties of the eye.

Behind the lens there is *vitreous humor*. It fills whole eye until the retina. Rays of light focused by the optical system reaches finally the retina.

Retina works as a spherical screen. Surrounding world is projected on this screen. From physics we know that converging lens gives us inverse image of the object. Cornea and crystalline lens are converging lenses, so the projective image on the retina is also inverted. Retina from embryological point of view is just a part of brain. It consists of 10 layers. There are three hierarchically organized structures: an external layer, an internal layer and a layer of nerve cells. O*ptic nerve* is formed from these cells (information reaches brain through this channel). Distribution of cellular elements varies over the retina, the density of photoreceptors decreases from the center to periphery**.**

Macula luteum is the central part of the retina. It is in judge of the acuity of vision. Other parts of the retina are not so sensitive. The central part of the *macula luteum* is known as *fovea***.** In *fovea* all conditions exist for perception of fine details, it is in judge of the central vision [41].

In the retina there are two types of photoreceptors - *cones* and *rods*. Rods are used for scotopic vision (night vision when we can see only in the gray scale mode), and cones are used for daylight (photopic vision) [34], [16]. Majority of cones are concentrated in *fovea*. Fovea's size is about $50_{\mu m}$ x $50_{\mu m}$. The greatest density of cones is 147 000 – 238 000 per1_{mm}^2. Further from the center the density of cones decreases. The central zone 50 – $75_{\mu m}$ is free from rods. The density of rods is maximal in a ring around fovea. Their density is about 150-160 thousand on one mm^2, and then their quantity decreases to periphery where their amount is about 60 thousand rods on one mm^2. Average density of rods is 80 – 100 thousand on one mm^2 [41].

Retina is a superfine inner coat of the eye which has very high sensitivity to the light, caused by photoreceptors. Millions of nerve cells transform the light signal to electrical impulses [45]. Then other cells of the retina process this signal and pass it as electric pulses via the nerve fibres to the brain. The final analysis and synthesis of the visual information takes place in the brain. All that we call "perception" of information at a level of consciousness. The bundle of nerve fibres going from an eye to a brain is called as an *optic nerve* [41].

2.4. Human Color Response

As mentioned above cone cells are sensitive to color stimulus. Cones can be divided in subgroups sensitive to *Short* wavelengths (blue range of colors), *Middle* wavelength (green colors) and *Long* wavelength (red colors). Spectral sensitivities see in Fig. 11.

If two different light stimuli cause the same cone response, then human percepts these stimuli as the same color. Young (1802) and Helmholtz (1866) built their *trichromatic* theory for this phenomenon [2]. According this theories color can be represented by three components which nowadays are called *primaries*.

The cone responses c_i, $i = S, M, L,$ for a spectral distribution of light, $l(\lambda)$, over wavelength λ are [34]:

$$c_i = \int_{\lambda_{min}}^{\lambda_{max}} S_i(\lambda) l(\lambda) d\lambda \qquad (3)$$

where $S_i(\lambda)$ - is the function of sensitivity of *i*-th type of cones,
$[\lambda_{min}, \lambda_{max}]$ – is an interval of visible spectrum, typically $[380_{nm}, 780_{nm}]$.

From Mathematical point of view, equation (3) is a Fredholms equation of first – order. If we define an integral operator as:

$$L\, l = \int_{\lambda_{min}}^{\lambda_{max}} s_i(\lambda) l(\lambda) d\lambda\,, \qquad (4)$$

i.e. operator L is an operator which projects a Hilbert space into another Hilbert space; this Hilbert space is a space of square integrable functions [34] .Using (4) in (3) can rewrite it in form:

$$c = L\, l \qquad (5)$$

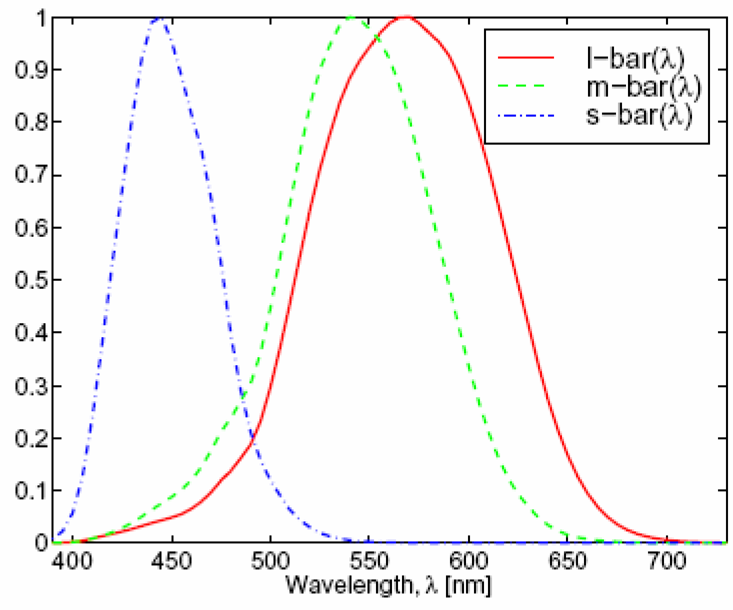


Fig. 11. Normalized cone fundamentals of the S, M and L cones [16].

Equation (5) shows a classic form of linear transformation – spectrum of light is transformed into the cones responses through inner product. This transformation is defined by the sensitivity functions $\{s_i\}_{i=S,M,L}$. Space which is defined by $\{s_i\}_{i=S,M,L}$ is called *human visual subspace* (HVSS, Horn, 1984, Vora and Trussell, 1993).

Equation (3) can be rewritten for the discrete case. Then color stimuli is not a continuous function of wavelength, but have some sampling step Δλ

$$\Delta\lambda = \lambda_i - \lambda_{i-1} = \frac{\lambda_{\max} - \lambda_{\min}}{N}.$$

Thus, integration is substituted by a discrete summing. If N is the number of samples, we have [34]:

$$c_i = \sum_{i=1}^{N} s_i(\lambda_i) l(\lambda_1) \Delta\lambda = \mathbf{s}_i^T \mathbf{l} \Delta\lambda \qquad i = S, M, L \tag{6}$$

where

$$\mathbf{s}_i = [s_i(\lambda_1), s_i(\lambda_2), s_i(\lambda_3), \ldots s_i(\lambda_N)]^T \qquad \text{and} \qquad \mathbf{l} = [l(\lambda_1), l(\lambda_2), \ldots, l(\lambda_N)]^T$$

Superscript mark "T" denotes vector transpose operation. In matrix form Eq.(6) takes form:

$$\mathbf{c} = \mathbf{S}^T \mathbf{l} \Delta\lambda, \tag{7}$$

where

$$\mathbf{c} = [c_S, c_M, c_L]^T, \qquad \mathbf{S} = \begin{bmatrix} s_{S1} & s_{M1} & s_{L1} \\ s_{S2} & s_{M2} & s_{L2} \\ \vdots & \vdots & \vdots \\ s_{SN} & s_{MN} & s_{LN} \end{bmatrix}, \qquad \mathbf{l} = [l(\lambda_1), l(\lambda_2), \ldots, l(\lambda_N)]^T$$

As on can see form (7), color can be specified by the vector **c[1x3]**, which is know as *tristimulus* vector.

If we perceive light that is reflected from a surface, instead of light that is directly emitted from a light source, our eyes receive result of the scalar product of reflectance and radiance spectrum, as it is shown on Fig. 12.
In continuous case human response is:

$$c_i = \int_{\lambda_{min}}^{\lambda_{max}} S_i(\lambda) r(\lambda) l(\lambda) d\lambda \qquad i = S, M, L$$

where $r(\lambda)$ is spectral reflectance of the surface .

For the discrete case:

$$\mathbf{c} = \mathbf{S}^T \mathbf{lr} \Delta\lambda \tag{8}$$

In the sampled case, the HVSS corresponds to the *vector space* spanned by the column vectors of the matrix **S**.

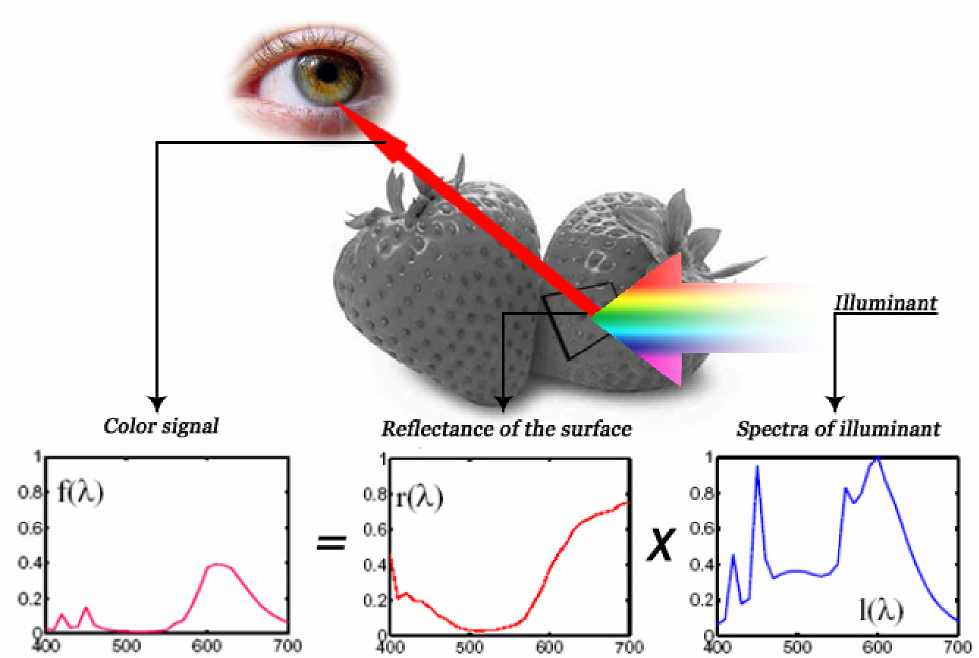


Fig. 12. Color stimulus. The spectral radiance (color signal) *f(λ)*, of the light reflected from a surface with a spectral reflectance *r(λ,)* under illuminant with a spectral radiance *l(λ)* is given by *f(λ) = l(λ)r(λ)* [16].

3. Colorimetry

In the reference [45] colorimetry is defined as a branch of color science which main idea is to study color in a trichromatic generalized form; to provide the coordinate systems of colors, to study things as color difference, color matching and provide psychophysical terms of color. The aim of colorimetry is to specify numerically the color of a physically defined visual stimulus in such a manner that:

- When an object is viewed by an observer with normal color vision under the same observing conditions, stimuli with the same specification look alike (are complete color-matches).
- Stimuli that look alike have the same specification.
- The numbers comprising the specification are continuous functions of the physical parameters defining the spectral radiant power distribution of the stimulus.

3.1. Basic Laws of Additive Color Mixing

The theory of Grassman for additive color mix (1853) is one of the fundamental Color Science theories.

(Grassman's *First law):* *Trichromatic generalization* – any color can be represented as an additive mixture of three independent fixed primary stimuli whose radiant powers are adjusted.

Because according the standard model our color system is three – dimensional, due to human cone responses (see Fig. 11) usually Red, Green and Blue colors are chosen as primary colors. The main feature of the system is color-independency of the primaries, i.e. any of three chosen primaries should not be achieved as a mixture of other two. Hence

$$A = \alpha R + \beta G + \gamma B \qquad \forall A \in V \,,\ \alpha, \beta, \gamma \in R^1$$

The main point for the other laws is that we are going to consider the liner theory of light, i.e. light obeys laws of linearity. The mathematical basis is within the theory of linear vector spaces, but the laws are generally reformulated according to the color terminology [45] as follows:

(Grassman's *Second law):* *Symmetry Law* – if a color stimulus *A* matches a color stimulus *B*, then color stimulus *B* matches color stimulus *A*. The result of an additive mixture of colored light depends only on the psychophysical characterization, and not on the spectral composition of colors [16].

Transitivity law: if *A* matches *B* and *B* matches *C*, then *A* matches *C*

(Grassman's *Third law):* *Proportionality law:* if *A* matches *B*, then αA matches αB, where α is any positive factor by which the radiant power of the color stimulus is increased or reduced, while its relative spectral distribution is kept unchanged.

Additivity law: if *A, B, C, D* are any four color stimuli, then if any of the following three conceivable color matches: *A* matches *B, C* matches *D,* and *(A+C)* matches *(B+D),* then *(A+D)* matches *(C+B);* where *(A+C)*,*(B+D)*,*(A+D), (C+B)* denote additive mixtures of *the pairs A and C, B and D, A and D, C and B* respectively [45].

3.2. Color Matching Experiment

The aim of psychophysical experiment is to define the dependencies (functions) of the proportions of the chosen primary colors as a function of wavelength so, that the combination of primary colors produces the same perception as the monochromatic color stimuli of the corresponding wavelength (to find spectral relative power distribution of primaries, their intensities as functions of wavelength). In other words input is a spectral power distribution of the test light and the resulting output is a three dimensional vector.

Target settings: a user see two adjacent areas, as shown in Fig. 13. On one side a *test color* (test light) is shown and on the opposite side there is an area (*matching area*) where user adjusts three *primary colors,* in a way, that for user both areas look perceptually the same.

