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COLOUR APPEARANCE METRIC FOR USE IN VIDEO APPLICATIONS

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МЕТРИКА КОЛЬОРОСПРИЙНЯТТЯ ДЛЯ ЗАСТОСУВАННЯ У ВІДЕОЗАСТОСОВАННЯХ

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МЕТРИКА ЦВЕТОВОСПРИЯТИЯ ДЛЯ ИСПОЛЬЗОВАНИЯ В ВИДЕОПРИЛОЖЕНИЯХ

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Abstract. The article presents a description of the new CAM16 color appearance model developed by the CIE to replace the currently acting model CIECAM02, improved with respect to the correctness of the algorithm for its implementation, taking into account the approach published in the literature, as well as the corresponding uniform color space CAM16-UCS designed to replace the CAM02-UCS space. Examples of quantitative estimates characterizing the properties of new color space metric with regard to image observation conditions are given..

Key words: color perception model, uniform color space, color space metric, colorimetric image quality, CIECAM02, CAM16, CAM02-UCS, CAM16-UCS

Анотація. У статті представлено опис нової моделі кольоросприйняття CAM16, розробленої МКО на заміну чинної нині моделі CIECAM02, вдосконалене щодо коректності алгоритму його реалізації з урахуванням опублікованого в літературі підходу, а також відповідного рівноконтрастного колірного простору CAM16-UCS, розробленого на заміну простору CAM02-UCS. Наводяться приклади кількісних оцінок, які характеризують властивості метрики нового колірного простору з урахуванням умов спостереження зображення.

Ключові слова: модель кольоросприйняття, рівноконтрастний колірний простір, метрика колірного простору, колориметричне якість зображення, CIECAM02, CAM16, CAM02-UCS, CAM16-UCS

Аннотация. В статье представлено описание новой модели цветовосприятия CAM16, разработанной МКО на замену действующей в настоящее время модели CIECAM02, усовершенствованное в отношении корректности алгоритма его реализации с учётом опубликованного в литературе подхода, а также соответствующего равноконтрастного цветового пространства CAM16-UCS, разработанного на замену пространства CAM02-UCS. Приводятся примеры количественных оценок, характеризующих свойства метрики нового цветового пространства с учётом условий наблюдения изображения.

Ключевые слова: модель цветовосприятия, равноконтрастное цветовое пространство, метрика цветового пространства, колориметрическое качество изображения, CIECAM02, CAM16, CAM02-UCS, CAM16-UCS

Introduction

For present time CIE elaborated new colour appearance model CIECAM16 for replacement model CIECAM02 [1] used widely as a best colour appearance model. Presented here description is based on publication this model named CAM16 [2] together with corresponding uniform colour space proposed in [3]. The description is made inclusive propositions for algorithmic enhancement this model [4].

The chromaticity diagram in CAM16-UCS space with consideration its dependence on adapting luminance and viewing conditions is presented. This diagram is similar to the diagram in CAM02-UCS [5] but more critical for highly saturated colours.

The description of CAM16-UCS uniform colour space as the best space for colorimetry evaluations is presented. Examples of quantitative estimates characterizing the properties of new color space metric with regard to image observation conditions are given.

1 CAM16 colour appearance model

Forward conversion equations

Initial data

X, Y, Z – CIE 1931 tristimulus values of the sample;

X_W, Y_W, Z_W – CIE 1931 tristimulus values for reference white;

$L_W, \mathrm{cd}\cdot\mathrm{m}^{-2}$ – reference white luminance;

$L_{SW}, \mathrm{cd}\cdot\mathrm{m}^{-2}$ – surround white luminance;

$L_A = \dfrac{Y_b}{Y_W} L_W$ – adapting luminance;

$S_R = L_{SW}/L_W$ – surround factor,

Y_W – reference white luminance factor;

Y_b – background luminance factor;

c – surround impact factor;

N_C – chromatic induction factor;

F – factor for degree of adaptation;

If data on c, N_C and F are unavailable they can be chosen as it is shown in Table 1.

Table 1 – Surround parameters

	c	N_C	F
Average surround	0.69	1.0	1.0
Dim surround	0.59	0.9	0.9
Dark surround	0.525	0.8	0.8

Surround type may be defined via S_R. The value $S_R = 0$ corresponds to dark surround, $S_R < 0.2$ to dim one and $S_R \geq 0.2$ to average one. N_C and F are modelled as a function of c, and their values can be linearly interpolated as shown in Figure 1.

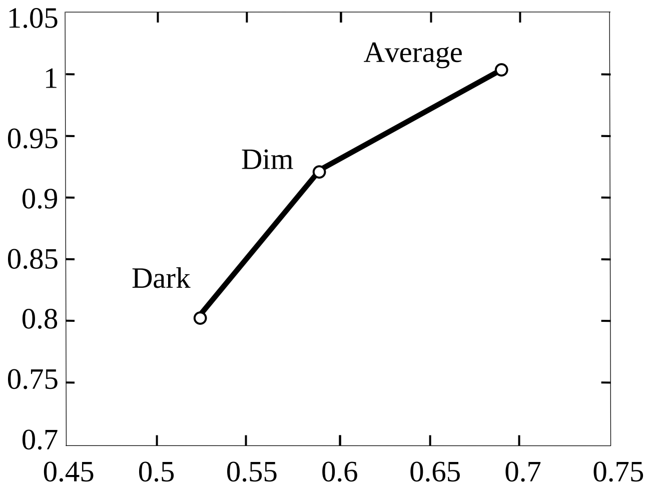

Figure 1 – Linear interpolation to obtain N_C and F

Calculate values/parameters independent of the evaluated sample

The cone responses for reference white are:

$$\begin{bmatrix} R_W \\ G_W \\ B_W \end{bmatrix} = \mathbf{M_{16}} \cdot \begin{bmatrix} X_W \\ Y_W \\ Z_W \end{bmatrix}, \tag{1}$$

where

$$\mathbf{M}_{16} = \begin{bmatrix} 0.401288 & 0.650173 & -0.051461 \\ -0.250268 & 1.204414 & 0.045854 \\ -0.002079 & 0.048952 & 0.953127 \end{bmatrix}. \tag{2}$$