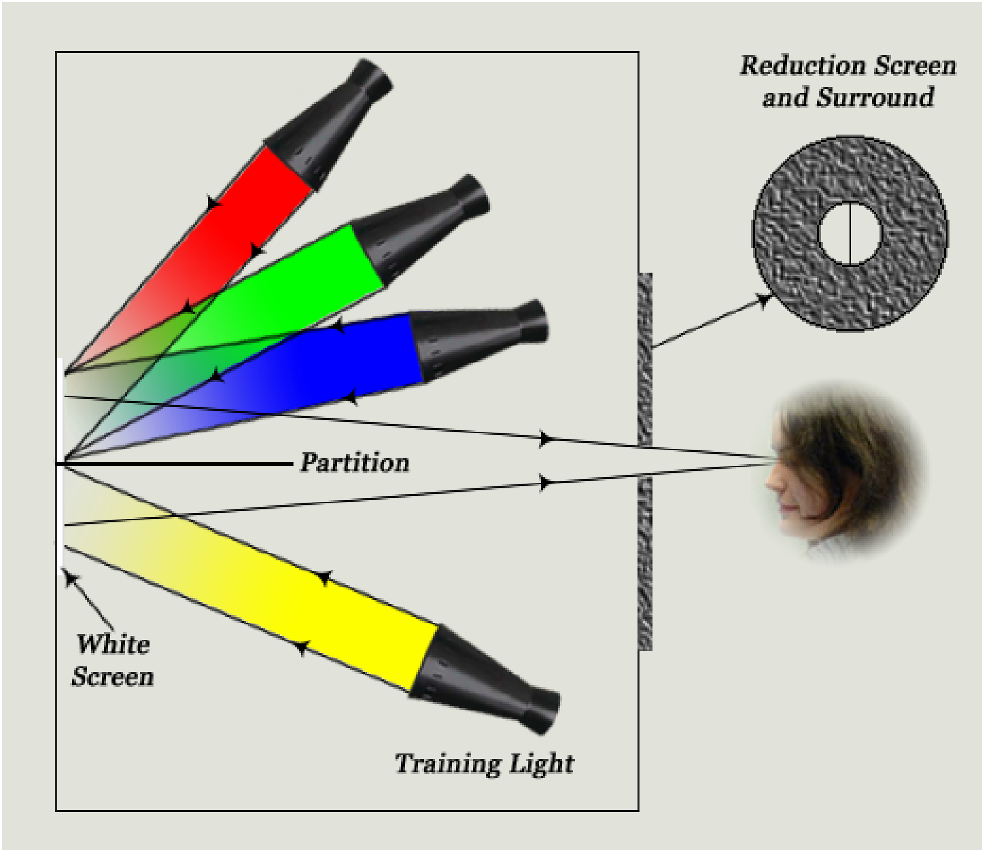


Fig. 13. Principle of color matching experiment.

Amount of the primaries depends on what kind of vision we consider. If we want to study night vision (scotopic) then we need only one primary. For the color vision (photopic) three primary colors are needed for mixing [42].

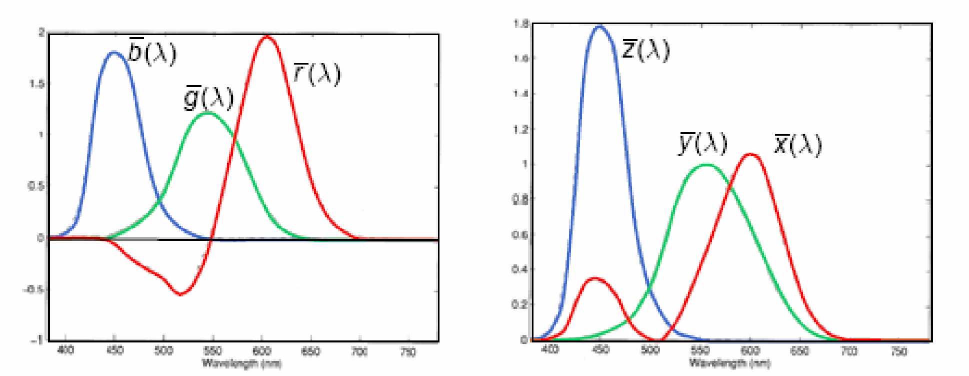
Metamerism

Colors l_1 and l_2 match if they produce the same visual response: $\mathbf{S}^T l_1 = \mathbf{S}^T l_2$.

In fact, if two colors match in a color matching experiment– the test color and a color as a result of mixture of three primaries, from visual (perceptual) point of view it does not mean that they match from physical point of view, i.e. these colors might have completely different spectral power distribution.

Such two colors are called *metamers,* and the phenomenon is called *Metamerism.* There are different types of metamerism. If a pair does not match under different illuminations, then we speak about illuminant Metamerism. If the pair does not match under changing the observer, then it is observer Metamerism.

This phenomenon is in the background of the of the color reproduction in CRT and other trichromatic monitors.



(a) **(b)**

Fig. 14. Color matching functions of the CIE1931 standard colorimetric observer a) in the system of real primary stimuli R,G,B and b) in the transformed system of imaginary primary stimuli X,Y,Z.

The color matching functions of the CIE standard observer in case of Red, Green and Blue colors as primaries are shown in Fig. 14.a). Note, that there is a part of red curve that has a negative values. It means that for certain test colors for matching it was needed to move Red primary lamp to the area where test color was.

3.3. Color Coordinate Systems

3.3.1. XYZ color space

In 1931 CIE (Committee Internationale d'Eclairage) decided to propose a particular set of color matching functions as a standard. These functions are denoted as $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$, (shown in Fig. 14. b)). According to Eq. (6) the corresponding tristimulus values X, Y, Z for stimuli *f* are:

$$\begin{aligned} X &= k\sum_{\lambda}\bar{x}(\lambda)f(\lambda)\Delta\lambda \\ Y &= k\sum_{\lambda}\bar{y}(\lambda)f(\lambda)\Delta\lambda \\ Z &= k\sum_{\lambda}\bar{z}(\lambda)f(\lambda)\Delta\lambda \end{aligned} \qquad (9)$$

where *k* is a constant normalization factor. We can rewrite (9) in compact form by using the notation as in Eq. (7): $S = [\bar{x}\bar{y}\bar{z}]$,

$$S = \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ \vdots & \vdots & \vdots \\ x_N & y_N & z_N \end{bmatrix}$$

Here each row is intensities to match a single monochromatic light, each column is a complete set of intensities over wavelength (with amount of samples N) of one primary. So, (9) will be now:

$$f_{XYZ} = kS^T f\Delta\lambda, \qquad k = \frac{100}{\sum_{\lambda} l_\lambda \overline{y_\lambda}\Delta\lambda} \qquad (10)$$

Y value for the pure white surface is usually normalized to 100.

If *f* is the radiance measured in units ($W \cdot sr^{-1} \cdot m^{-2}$), then Y can be expressed in photometric units by using value 683 ($lm \cdot W^{-1}$) for constant k. Then Y is called as luminance. Units of luminance is $lm \cdot m^{-2} \cdot sr = cd \cdot m^{-2}$

Candela is a photometric unit of luminouse intensity defined as 1/683 (watt /sr) [2].

Relation between $\bar{r}, \bar{g}, \bar{b}$ and $\bar{x}, \bar{y}, \bar{z}$ is:

$$\begin{bmatrix} \bar{x} \\ \bar{y} \\ \bar{z} \end{bmatrix} = \begin{bmatrix} 0.49 & 0.31 & 0.20 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.00 & 0.01 & 0.99 \end{bmatrix} \cdot \begin{bmatrix} \bar{r} \\ \bar{g} \\ \bar{b} \end{bmatrix}$$

Due to the Grassman's third law and Eq.(10) it is convenient to have some average values for representation of colors in the form like αX αY αZ. Because color attributes are related to the relative magnitudes of the tristimulus values. For that purpose new relative tristimulus values we define:

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z} \qquad z = \frac{Z}{X+Y+Z}, \qquad x+y+z=1,$$

where (x, y) – are chromatic coordinates. Now it is possible to represent color in a two-dimensional form. In fact, it is a projection of color on the unit plane X+Y+Z = 1. Such normalization removes information about "intensity" of the colors [34], (Fig. 15). Here is a $\bar{s}(\lambda)$ curve of monochromatic colors with constant radiance, which is projected on the unit plane. Fig. 16. shows the diagram (x, y) [45].

One lack of the (x,y) coordinates is, that the place of black color is not strictly defined. From mathematical point of view this is the point in the XYZ space with zero coordinates, but it is not specified for (x, y) plane.

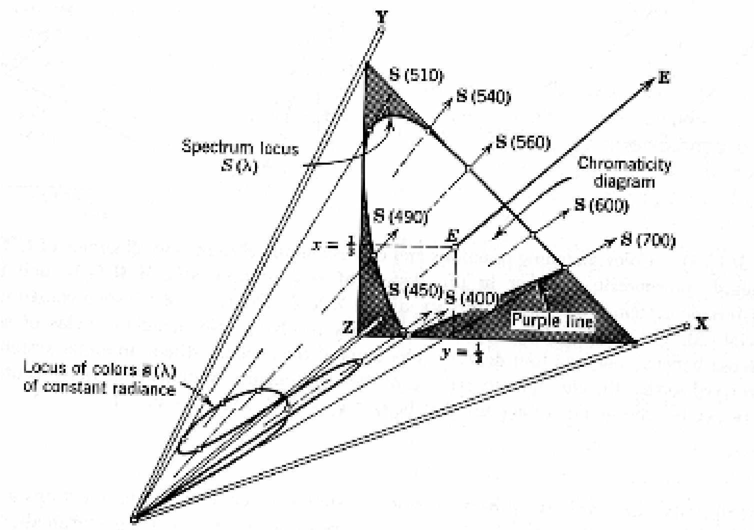


Fig. 15. Color space based on imaginary stimuli X,Y,Z, showing the (x,y) – chromaticy diadram, $\bar{s}(\lambda)$ represents a locus of all monochromatic stimuli of equal-energy stimulus **E.** The vector **E** intersects the chromaticy diagram at the white point with coordinates x=1/3,y=1/3 [45].

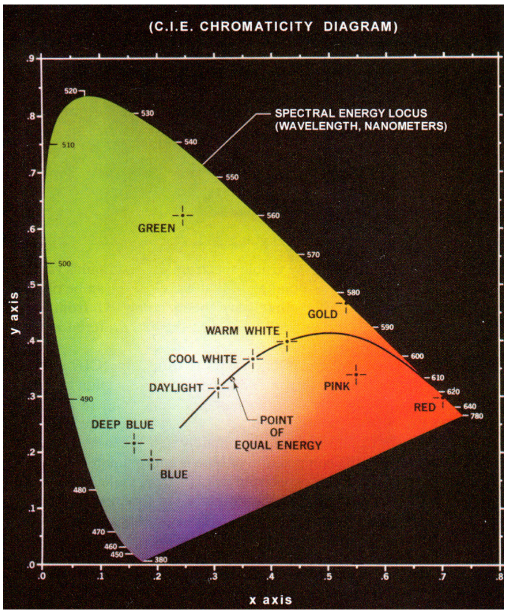


Fig. 16. (x,y) chromaticity diagram [15].

If one links to colors by straight line in the (x,y) chromaticity diagram, then one will mark all possible colors that can be produced as combination of these two colors. Purple line is the line between the stimuli with 380_{nm} and 780_{nm} wavelength. Originally projection curve is not closed.

3.3.2. $L^*a^*b^*$ Color Space

The $L^*a^*b^*$ color space is defined as follows [35], [2], [15]:

$$L^* = 116 f\left(\frac{Y}{Y_n}\right) - 16$$

$$a^* = 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right]$$

$$b^* = 200\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right]$$

$$f(t) = \begin{cases} (t)^{1/3}, & t > 0.008856 \\ 7.787t + \frac{16}{116}, & t < 0.008856 \end{cases}$$

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

$$h_{ab} = \arctan\left(\frac{b^*}{a^*}\right)$$

Here X_n, Y_n, Z_n are corresponding XYZ – tristimulus values for reference white poin, h represents the hue angle and C^* denotes the chroma. Fig. 16 shows the structure of the CIELAB system.

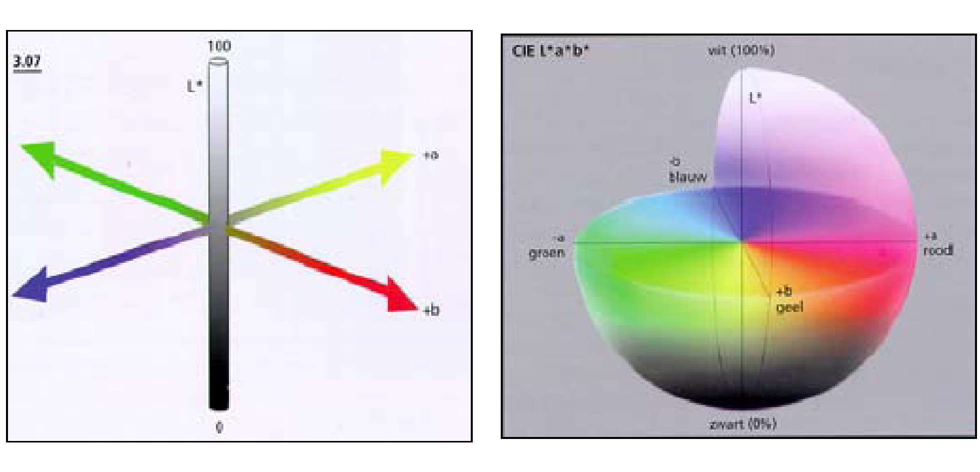


Fig. 17 The CIELAB coordinate system**.**

3.3.3. Munsell Color System

Before every discussion concerning color it is better to make an agreement what do we mean by certain terms, otherwise discussions do not make sense, people won't understand each other or meet confusions. For convenience, there are seeral color order systems to clarify the color notations as different hues, saturation, brightness, and chroma.

One of one of the color order systems was created by Albert H. Munsell. He specified an order of colors by classifying them. He organized ten principal hues, and each principal hue has 10 subhues. Chroma specification was done by selecting samples in a way, that difference between neighbor colors seems the same [34].

Munsell value refers to the lightness. Munsell gave a value "0" for black color and "10" for white color, thus, intermediate grays belong to the range from 0 to 10. For example, if a Neutral Color has Munsell's Value 5 (N5), it means that perceptually this color is at the same distance from white and black. Relation between Munsell Value V and relative luminance Y is defined by the fifth order polynomial [11]:

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

Because it is difficult to solve the inverse equation analytically, there is an approximation to find V as L^* divided by 10, since the CIE lightness scale, L^*, was designed to model the Munsell's system.

The *hue* coordinate in the Munsell system forms a circle. It is divided into 5 main hues: Purple, Blue, Green, Yellow, Red (notation respectively is 5P, 5B, 5G, 5Y, 5R) to divide whole hue circle into equal perceptual intervals.

The Munsell *chroma* scale shows increments from zero for neutral samples to increasing chromas for samples with a hue content, theoretically there is no maximum value for the chroma scaling.

Munsell's idea was to obtain such a color atlas where all samples over each of the three perceptual axes (Hue, Chroma, and Lightness) would be in the same distance from each other. All of his samples were made from reflective surfaces under the daylight illumination.

3.3.4. Uniform Color Space and Color Differences.

If we want to compare colors we need to have some measure for that purpose. In view of assumption linear properties of color mixing it makes sense to define an Euclidian distance as a measure of color difference. To use Euclidian distance we need to have a uniform space. We are interested in uniform space from perceptual point of view as well. Also it is necessary to have numerical value for perceptual changes of color. Munsell samples can be used as a criterion to test the uniformity of a color space. Fig. 18 shows locus of constant Munsell hue and chroma plotted in (x, y) and (a^*,b^*) planes.

The above mentioned two systems of colors would be uniform if locus of constant chroma would form circles and constant hue would be represented as a straight radiant line.

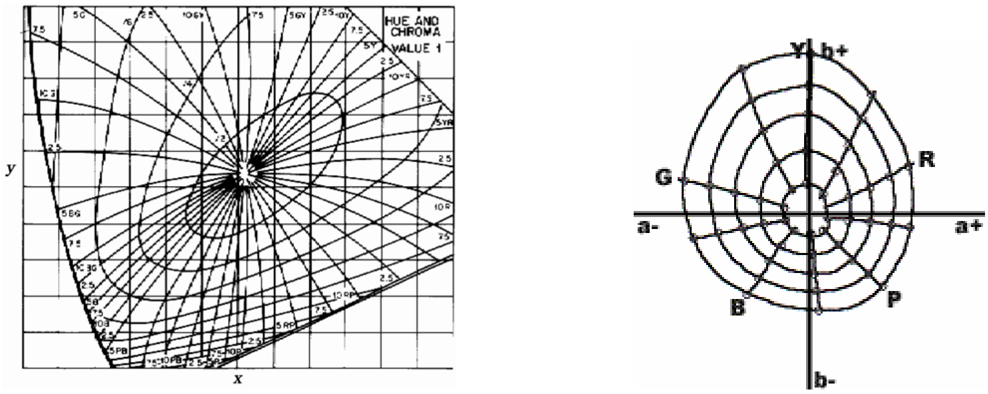


Fig. 18. Musell samples in the (x, y) – chromaticity diagram and in the (a^*,b^*) chroma diagram [45]**.**

One can note from Fig. 18 Lab system is more convenient for calculating colors differences. Formula for the Euclidian distance between CIELAB coordinates of two colors is [35]:

$$\Delta E_{ab}^* = \sqrt{\left(\Delta L^*\right)^2 + \left(\Delta a^*\right)^2 + \left(\Delta b^*\right)^2}$$

Just noticeable color difference, e.g. MacAdam ellipses, is another way to compare color data. From each ellipse it is possible to compute ΔE_{ab}^* that corresponds to 1.96 [35]; if ΔE_{ab}^* in average over the image is no more than 2.2 then colors match perceptually. CIE 1994 color – difference model is an other color difference measure based on the CIELAB space and it is defined by equation:

$$\Delta E_{94}^* = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C^*}{k_C S_C}\right)^2 + \left(\frac{\Delta H_{ab}^*}{k_H S_H}\right)^2}$$

where

$$S_L = 1$$
$$S_C = 1 + 0.045 C_{ab\_s}^*$$
$$S_H = 1 + 0.015 C_{ab\_s}^*$$

where $C_{ab\_s}^*$ is the chroma coordinate of sample from which differences are being computed.

3.4. CIECAM97 Model

CIECAM97 color appearance model consist of three stages [24]:

- Chromatic adaptation transform
- Dynamic response function
- Color space, representation the correlates of the perceptions.

Input of the model:

sample in test conditions (x, y, Y);
adopted white in test conditions (x_w, y_w, Y_w);
background in test conditions (x_b, y_b, Y_b);
reference white in reference conditions (x_{wr}=1/3, y_{wr}=1/3, Y_{wr}=100);
luminance of test adapting field in cd/m^2 L_A is 1/5 of the adapted test white
Surround parameters F, c, F_{LL}, N_c

Output of the model:

prediction of hue H
lightness J;
brightness Q;
saturation s;
chroma C;
colourfulness M.

First test stimulus should be encoded by the visual system – to calculate CIE XYZ coordinates of the test. Then context of the stimulus is taking into account by transforming tristimulus coordinates to coordinates of the adapted cone responses (sensitivities to Short, Middle and Long wavelength under certain conditions). For this purpose we need to set a number of parameters to specify the completeness of adaptation to the viewing context [35].

Second stage – to show relation between adapted cones coordinates and appearance attributes. Signals originating in the three classes of cones are recombined to form a non-opponent achromatic signal and opponent chromatic signals. Each of the opponent signals is formed as a weighted sum of the adapted cone signals; achromatic signal is formed as a weighted sum of three adapted cone signals [35] as follows:

- Red – Green signal is obtained by opposing signals from adapted L and S cones with signals from adapted M cones.

- Yellow – Blue signal is obtained by opposing signals from adapted L and M cones with signals from adapted S cones.

Relation between adapted cone responses and the appearance scales does contain dependencies of the viewing context. The problem with creating a color appearance model that there are a lot of such contexts and conditions with should be consider [35].

Formulas for calculations [24]:

Step 1: Background parameters [34]:

induction factor and chromatic induction factor $N_{bb} = N_{bc} = 0.725(1/n)^{0.2}$

base exponential linearity $z = 1 + F_{LL} n^{1/2}$

background induction factor $n = \frac{Y_b}{Y_w}$

If chromaticities of background are not same as adopted test white, then instead of Y_b and Y_w use Y_{bc} and Y_{wc} .

Calculate for the sample [25], [23]:

$$X = \frac{xY}{y}, \qquad Y, \qquad Z = \frac{Y(1-x-y)}{y}, \qquad \frac{X}{Y}, \frac{Y}{Y}, \frac{Z}{Y}$$

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = M_{BFD} \begin{pmatrix} X/Y \\ Y/Y \\ Z/Y \end{pmatrix} \qquad M_{BFD} = \begin{pmatrix} 0.8951 & 0.2664 & -0.1614 \\ -0.7502 & 1.7135 & 0.0367 \\ 0.0389 & -0.0685 & 1.0296 \end{pmatrix}$$

in a similar manner one calculates R_w, G_w, B_w from x_w, y_w, Y_w,
R_b, G_b, B_b from x_b, y_b, Y_b,
R_{wr}, G_{wr}, B_{wr} from x_{wr}, y_{wr}, Y_{wr}

Step 2: Degree of chromatic adaptation, D:

$$D = F - \frac{F}{\left(1 + 2L_A^{1/4} + \frac{L_A^2}{300}\right)}$$

If illuminant color is completely discounted D = 1, and if there is no chromatic adaptation D = 0.

Step 3: Calculating values of sample under reference conditions:

$$R_c = \left(D\frac{R_{wr}}{R_w} + 1 - D\right)R$$

$$G_c = \left(D\frac{G_{wr}}{G_w} + 1 - D\right)G$$

$$B_c = \left(D\frac{B_{wr}}{B_w^p} + 1 - D\right)\left|B\right|^p, \ p = \left(\frac{B_w}{B_{wr}}\right)^{0.0834}$$, B and B_c must be of same sign

in a similar manner calculate R_{wc}, G_{wc}, B_{wc} from R_w, G_w, B_w,
R_{bc}, G_{bc}, B_{bc} from R_b, G_b, B_b

Step 4: $F_L = 0.2k^4(5L_A) + 0.1(1-k^4)^2(5L_A)^{1/3}$, where $k = 1/(5L_A + 1)$

$$\begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} = M_H M_{BFD}^{-1} \begin{pmatrix} R_c Y \\ G_c Y \\ B_c Y \end{pmatrix} \qquad M_H = \begin{pmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} R'_w \\ G'_w \\ B'_w \end{pmatrix} = M_H M_{BFD}^{-1} \begin{pmatrix} R_{wc} Y_w \\ G_{wc} Y_w \\ B_{wc} Y_w \end{pmatrix} \qquad M_{BFD}^{-1} = \begin{pmatrix} 0.98699 & -0.14705 & 0.15996 \\ 0.43231 & 0.51836 & 0.04929 \\ -0.00853 & 0.04004 & 0.96849 \end{pmatrix}$$

$$Y_{bc} = Y_b(0.43231R_{bc} + 0.51836G_{bc} + 0.04929B_{bc})$$
$$Y_{wc} = Y_w(0.43231R_{bc} + 0.51836G_{bc} + 0.04929B_{bc})$$

$$R'_a = \frac{40\left(\frac{F_L R'}{100}\right)^{0.73}}{\left(\frac{F_L R'}{100}\right)^{0.73} + 2} + 1 \quad G'_a = \frac{40\left(\frac{F_L G'}{100}\right)^{0.73}}{\left(\frac{F_L G'}{100}\right)^{0.73} + 2} + 1 \quad B'_a = \frac{40\left(\frac{F_L B'}{100}\right)^{0.73}}{\left(\frac{F_L B'}{100}\right)^{0.73} + 2} + 1$$

in a similar manner one calculates $R'_{aw}, G'_{aw}, B'_{aw}$ from R'_w, G'_w, B'_w

if $R' < 0$ then $R'_a = -\frac{40\left(\frac{-F_L R'}{100}\right)^{0.73}}{\left(\frac{-F_L R'}{100}\right)^{0.73} + 2} + 1$ and similarly for R'_{aw}, G, B .

Step 5:

Redness – Greenness $a = R'_a - \frac{12}{11} G'_a + \frac{1}{11} B'_a$

Yellowness – Blueness $b = \frac{1}{9}\left(R'_a + G'_a - 2B'_a\right)$

Hue angle $h = \arctan\frac{b}{a}$

Step 6: Hue quadrature with help of unique data:

	Red	***Yellow***	***Green***	***Blue***
h	20.14	90.00	164.25	237.53
e	0.8	0.7	1.0	1.2

$e = e_1 + (e_2 - e_1)\frac{h - h_1}{h_2 - h_1}$, where e_1 and h_1 are the nearest lower values of e and h; e_2 and h_2 represent nearest upper values respectively.

Hue quadrature $H = H_1 + 100\frac{(h - h_1)/e_1}{(h - h_1)/e_1 + (h_2 - h)/e_2}$

If the nearest lower:

	Red	***Yellow***	***Green***	***Blue***
H_1	0	100	200	300

Step 7: lightness J

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

where $$A = N_{bb}\left(2R'_a + G'_a + \frac{1}{20}B'_a - 2.05\right)$$

$$A_w = N_{bb}\left(2R'_{aw} + G'_{aw} + \frac{1}{20}B'_{aw} - 2.05\right)$$

Step 8: brightness Q

$$Q = \frac{1.24}{c}\left(\frac{J}{100}\right)^{0.67}\left(A_w + 3\right)^{0.9}$$

Step 9: saturation s

$$s = \frac{50\left(a^2 + b^2\right)^{1/2} 100e\frac{10}{13}N_c N_{cb}}{R'_a + G'_a + \frac{21}{20}B'_a}$$

Step 10: chroma C

$$C = 2.44s^{0.69}\left(\frac{J}{100}\right)^{0.67n}\left(1.64 - 0.29^n\right)$$

Step 10: colourfulness M

$$M = CF_L^{0.15}$$

4. Structure of the Monitor

4.1. CRT Monitor

Cathode Ray Tube is a glass bulb with electron-beam guns in its orifice. There are tree guns – one gun for each primary color (Representation of the color is based on the RGB system). In front of these guns or the bottom of this bulb is covered with phosphor (face plate). See Fig. 19.

Electron beam gun consist of economizer, emissive cathode and grid which accelerates and focuses electrons. Economizer provides heating of the Cathode till 850 ^{o}C, and then electron emission from the surface of the Cathode begins. Other electrodes are needed to form beam of electrons. Video input voltage (corresponding DAC values in GOG model, see chapter 5.2) is applied to each of three electron guns to form an electron beam for the corresponding color (for each primary i.e. R, G, and B phosphor a particular voltage is applied).

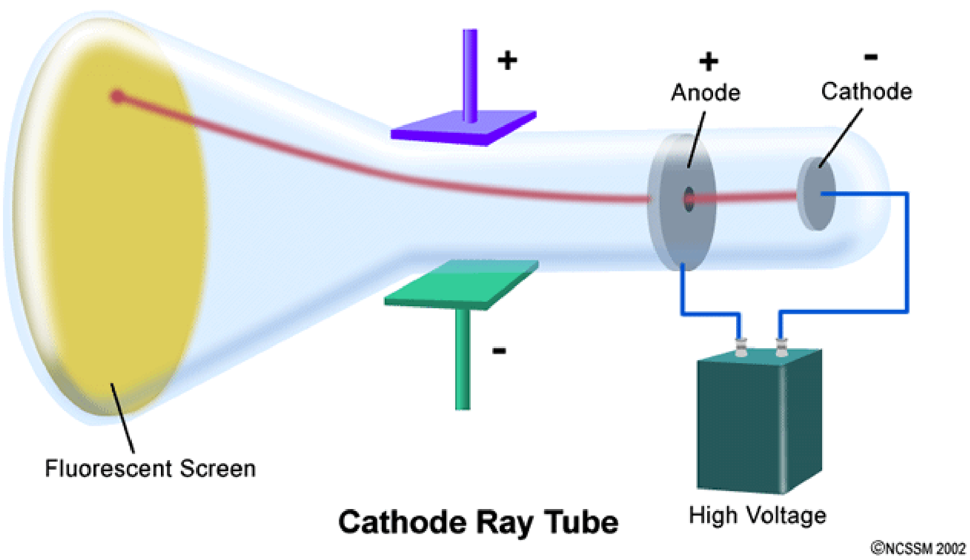


Fig. 19. Sketch of the CRT monitor structure [39].

When the Gun is heated enough it shoots constant flow of electrons. These electrons with high speed moves towards the faceplate. They go through the electromagnetic coils – one of them for the focusing and other for the deflection the beam. Also, coils prevent the scattering of electrons which can lead to the not sufficient contrast and intensity representation of the image. When phosphor absorb an electron it starts shining (emit light) actually this light we see. This process is called cathodoluminescence [35].

After electrons are directed by electromagnets they need to pass a mask. The purpose of mask is to provide properly hitting places on the screen by electrons.

Mask can be one of three kinds:

- *Dot trio shadow masks* are perforate metal planes with uniform located set of round dots. These holes consist of three phosphors – Red, Green and Blue, called triads. Under flow of electron beams these dots start emitting. When intensity of each ray is changing then color of a pixel is changing (pixel which is formed by this triad). Monitors with such mask have rich colors, sharp representation of text and they are cheap, but screen is not flat, therefore resulting flashes [21], [31].

- *Slot mask.* In this case phosphor on the surface has a form of stripes and mask is a metal plane with chinks. Each chink has its own triad. Such technology has same advantages as in the previous case.
- *Aperture grill.* Now phosphor is applied on the surface as stripes and in guns magnetic quadrupoles are used. These magnetic quadrupoles provide to form a thin and accurately directed electron beam [31], [29]. In this technology wire grate is used. In this case monitor is flat, brightness and contrast are high. Aperture grid was investigated by Sony Company, and it is called Trinitron technology.

4.2. Structure of the Thin-Film Transistor Liquid Crystal Display (TFT - LCD)

How colors are formed. After a beam of fluorescent light (backlight) is passed through the liquid crystals, it reaches a color filter. This color filter is in the upper glass. Each individual pixel has three color filter elements RGB (Red, Green and Blue). The color of each pixel is varied by adjustment of the proportion of the three primary colors [6].

Liquid crystal is substance that behaves like a solid body at one condition and like a liquid at the other one. That is possible because liquid crystals change their crystal grade in different conditions. In this case behavior of the LC is specified by the drive voltage. While there is no voltage liquid crystals are in amorphous form. When voltage appears LC changes orientation and refract polarized light in necessary direction, and also this controls intensity of the light (luminance).

Polarization. We consider light as an electromagnetic wave. Normal or non-polarized light oscillates in multiple directions. Lineary polarized light oscillates only in one direction. It is necessary to polarize light before it goes through the crystals. Two sheets of polarizes are aligning LC in twist pattern. The bottom polarizer layer is aligned in opposite direction with respect to the top polarizer layer [29].

So, when we vary the voltage we vary the behavior of LC and, hence, we change light pass through the system.

TFT (thin-film transistor). A LCD may contain either a *passive matrix* or *an active matrix* display grid.

An *active matrix* has a transistor (diode) located at each pixel intersection. It requires less current to control the luminance of each pixel. Due to that such a matrix can change switch state frequently. This possibility improves the screen refresh time. Amount of pixels defines the resolution of the screen.

A *passive matrix* LCD has a grid of conductors, where pixels are located at each intersection of the grid. On the TFT LCD panel, a data source drive is attached to each column while a gate drive is attached to each row. Each cell's TFT drain is connected to the electrode [29].

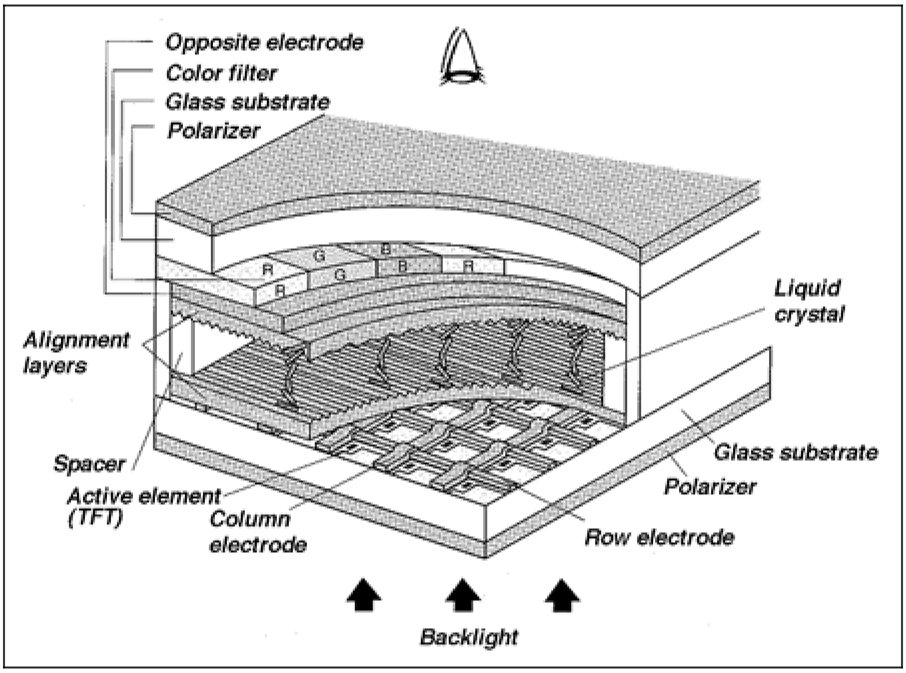


Fig. 20. Structure of the LCD [27].

5. Device Characterization

5.1. sRGB Model

In our days there are a lot of devices that use digital representation of images. Several of them just show pictures, some of them make pictures, others – simulate them. Very often it is needed to transfer an image from one device to another, for instance, from computer to paper via printer (it is assumed that user wants to produce similar image on the paper as he sees on the monitor), or, on a broadcasting TV – many users should receive the same image from one source and all of them have their own slightly different devices [46]. Usually, every device has its own features and quirks. So, the question is how to map color information from one color space into another [12]. One solution is to attach a profile, but people are not interested to go into the matter in greater details of the mechanism of passing information. As a simplification it makes sense to create a single color space, make as standard default ICC RGB implicit profile, especially it is interesting when we are speaking about representating image on the screen, because :

- Most computer displays are technically similar – the phosphor chromaticity and transfer functions are similar.
- RGB spaces are native to displays, scanners and digital cameras.
- RGB spaces can describe enough colors for common applications [36].

For the definition of the sRGB color space we need to take into account viewing environment i.e. reference conditions:

- *Reference display conditions*
    1. Luminance level 80 cd/m^2
    2. White point D_{65}, x=0.3127, y=0.3291
    3. Phosphors ITU-R BT.709:

	Red	Green	Blue
x	0.6400	0.3000	0.1500
y	0.3300	0.6000	0.0600
z	0.0300	0.1000	0.7900

4. Display model offset of R,G, and B is 0.055
5. Display gamma parameter of Gun-phosphor is 2.4; display is characterized by equation:

$$V_{sRGB} = \left[\left(V'_{sRGB} + 0.055 \right) / 1.055 \right]^{2.4} \tag{11}$$

- *Reference viewing conditions* [38]*:*
  1. Background. As part of the display screen, the background is 20% of the reference display maximum white luminance level (can be approximated by L^*=50 in CIELAB color space)
  2. Surrounding. 20% ferlectance of the reference ambient illuminance level.
  3. Proximal field. 20% reflectance of the reference display luminance level.
  4. Ambient illuminant level: 64 lux.
  5. Ambient white point D_{50}: x=0.3457, y=0.3585
  6. Viewing flare: 1%

- Reference observer:
  CIE 1931 standard observer
- Color appearance model :
  CIE CAM97s [37]

The relationship between sRGB and CIEXYZ color coordinate systems are defined as follows:

$$R'_{sRGB} = R_{8bit} / 255$$
$$G'_{sRGB} = G_{8bit} / 255$$
$$B'_{sRGB} = B_{8bit} / 255$$

Where $sR'G'B'$ values represent the appearance of image on the reference monitor in reference environment, and R_{8bit} represents 8 bit RGB value.

If $R'_{8bit}, G'_{sRGB}, B'_{8bit} \leq 0.03928$, then:

$$R_{sRGB} = R'_{sRGB} / 12.92$$
$$G_{sRGB} = G'_{sRGB} / 12.92$$
$$B_{sRGB} = B'_{sRGB} / 12.92$$

If $R'_{8bit}, G'_{sRGB}, B'_{8bit} > 0.03928$, then according to Eq. (11):

$$R_{sRGB} = \left[\frac{R'_{sRGB} + 0.055}{1.055} \right]^{2.4}$$
$$G_{sRGB} = \left[\frac{G'_{sRGB} + 0.055}{1.055} \right]^{2.4}$$
$$B_{sRGB} = \left[\frac{B'_{sRGB} + 0.055}{1.055} \right]^{2.4}$$

Transformation between $(X, Y, Z)^T$ and $(R_{sRGB}, G_{sRGB}, B_{sRGB})^T$ is

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \begin{bmatrix} R_{sRGB} \\ G_{sRGB} \\ B_{sRGB} \end{bmatrix}$$

And the inverse transformation from CIEXYZ to sRGB is [18]:

$$\begin{bmatrix} R_{sRGB} \\ G_{sRGB} \\ B_{sRGB} \end{bmatrix} = \begin{bmatrix} 3.2410 & -1.5374 & -0.4986 \\ -0.9692 & 1.8760 & 0.0416 \\ 0.0556 & -0.2040 & 1.0570 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

Values of sRGB belongs to [0,1], usually if some values are below zero they are substituted by 0 and if they are over then one , they are substituted by one.

5.2. Gain – Offset – Gamma Model

Notation:

DAC – Digital to Analog Converter
n – number of DAC bits
V_p – video voltage p, where component $p \in \{R, G, B\}$
V_{min} – minimum video voltage
V_{max} – maximum video voltage
$V_{c,p}$ – cutoff voltage of a component p
i_p – electron beam current
M_p – spectral radiant exitance of the phosphor emission
$V_{q,p}$ – grid voltage
a_p – channel gain
b_p – channel offset
$k_{gamma,p}$ – model gamma coefficient
$k_{gaine,p}$ – model gain coefficient
$k_{offset,p}$ – model offset term

There is a model developed by Bern's, Gorzynski and Motta for CRT (Cathode Ray Tube) monitors. This model defines relationship between the emitted spectral radiant exitance and digital counts [21]:

1. Digital information is quantized to video voltage V_p in the DAC. DAC determinates the number of quantization levels. The range of the quantization levels is from 0 to $2^n - 1$. The DAC value d_p is linearly proportional to V_p :

$$V_p = \left(V_{max} - V_{min}\right)\frac{d_p}{2^n - 1} + V_{min} \tag{12}$$

2. The video amplifiers transform the positive V_p into negative voltage $V_{g,p}$:

$$V_{g,p} = a_p V_p + b_p \tag{13}$$

3. Dependency between the current of the electron beam and the amplified video voltage is nonlinear:

$$i_p = \left(V_{g,p} - V_{c,p}\right)^{k_{gamma}} \qquad V_{c,p} < V_{g,p}$$
$$i_p = 0 \qquad V_{c,p} > V_{g,p} \tag{14}$$

4. There is a linear relation between the phosphor emissions measured in radiometric terms and beam current. ($k_{\lambda,p}$ – is a spectral constant for particular CRT phosphor):

$$M_{\lambda,p} = k_{\lambda,p} i_p \tag{15}$$

5. Summarizing formulas (12)-(15) we have defined the dependency between of the radiant exitance and digital counts:

$$M_{\lambda,p} = k_{\lambda,p}\left(a_p \cdot \left[\frac{\left(V_{\max} - V_{\min}\right)d_p}{2^n - 1} + V_{\min}\right] + b_p - V_{c,p}\right)^{k_{gamma,p}} \tag{16}$$

6. Maximum value of the spectral radiant exitance:

$$M_{\lambda,p,\max} = K_{\lambda,p}\left(a_p V_{\max} + b_p - V_{c,p}\right)^{k_{gamma,p}} \tag{17}$$

The constants $k_{gain,p}$ and $k_{offset,p}$ as defined by:

$$k_{gain,p} = \frac{a_p\left(V_{\max} - V_{\min}\right)}{a_p V_{\max} + b_p - V_{c,p}}$$

$$k_{offset,p} = \frac{a_p V_{\max} + b_p - V_{c,p}}{a_p\left(V_{\max} - V_{\min}\right)} \tag{18}$$

$$k_{offset,p} + k_{gain,p} = 1$$

If we normalize (16) by (17) and use notation (18) we will have [21], [2]:

$$\frac{M_{\lambda,p}}{M_{\lambda,p,\max}} = \left(\frac{k_{gain,p} d_p}{2^n - 1} + k_{offset,p} \right)^{k_{gamma,p}} \tag{19}$$

CRTs can be considered as a Lambertian radiator within typical viewing angles. Because spectral radiance is constant over viewing angel, it is possible to derive the relation between spectral radiance, L_λ, and spectral exitance, M_λ:

$$L_\lambda = \frac{M_\lambda}{\pi} \tag{20}$$

Equations (19) and (20) define dependency between L_λ and d_p :

$$L_{\lambda,p} = \begin{cases} L_{\lambda,p,\max} \cdot \left(\frac{k_{gain,p} \cdot d_p}{2^n - 1} + k_{offset,p} \right)^{k_{gamma,p}} & if \quad \left(\frac{k_{gain,p} \cdot d_p}{2^n - 1} + k_{offset,p} \right) \geq 0 \\ 0 & if \quad \left(\frac{k_{gain,p} \cdot d_p}{2^n - 1} + k_{offset,p} \right) < 0 \end{cases} \tag{21}$$

If $f(\lambda)$ is a spectral radiant power distribution or in this case radiance spectrum, then according to Eq.(3):

$$\begin{aligned} X &= \int_\lambda f(\lambda)\bar{x}(\lambda)d\lambda \\ Y &= \int_\lambda f(\lambda)\bar{y}(\lambda)d\lambda \\ Z &= \int_\lambda f(\lambda)\bar{z}(\lambda)d\lambda \end{aligned} \tag{22}$$

For discrete data, integration is replaced by summation and if the radiance spectrum and the color-matching functions are considered as column vectors, equations (22) can be expresses in following form:

$$
\begin{aligned}
X &= \bar{x}^T f \Delta\lambda \\
Y &= \bar{y}^T f \Delta\lambda \\
Z &= \bar{z}^T f \Delta\lambda
\end{aligned} \tag{23}
$$

Because channel constancy was assumed by Eq. (15), each channel can be scaled by its maximum. Scalars R,G, and B can be written as [3]:

$$
R = \frac{\int_\lambda L_{\lambda,r} S_\lambda d\lambda}{\int_\lambda L_{\lambda,r,\max} S_\lambda d\lambda} \qquad G = \frac{\int_\lambda L_{\lambda,g} S_\lambda d\lambda}{\int_\lambda L_{\lambda,g,\max} S_\lambda d\lambda} \qquad B = \frac{\int_\lambda L_{\lambda,b} S_\lambda d\lambda}{\int_\lambda L_{\lambda,b,\max} S_\lambda d\lambda} \tag{24}
$$

where S_λ is detector's spectral response. These scalars can be approximated by:

$$
R = \frac{X}{X_{\max}} \qquad G = \frac{Y}{Y_{\max}} \qquad B = \frac{Z}{Z_{\max}} \tag{25}
$$

R,G,B are functions of DAC values d_r, d_g, d_b correspondingly,and

$$
R = \begin{cases} \left(\dfrac{k_{gain,red} d_r}{2^n - 1} + k_{offset,red} \right)^{k_{gamma,red}} & if \quad \left(\dfrac{k_{gain,red} d_r}{2^n - 1} + k_{offset,red} \right) \geq 0 \\ 0 & if \quad \left(\dfrac{k_{gain,red} d_r}{2^n - 1} + k_{offset,red} \right) < 0 \end{cases} \tag{26}
$$

$$G = \begin{cases} \left(\frac{k_{gain,green} d_g}{2^n - 1} + k_{offset,green} \right)^{k_{gamma,green}} & if \quad \left(\frac{k_{gain,green} d_g}{2^n - 1} + k_{offset,green} \right) \geq 0 \\ 0 & if \quad \left(\frac{k_{gain,green} d_g}{2^n - 1} + k_{offset,green} \right) < 0 \end{cases} \quad (27)$$

$$B = \begin{cases} \left(\frac{k_{gain,blue} d_b}{2^n - 1} + k_{offset,blue} \right)^{k_{gamma,blue}} & if \quad \left(\frac{k_{gain,blue} d_b}{2^n - 1} + k_{offset,blue} \right) \geq 0 \\ 0 & if \quad \left(\frac{k_{gain,blue} d_b}{2^n - 1} + k_{offset,blue} \right) < 0 \end{cases} \quad (28)$$

Corresponding formulas for DAC values d_r, d_g, d_b inverted from equations (26)-(28) are:

$$d_r = \frac{2^n - 1}{k_{gain,red}} \left(R^{\frac{1}{k_{gamma,red}}} - k_{offset,red} \right) \qquad if \qquad 0 \leq R \leq 1$$

$$d_g = \frac{2^n - 1}{k_{gain,green}} \left(G^{\frac{1}{k_{gamma,green}}} - k_{offset,green} \right) \qquad if \qquad 0 \leq G \leq 1 \qquad (29)$$

$$d_b = \frac{2^n - 1}{k_{gain,blue}} \left(B^{\frac{1}{k_{gamma,blue}}} - k_{offset,blue} \right) \qquad if \qquad 0 \leq B \leq 1$$

The relation between scalars R,G,B and XYZ – tristimulus values is defined by linear transformation:

$$\begin{bmatrix} R(d_r) \\ G(d_g) \\ B(d_b) \end{bmatrix} = \begin{bmatrix} X_{r,\max} & X_{g,\max} & X_{b,\max} \\ Y_{r,\max} & Y_{g,\max} & Y_{b,\max} \\ Z_{r,\max} & Z_{g,\max} & Z_{b,\max} \end{bmatrix}^{-1} \cdot \left[\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} - \begin{bmatrix} X_{reflection} \\ Y_{reflection} \\ Z_{reflection} \end{bmatrix} \right] \tag{30}$$

Where vector $[X_{reflection} \;\; Y_{reflection} \;\; Z_{reflection}]^T$ is the stimuli of light reflected from the surface of the monitor under viewing conditions.

Another well know characterization model is three dimesional Lookup Table (LUT). This method also provides mapping stimuli from XYZ coordinate color system into device space and vice versa, but this method required a lot of measurements and is very difficult in calculation the inverting matrixes. Since for the characterization the CRT colorimetric behavior it is enough to know some measured data and for other points makes a linear interpolation (as most accurate one approximation [21], [1]). The three dimensional LUT model can be simplified to one dimensional as:

$$\begin{bmatrix} R(d_r) \\ G(d_g) \\ B(d_b) \end{bmatrix} = \begin{bmatrix} X_{r,\max} & X_{g,\max} & X_{b,\max} \\ Y_{r,\max} & Y_{g,\max} & Y_{b,\max} \\ Z_{r,\max} & Z_{g,\max} & Z_{b,\max} \end{bmatrix}^{-1} \cdot \left[\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} - \begin{bmatrix} X_{offset} \\ Y_{offset} \\ Z_{offset} \end{bmatrix} - \begin{bmatrix} X_{reflection} \\ Y_{reflection} \\ Z_{reflection} \end{bmatrix} \right] \tag{31}$$

Where $[X_{offset} \;\; Y_{offset} \;\; Z_{offset}]^T$ is a stimuli obtained from the surface of the screen when device is switched off, $[X_{reflection} \;\; Y_{reflection} \;\; Z_{reflection}]^T$ is stimuli of light reflected from the surface of the monitor under predefined viewing conditions. The 1-D model has been widely used for CRT monitors but has been criticized for its assumption of channel independence [1].

6. Image's Visual Quality Estimation

6.1. Memory Color

Have you ever tried to explain what is "white" for a blind from birth person? What is your first though when you hear word "red"? It is not a thing, it is like a taste or smell, it is something which you can recognize and what is clear and common for you, but it is difficult to describe. We have very similar feelings when we are looking at photos which we have taken. We look at the picture and see in our mind that scene what were there; actually we just help to recollect out of brain that scene what we had on the moment when picture was made. Is it just an association or something more? Then naturally other questions arise – how do we percept a picture, if we have never seen represented place or objects in real life? What things look naturally for us and what does not.

There are many works done in this field, but there is not yet a solid theory which can answer to question what kind of information we keep in our minds by color experience [32]. We just know by the latest investigations that particular sensitivities to certain colors and invent such a phenomenon as memory of color and shifting color idea due to memory experience [17], [4], [28]. Also there were found empirically several dependencies of the perception of color and association between colors and objects. For example, we use to see grass. We use to see green grass in summer time, yellow and almost brown in the autumn, no grass in winter and a bit yellowish in spring time. We have certain idea how should a tomato look like when it is ripe. It has special tint of red. And actually if we have not touched this tomato the color of the vegetable is only one thing to make judgments. Actually it is a vitally important factor – the color of the object, *hue* of the color. I am doubt that a lot of people dare to buy a blue tomato or even magenta one [17].

Interesting remark about cause-effect relation: if we wake up in the morning and see brownish grass, but we remember that yesterday it was rich green color would we think that autumn has come? Well if it is September – yes but what if it is July? So, here appears one more factor – the context of the current color, or better to say concomitant [5].

Then there is another property of color that is also important – the tone reproduction or correctness of lightness. Here can be confusions due to big differences with background and considered color. This color-appearance phenomenon is called simultaneous contrast or *induction* [11] see Fig. 21.

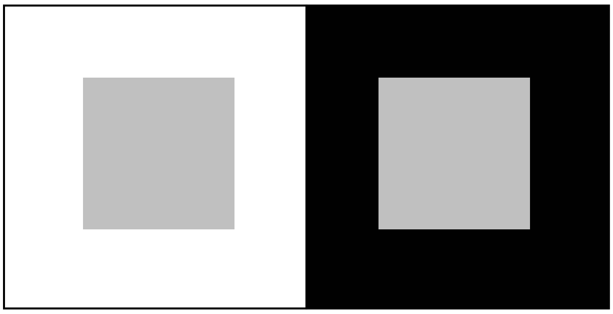


Fig. 21. When background is changed it causes a shift of stimulus in color appearance.

Related effects are:

- *crispening* – increasing perceptually of the sample area if background color is close to the samples stimuli

- *spreading* – evident merging of stimuli color and its surround [11]

Variations of *colorfulness* are playing not last role in judgment. On the example with tomato it will sound like "this tomato looks like not to be ripe" if color of the vegetable is pale or not enough saturated, or if we see whitish grass we get an feeling that it is foggy.

So, the summary of all said above factors that affect on color appearance (they are listed in order of priority according to Hunt's book [17]) is:

1. Correctness of hue
2. Correctness of lightness (tone reproduction)
3. Colorfulness and color balance
4. Brightness

6.2. Pairs Comparison

The method of paired comparison is constituted of consecutive pairs of samples to observer and asking the observer which one of the pair he prefers (looks better, looks acceptable etc). Let's assume that there are n samples and now sample i and j (i>j) are compared. If user choose from current pair sample j to look better on PDA screen, we need to put 1 in the j^{th} column and i^{th} row. When we ask all users we will have information how many times j object was preferred over i. This information will be in matrix of frequencies **F** where in each location f[i,j] is a number of observers who made same choice.

Proportion matrix, **P,** is formed by dividing each element of matrix **F** by the total amount of observers that assess the pair. In case of different amount of observers one could define the relationship:

$$p_{ij} = \frac{f_{ij}}{f_{ij} + f_{ji}} \qquad (32)$$

The proportion matrix **P** is needed to generate an interval scale value. Proportion of times that i sample judged greater than j sample is an indirect measure of distance in psychometric scale between i and j samples. In statistical theory the expectation value characterizes random values, so, the expectation value of difference of two random variable i and j is a difference between scale values X_i and X_j , i.e. $X_i - X_j$.

Probability Theory contains so-called *central limit theorem*. It says that if we have a situation which consists of many events, where each of these events is a variate, the probability distribution of their sum (in other words Probability Density Function) with the increasing amount of the events converges to the normal distribution.

Thurstone (1927) [10] assumed that sampling process is a random variable whose probability in density function is Gaussian. Thurstone call it "discriminal process". "Discriminal dispersion" – standard deviation or spread of the observes' responses. The difference of two samples is described by the variance:

$$\sigma^2(X_i - X_j) = \sigma_i^2 + \sigma_j^2 - 2\rho\sigma_i\,\sigma_j \qquad (33)$$

where $\rho \in [-1,+1]$ is correlation between X_i and X_j, and σ_j, σ_i - corresponding standard deviations of X_i and X_j

Difference of scale values can be normalized by dividing the standard deviation, result will be in terms of z-values:

$$Z_{ij} = \frac{X_i - X_j}{\sqrt{\sigma_i^2 + \sigma_j^2 - 2\rho\sigma_i\sigma_j}} \qquad (34)$$

From math *measure of accuracy* (PDF of x - mistake, random variable)is :

$$\varphi(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-x^2}{2\cdot\sigma^2}} \qquad (35)$$

σ^2 is called as *parameter* of the Normal distribution law. While σ^2 is increasing the maximum of $\varphi(x)$ is decreasing. Maximum is at point x=0 and equals to $1/\sigma\sqrt{2\pi}$ [8].

Thurstone's assumption that PDF of the discriminal difference process has Gaussian form, N(0,1). It is used now to show the relationship between scale values and probability of $\Pr(X_i > X_j)$ i.e. that the sample X_i would be preferred over X_j in the pair. For that purpose we need to consider the area under line of the curve of the PDF, see Fig.21. These two areas can be expressed by formulas:

$$\Pr\left(X_i \succ X_j\right) = \frac{1}{\sigma_{i-j}\sqrt{2\pi}} \int_0^{+\infty} e^{-\frac{1}{2}\left(\frac{t-(X_i - X_j)}{\sqrt{\sigma_i^2+\sigma_j^2-2\rho\sigma_i\sigma_j}}\right)} dt \qquad (36)$$

Using Eq.(34) results:

$$\Pr\left(X_i \succ X_j\right) = \frac{1}{\sqrt{2\pi}} \int_{-z_{ij}}^{\infty} e^{-t^2} dt = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z_{ij}} e^{-t^2} dt \qquad (37)$$

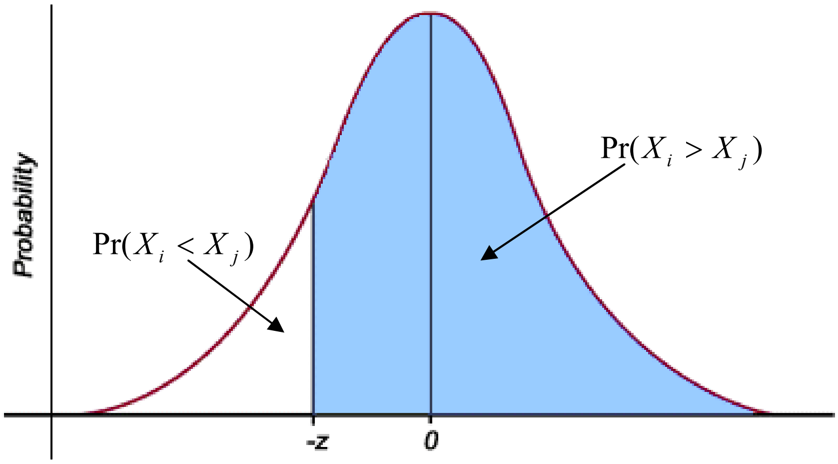


Fig. 22. Proportion of probabilities**.**

Thurstone developed an expression for the scale value difference (Law of Comparative Judgement):

$$X_i - X_j = Z_{ij}\sqrt{\sigma_i^2 + \sigma_j^2 - 2\rho\sigma_i\,\sigma_i} \tag{38}$$

For solving this problem Thurstone made several simplifying assumptions. In this work so-called case V was used:

$$\begin{aligned} &\rho = 0 \\ &\sigma_i^2 = \sigma_j^2 = \sigma \\ &X_i - X_j = Z_{ij} \cdot \sigma\sqrt{2} \end{aligned} \tag{39}$$

Because the empirical proportion is used as the estimate of the probability of chosen sample over another can be written [10]:

$$\Pr(X_i \succ X_j) = \Phi(z_{ij}) \tag{40}$$

From Eq.(39) and Eq.(40) one has:

$$z_{ij} = \Phi^{-1}(\,\Pr(X_i \succ X_j)\,)\,, \tag{41}$$

where $$\Phi(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{-t^2} dt$$

After using Eq.(41) to transform each element of the matrix P we have matrix S (of scale value difference):

$$S = \begin{bmatrix} X_1 - X_1 & X_2 - X_1 & \dots & X_n - X_1 \\ X_1 - X_2 & X_2 - X_2 & \dots & X_n - X_2 \\ X_1 - X_3 & X_2 - X_3 & \dots & X_n - X_3 \\ \vdots & \vdots & \dots & \vdots \\ X_1 - X_n & X_2 - X_n & \dots & X_n - X_n \end{bmatrix}$$

Here n is number of samples. Sum of the first column of S matrix divided by the number of samples is:

$$\frac{1}{n}\sum_{i=1}^{n}\left(X_1 - X_i\right) = \left(X_1 - \overline{X}\right) \tag{42}$$

If $\overline{X} = 0$ then the column sums give scale value directly: $X_1 - 0 = X_1$. Due to we use statistic approach, if in matrix **F** we have a sample that was chosen by total amount of interviewers, then it should be replaced by its approximate value so, that the total sum with the opponent sample (which was not chose by any interviewer) frequency (which is equal to 0) would be satisfy equation $f_{ij} + f_{ji} = J$,where J in total amount of interviewers of this pair.

7. Experiment

7.1. Aim of the Experiment

The purpose of the experiment was to characterize a DPA Pocket PC COMPAQ IPAQ with traditional techniques that have been applied to CRT monitors and find out whether they are applicable to the PDA. To characterize screen of the monitor means to determine its performance i.e. to find primaries of the device, to check additive properties, and to fix the dependencies between DAC values per scalars of each channel. PDA was equipped with two fine tuning regulators: "Battery" and "Power". This device was studied in two modes: first mode both parameters were set to the maximum value; second one with half of the maximum.

Other part of the experiment was to make human tests on this Pocket PC with purpose to evaluate color accuracy representation. The idea was to discover how good PDA represents color images which are shown on paper. There were done several, and if to be precise – three, ways to represent an original image on the iPAQ, one of them used classical Gain Offset Gamma model to create RGB image to show one more time if traditional technique is applicable. Users' task was to choose what representation of the original image looks better on DPA from their point of view and to write brief comments what harms of color do they see if they had mentioned some. In this experiment a psychometric scaling method, Paired Comparison was used.

7.2. Characterization of the Monitor

The monitor characterization follows the procedure of reference [2]:

- First was created a sixteen-step ramp from 0-255 digital counts. This ramp data was used for red, green, and blue channels, as well as combined to create a neutral ramp. Each slice of color was made in Matlab 6.5 as 240x320 pixel BMP format files. Ramp data was sequentially displayed on the screen of the PDA and their radiance data were obtained using the Spectra Scan PR705. All measurements were done in darkness and all equipment was warmed up as necessary.

- Then with help of this information additive property of the device was checked. It was made by comparing curves of the relative power distribution of neutral samples with corresponding sum of primary colors.

- Next stage to find dependencies between DAC values and scalars of corresponding primary channel. According to GOG model there were found coefficients *gain, gamma, offset*, see formula (18) in paragraph 5.2.

This procedure was made two times i.e. it was chosen two work modes of the PDA as explained above. Amount of ramping slices is 16 for each primary channel and 7 for neutral data.

7.3. Setup of the Experiment with Users

The main idea was to simulate work conditions of user with the PDA. It was assumed that majority of work takes place under the daylight, so, the paired comparison experiment and selecting areas of color distortion was in room with a simulation of the daylight.

In both cases surfaces of the PDA and original picture were on same plane level with respect to the user's eyes. Look of the user was straight to the screen of Pocket PC (angle is 90 degree). Light falls on the surface of the plane at the angle 45 degree. It is for the purpose that reflected beam does not get into the user's eyes, See Fig. 23, Fig. 24, Fig. 25. Also for same purpose a chair was selected with height adjusting. Distance between user's eyes and DPA was approximately 45 cm as supposed to be working distance with Pocket PC. Computer for fixing comments was next to user from right hand side.

Mode of PDA was selected with both tuning regulators as half of energy.

There were measured color temperatures of reference white and PDA white point and corresponding luminance levels, reflectance of the Pocket PC under experiment conditions. This information was used during calculation the RGB format of training images.

Fig. 23. Camera on user's position**.**

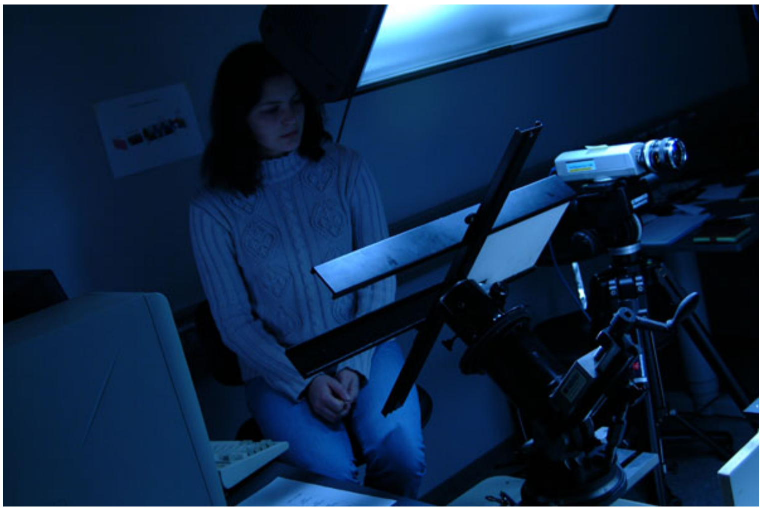


Fig. 24. Set-up for human observation of PDA.

Fig. 25. Set-up for human observation of PDA.

7.4. Test Images

There were chosen four pictures to examine color properties of the iPAQ. Three of them with human and one image with set of standard colors. Users were asked to test three training pictures for each original picture, see Fig. 26.

Fig. 26. Original images used in tests. sRGB representation.

Another way to test if traditional technique is applicable to LCD display was in interviewing directly users. These tests were tried to find out what is better to use GOG or sRGB transformation to construct RGB images for iPAQ. For the processing results of this survey was used one of the psychometric scaling method, pairs comparison. Reproduction pictures Test1, Test2 and Test3 were created in same manner for every original one:

1. *Test1* for each picture is build on Primaries of the PDA using, see formula (43):

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_{r,\max} & X_{g,\max} & X_{b,\max} \\ Y_{r,\max} & Y_{g,\max} & Y_{b,\max} \\ Z_{r,\max} & Z_{g,\max} & Z_{b,\max} \end{bmatrix} \cdot \begin{bmatrix} R(d_r) \\ G(d_g) \\ B(d_b) \end{bmatrix} + \begin{bmatrix} X_{offset} \\ Y_{offset} \\ Z_{offset} \end{bmatrix} + \begin{bmatrix} X_{reflection} \\ Y_{reflection} \\ Z_{reflection} \end{bmatrix} \quad (43)$$

   Here square matrix of linear transformation is a matrix of primaries of Compaq. Values in vector $[R(d_r), G(d_g), B(d_b)]^t$ were obtained as linear interpolatinion between measured values.

2. *Test2* for each picture is built on Primaries of the PDA by formula (43) but non-linear part of the transformation is built by GOG model.

3. *Test3* for each picture is based on standard sRGB transformation, see section 5.1.

Fig. 27. Test pictures of "SunGirl" image.

The prototype of each test images was a spectral appearance of the corresponding originals. They were obtained by spectral camera Imspector V8 in experiment conditions. On the moment of scanning the background was white. Pixels of these images were as “input” for creating tested images for PDA, i.e. sample colors $[X\ Y\ Z]^t$ in formula (37). Since the background of the picture on PDA is black as you can see originals images were showed for users on the black background as well, but between printed sample and the background paper was another sheet of white paper. It was made for the purpose less appearing of black color through the picture. It simulates equivalent reflected light from the moved to black background original image to the reflected on the moment of scanning this original image on white background.

Test images were zoomed in to be approximately of the same size as original image. See Fig. 28.

Fig. 28. Comparison original and test images of picture “Old Lady”.

7.5. Interview

First stage of the interview was comparison each test image on the PDA with original one on paper. Users’ task was to look at these two images and to say his/her opinion about color representation on the device. Their answers consisted of three parts: indicate the area where color distortion is seen, write comments, to classify the test image in general. See Fig. 28the pictures comparison process.

For the keeping information of users' opinions a tool was created. See interface Fig. 29.

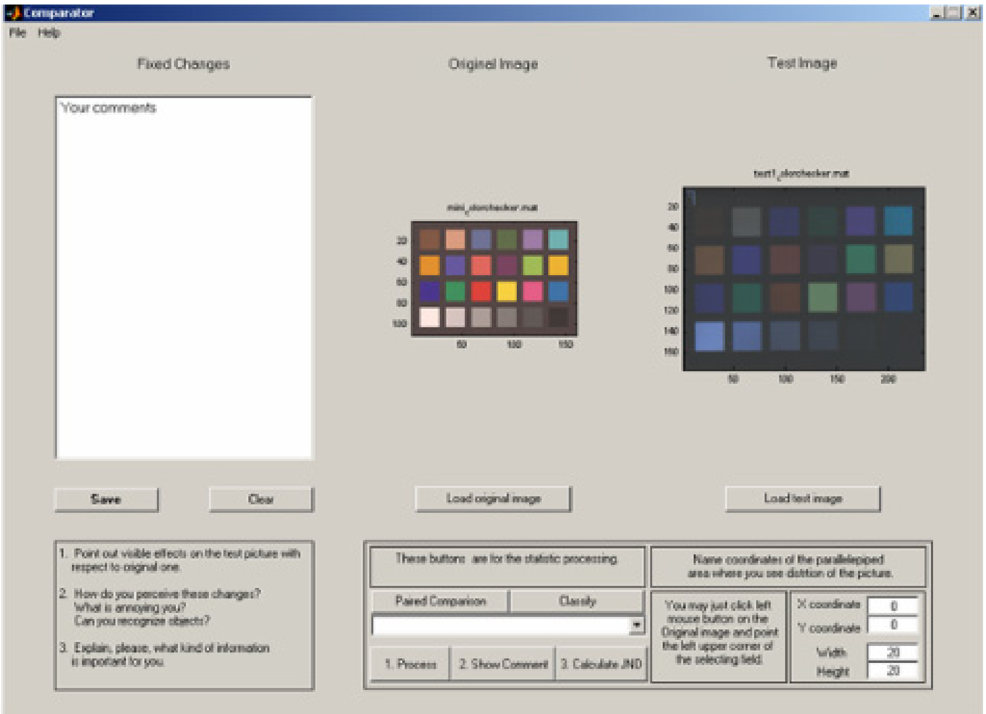


Fig. 29. Comparator. *Viewer.m*

On this tool sketches of original and test images were represented. Users selected areas of color distortion on the original region by mouse click (coordinates of this click is writing in the left lower corner of the figure for self checking). Original side was chosen because users preferred to point it on that image. Users wrote comments for the just selected area. They typed opinions in text field and pressed "SAVE" button after each selection. It was quite short explanations of user's feelings, only answers on following questions:

- Point out visible effects on the test picture with respect to original one.
- How do you perceive these changes? What is annoying you? Can you recognize objects?
- Explain, please, what kind of information is important for you.

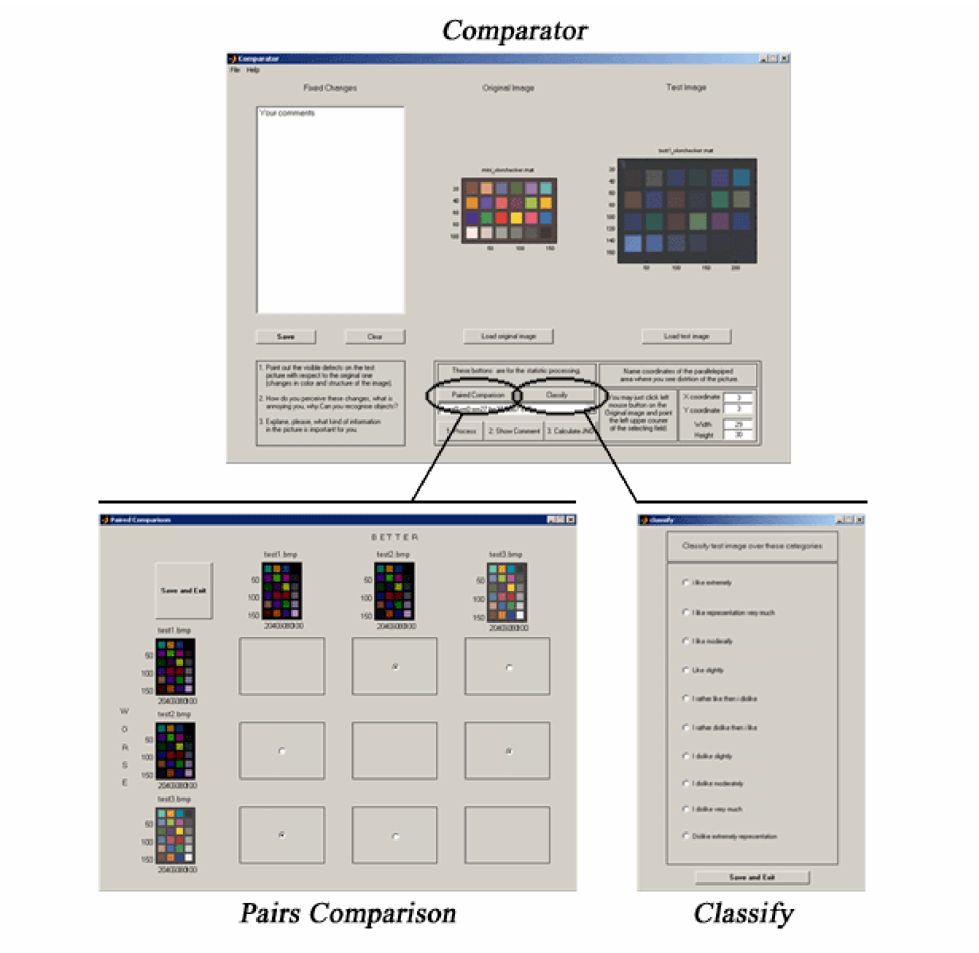


Fig. 30. System of windows in Comparator.

After all selections were done, current test image was evaluated in general by next gradations (Button "Classify", see Fig. 30):

I like extremely
I like representation very much
I like moderately
I like slightly
I rather like then I dislike
I rather dislike then I like
I dislike slightly
I dislike moderately
I dislike representation very much
Dislike extremely representation

Such procedure was for every test image. After that was second stage of the interview – Pairs Comparison.

For each set of test pictures were made pairs. Amount of pairs is equal to $C_3^2 = 3$. All the time the original image was in range of user's vision. How pairs were presented for user see Fig. 31.

Fig. 31. Process of comparison. image "Young Girl".

Originally, I expected that Users would mark by which image do they prefer more in stated pair themselves in special form in my tool (see Fig. 30), but it took too much time for the explanation how to mark, so, I made tables for them, where they just point "better one":

NAME OF ORIGINAL

	LEFT	**RIGHT**
Pair1		✓
Pair2	✓	
Pair3	✓	

After users' answers I fill in form on tool by myself.

Totally there were 10 persons in the tests (5 women and 5 men). Average age of interviewers was 22. Duration of whole testing with 5 minutes brake was 2h 30 minutes for each person.

All the users were volunteers among students, they were not experienced testers. It was quite difficult to focus them on the color accuracy of the image. Very often observers tried to zoom out test image on PDA explaining that artifacts of scaling disturbing (in fact these artifacts were not so strong).

Other factor of the observers' intervene was the total lightness of the test image. If picture was darker than they would like, they did not want to see correctness of the hue representation and there was a tendency to characterize picture as "bad".

The images were tested in following order:

- Color checker
- Old Lady
- Sun Girl
- Young Girl

I decided to make Color checker first training image, because it contains a lot of areas of pure colors and invited users are "fresh" and have their maximum of attention to select area of color distortion. Other images have just a few of color areas.

8. Results

8.1. Characterization of the PDA Display

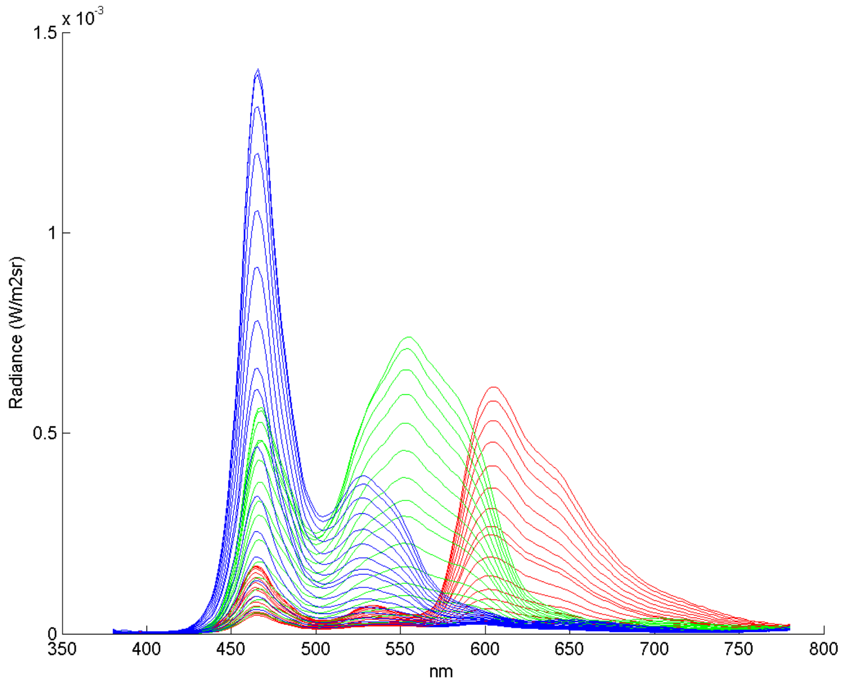


Fig. 32. PDA display's intensities of primaries colors.

Pocket PC COMPAQ IPAQ H3900 was characterized by standard method that has been applied to CRT displays. This technique (GOG model) was described by Berns to define dependencies between electro-optical properties of display [2]. This PDA was studied in two modes: first mode when two fine tuning regulators: "Battery" and "Power" both parameters were placed with the maximum of parameters; second one with half of the maximum values. Both measurements were done in darkness. On Fig. 32 you can see the distribution of the radiance over wavelength of the primaries ramping curves (second mode). Additive property of PDA as an example is shown for $Gray_{10}$ (see [33] Table1) on Fig. 33.

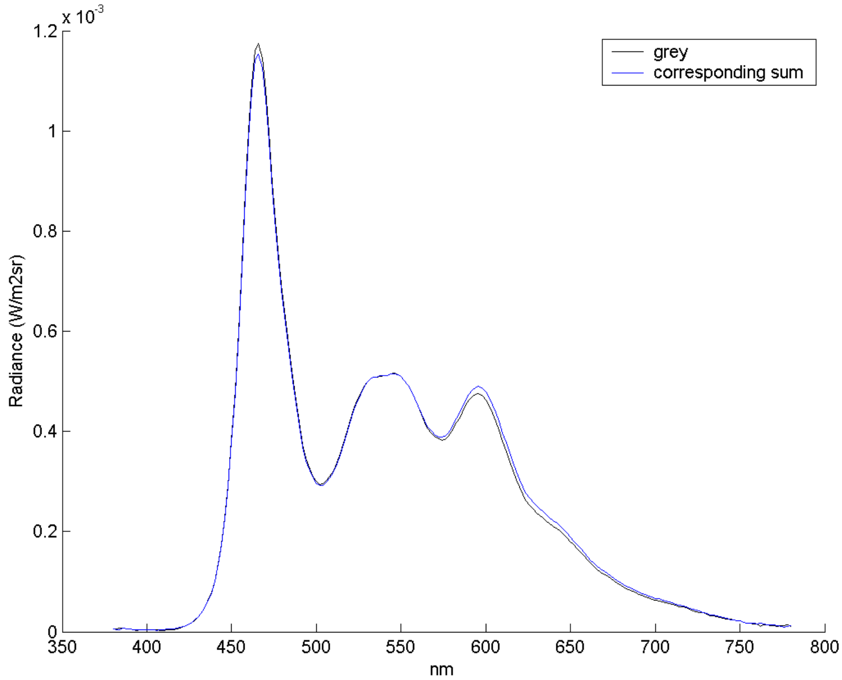
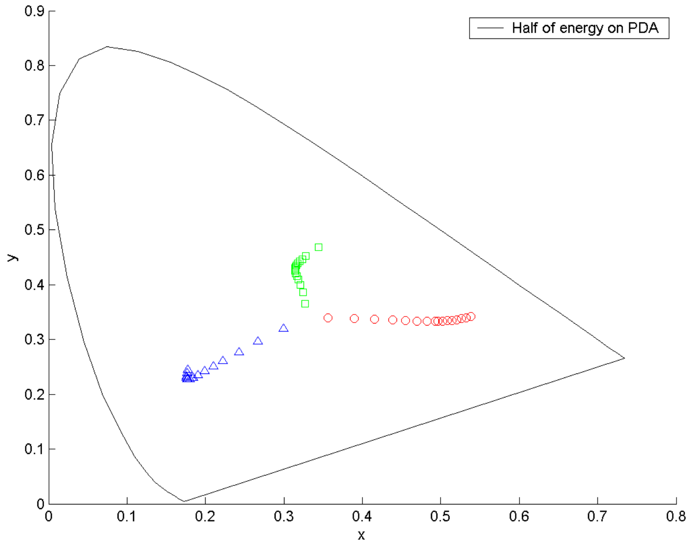


Fig. 33. Additive properties of the PDA display.

$$\text{Gray}_{10} = R(d_r = 0{,}6250,\ d_g = 0,\ d_b = 0) + G(d_r = 0,\ d_g = 0{,}6250,\ d_b = 0) + B(d_r = 0,\ d_g = 0,\ d_b = 0{,}6250)$$

Curves for other grays and intensities of ramping data for the first mode of PDA see in [33].

For reference primaries of the LCD of this Pocket PC and some of CRT display corresponding intensities of primaries were plotted on the xy-chromatic diagram, see Fig. 34. Gamuts of both devices are represented on Fig. 35.



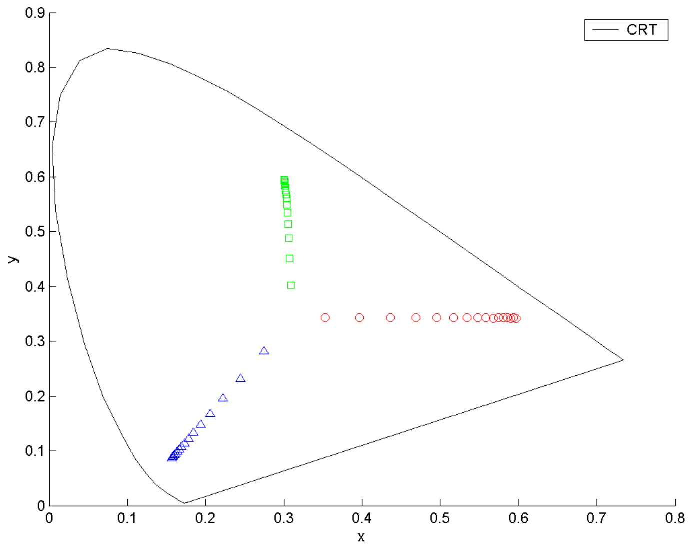


Fig. 34 Primaries of the PDA display (top) and CRT monitor (down).

As you can see from Fig. 34 PDA display has disproportional distribution of chromaticity values. Especially it is seen for the green primary color.

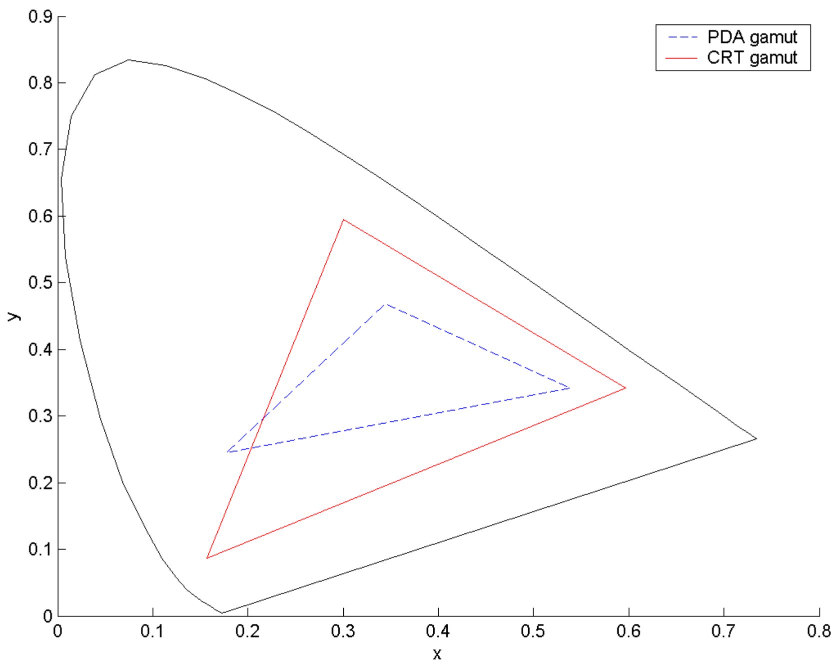


Fig. 35. Gamuts of the PDA and CRT monitor.

Gamut of the CRT monitor is greater than of the Pocket PC. It covers majority of Compaq colors. Only a small range of blue tints of the PDA display does not belong to color space of CRT monitor. See Fig. 35. Total amount of colors on the Pocket PC COMPAQ IPAQ H3900 is 64K color (65,536 colors).

Primaries of the PDA display are:

Components in XYZ System coordinate	RED	GREEN	BLUE
X	0.0267	0.0329	0.0139
Y	0.0163	0.0453	0.0197
Z	0.0049	0.0178	0.0490

Table. 1. Primaries of the PDA in set1 (maximum values on PDA).

Set 1	Gain	Offset	Gamma	Error
Red	0.8774	0.1546	1.4407	0.0880
Green	1.0792	-0.0128	1.2775	0.1326
Blue	0.9451	0.0860	1.5537	0.0848

Table. 2. GOG values for each of primaries of PDA in set1 (maximum values on PDA).

Components in XYZ System coordinate	RED	GREEN	BLUE
X	0.0153	0.0186	0.0079
Y	0.0094	0.0256	0.0112
Z	0.0027	0.0097	0.0276

Table 3. Primaries of the PDA in set2 (half of the maximum values on PDA).

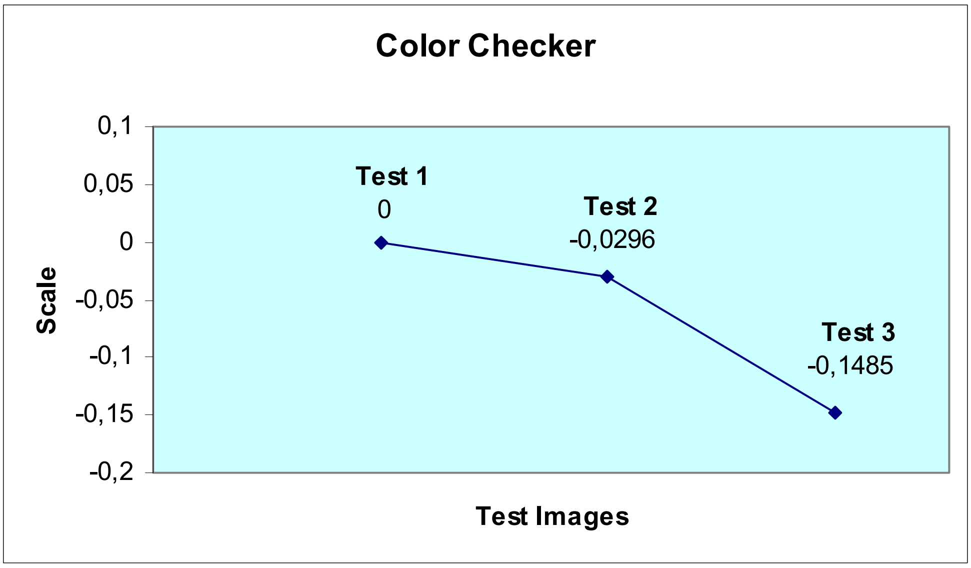
	Gain	Offset	Gamma	Error
Red	0.8722	0.1615	1.4106	0.0895
Green	1.0940	-0.0137	1.2259	0.1507
Blue	0.9377	0.0951	1.5636	0.0895

Table 4. GOG values for each of primaries of PDA in set2 (half of maximum values on PDA).

Gain, offset and gamma parameters do dependence from each other; see formula (18) in paragraph 5.2. Their sum is equal to 1, hence that values of gain and offset should be less than 1 but also greater then 0, because otherwise it means that screen absorbs light. As we can see from Table2 and Table3 only green primary is “out of theory” in both training modes. From other side, it is possible to approximate these values by zeros due to their small values or the level of accuracy of the measurements.

8.2. Psychophysical Experiments

Results of the psychometric scales are in next graphs, see Fig. 36. and Fig. 37. On the diagrams zero value is associated with "better" meaning and the lower value test image has the worse representation from users' point of view.



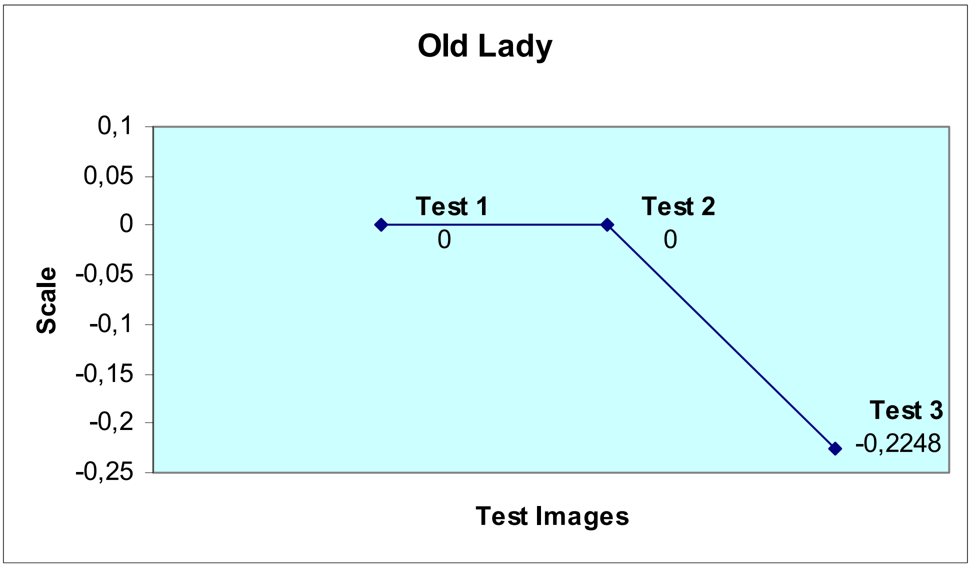


Fig. 36. Results of Pairs Comparison method (zero value is associated with "best" grade).

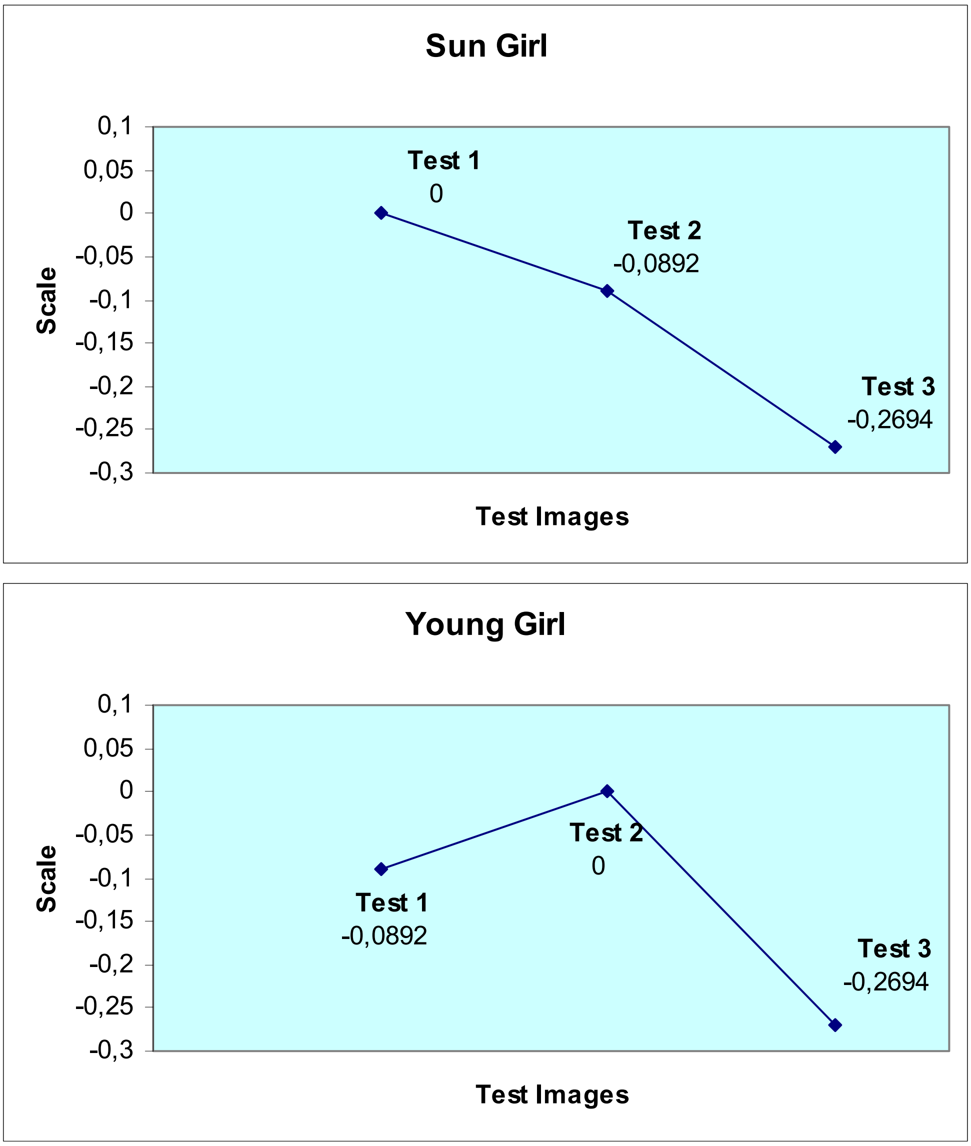


Fig. 37. Results of Pairs Comparison method (zero value is associated with "best" grade).

As it can be seen from graphs the best result has first type of conversion (Test1) and worst the third one (Test 3). Users explained these kinds of priorities of lightness of the images. They told that first of all when they look at the picture brightness is important, only after (waiting some time) when eyes are adapted users were evaluating the hue accuracy. If the brightness of the image is not good enough users was motivated to pay attention on tints. So, in paragraph 6.2. I would put the brightness on the top of the list of priorities. Test2 as you can see on Fig. 27 is darker then the Test1, but this difference is less obvious on the PDA screen, but some kind of “threshold” of brightness by Test2 is overstepped. That was the main factor in classification in Pairs Comparison; even all users mentioned that hue reproduction on Test1 not as good as on Test2 but still satisfactory, so their answer on question “Which representation do you prefer” was positive for Test1. Maybe reason of this phenomenon is that reflectance from the PDA screen was measured when device was switched off, but not when there is a black color representation. From my point of view when there is a black color the screen is darker, so problem of measure only reflectance component form the screen could affect on the reproduction of images and hence results.

	1	2	3	4
Test1	0	0	0	-0,0892
Test2	-0,0296	0	-0,0892	0
Tes3	-0,1485	-0,2248	-0,2694	-0,2694
	Color Cheker	Old Lady	Sun Girl	Young Girl

Fig. 38. Results of Pairs Comparison method (zero value is associated with “best” grade).

The common sRGB (Test3) representation appeared on Pocket PC too “foggy” for all of users, too bright, not enough richness of color (several comments see in IT [33]). Effect of it was quite strong on images – hues which are close to each other became one and since that fine details on images disappeared, i.e. wrinkles on “Old Lady”, stones on white part of the background on “Sun Girl”, light blue color of the background on “Young Girl” became white. That is why all users marked as worse one, see Fig. 36 Fig. 37. On Fig. 38 all training images together.

About most problematic colors:

Because it was not possible to view the test image and reproduction at the simultaneously, I assume that observer had to call original color from memory when comparing two images. We can propose that eyes can see two colored areas at the same time if these two areas are close to each other as like in color matching experiment, because our eyes always shimmy, but such comparison of whole images was not possible in this experiment. The original image was present just for renewing the appearance of the image, so one has to deal with colors that particularly brain remembers.

Purple – on all test images of Color Checker *purple* color attracted attention most of all and was chosen in the first place. So, as in work [28] *purple* color is best remembered. On iPAQ this color was not simulated good enough. On other training images *purple* did not present in pure form.

Blue. On Color Checker there are several cold tints – *blue*, *purplish blue*, and *blue sky* close to each other. Representation of difference between these colors was bad on all test images. Mentioning this fact proves one more time that hue is the one important criterion for correct color appearance. I would put hue on the second positions of priorities for my users. Quality of the representation of blue color on Test2 type images affect on “Water” and “Chair” areas on “Sun Girl” image, since the area of body color does not dominate on this image, observers’ preferences belongs to Test1 type representation then to Test2.

Another interesting observation from my point of view is that representation of *green* color (two samples on the Color Checker) was satisfied, especially the sample representing natural green color; in spite of the fact that human’s eyes are the most sensitive to green hues. It is reasonable to assume that they are well remembered by human [28], [4], so, corruption in their reproduction should attract attention.

Skin color. Instead of *light skin* color Caucasian people paid attention to the *orange-yellow* tint. It was second color in priority to paid attention to. On Test2 this color was not mentioned so many times as on Test1. This fits with results of paired comparison for “Young Girl” image i.e. from observes point of view color of baby’s body is represented better on Test2. For “Old lady” image observes did not mark out which representation do they prefer Test1 or Test2. I think it is due to even number of users.

As in work [28] *brown* is worst remembered color. At my experiment for the *dark skin* color was paid attention only once by dark skin person.

Summaries of all results about training transforming spectral images into RGB format:

	Advantages	**Disadventures**
Test1 **(interpolation)**	Blue hues representation is most successful on training images. The level of lightness of the image is good from observers’ point of view.	Color of body, white, purple, magenta – all these colors are not so good.
Test2 **(GOG)**	Body color is represented better than on other two types of test images.	Blue, white purple – all these colors are not so good. images in general are too dark
Test3 **(sRGB)**	Mistake is the same over all area of the image, so, after adaptation of eye, user cannot specify particular changes that belong to concrete color, and observer can speak about image in general.	Bad reproduction of any trained images, it is too light. Black color is gray.

9. Conclusions

Pocket PC COMPAQ IPAQ H3900 was characterized – there primaries were found, additive properties were checked, and determined the RGB-to-XYZ transformation and the nonlinear transfer function for each primary color channel in two modes of the device. Results showed that better additive properties of the iPAQ screen appeared in second of trained mode of adjusted parameters on PDA (with half of the maximum of both parameters).

Hence, for user will be better to work with Compaq in this mode.

There were made human tests on this Pocket PC with purpose to evaluate color accuracy representation. It was a try to find out what is better to use GOG or sRGB transformation to construct RGB images for iPAQ also. These tests showed that first type and second type were equal for users from color accuracy point of view.

In all types of transformations the most unsatisfied representation had purple color.

More accurate for the representation skin color (Caucasian) was second way of transformation (Test2 i.e. GOG model)

Fist way of transformation (Test1 i.e. interpolation) spectral images into RGB format for the representation on the PDA screen was more accurate in blue range of colors then other trained transformations.

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