The degree of adaptation:

$$D = F\left[1 - \left(\frac{1}{3.6}\right)e^{\left(\frac{-(L_A+42)}{92}\right)}\right]. \tag{3}$$

If D is greater than one or less than zero, set it to one or zero, respectively.

$$D_R = D \cdot \frac{Y_W}{R_W} + 1 - D; \quad D_G = D \cdot \frac{Y_W}{G_W} + 1 - D; \quad D_B = D \cdot \frac{Y_W}{B_W} + 1 - D. \tag{4}$$

The adaptation transform parameters:

$$k = 1/(5 \cdot L_A + 1); \qquad F_L = 0.2 \cdot k^4 \cdot (5 \cdot L_A) + 0.1 \cdot (1 - k^4)^2 \cdot (5 \cdot L_A)^{1/3};$$
$$n = \frac{Y_B}{Y_W}; \quad N_{bb} = N_{cb} = 0.725 \cdot (1/n)^{0.2}; \qquad z = 1.48 + \sqrt{n}; \tag{5}$$

$$\begin{bmatrix} R_{\mathrm{Wc}} \\ G_{\mathrm{Wc}} \\ B_{\mathrm{Wc}} \end{bmatrix} = \begin{bmatrix} D_R \cdot R_{\mathrm{W}} \\ D_G \cdot G_{\mathrm{W}} \\ D_B \cdot B_{\mathrm{W}} \end{bmatrix}; \tag{6}$$

$$R_{aW} = 400\frac{\left(\frac{F_L R_{Wc}}{100}\right)^{0.42}}{\left(\frac{F_L R_{Wc}}{100}\right)^{0.42} + 27.13}; \tag{7}$$

$$G_{aW} = 400\frac{\left(\frac{F_L G_{Wc}}{100}\right)^{0.42}}{\left(\frac{F_L G_{Wc}}{100}\right)^{0.42} + 27.13}; \tag{8}$$

$$B_{aW} = 400\frac{\left(\frac{F_L B_{Wc}}{100}\right)^{0.42}}{\left(\frac{F_L B_{Wc}}{100}\right)^{0.42} + 27.13}; \tag{9}$$

$$A_W = \left(2R_{aW} + G_{aW} + \frac{1}{20}B_{aW}\right)\cdot N_{bb}. \tag{10}$$

Calculate cone response signals

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \mathbf{M_{16}} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}. \tag{11}$$

Complete chromatic adaptation

$$\begin{bmatrix} R_C \\ G_C \\ B_C \end{bmatrix} = \begin{bmatrix} D_R \cdot R \\ D_G \cdot G \\ D_B \cdot B \end{bmatrix}. \tag{12}$$

Calculate chromatic adaptation cone responses (resulting in dynamic range compression)

$$R'_a = 400\,\mathrm{sign}\left(R_c\right)\frac{\left(\frac{F_L \left|R_c\right|}{100}\right)^{0.42}}{\left(\frac{F_L \left|R_c\right|}{100}\right)^{0.42} + 27.13}; \tag{13}$$

$$G'_a = 400\,\mathrm{sign}\left(G_c\right)\frac{\left(\frac{F_L \left|G_c\right|}{100}\right)^{0.42}}{\left(\frac{F_L \left|G_c\right|}{100}\right)^{0.42} + 27.13}; \tag{14}$$

$$B'_a = 400\,\mathrm{sign}\left(B_c\right)\frac{\left(\frac{F_L \left|B_c\right|}{100}\right)^{0.42}}{\left(\frac{F_L \left|B_c\right|}{100}\right)^{0.42} + 27.13}. \tag{15}$$

Calculate redness-greenness (a),* yellowness-blueness *(b) components, hue angle (h), and auxiliary variables $\left(p_2', u\right)$

$$\begin{bmatrix} p_2' \\ a \\ b \\ u \end{bmatrix} = \begin{bmatrix} 2 & 1 & \frac{1}{20} \\ 1 & -\frac{12}{11} & \frac{1}{11} \\ \frac{1}{9} & \frac{1}{9} & -\frac{2}{9} \\ 1 & 1 & \frac{21}{20} \end{bmatrix} \begin{bmatrix} R_a' \\ G_a' \\ B_a' \end{bmatrix}; \tag{16}$$

$$h = \arctan\left(b/a\right); \quad h_r = h \cdot 180/\pi; \tag{17}$$

$$h = \begin{cases} h_r & \text{for} \quad a > 0 \ \& \ b > 0; \\ h_r + 180 & \text{for} \quad a < 0; \\ h_r + 360 & \text{for} \quad a > 0 \ \& \ b < 0; \end{cases} \tag{18}$$

Eccentricity factor:

$$e_t = \frac{1}{4} \cdot \left[\cos\left(h \cdot \frac{\pi}{180} + 2 \right) + 3.8 \right]. \tag{19}$$

Colour quadrature H may be obtained via linear interpolation method:

$$H = H_i + \frac{100 \cdot \left(h' - h_i\right)/e_i}{\left(h' - h_i\right)/e_i + \left(h_{i+1} - h'\right)/e_{i+1}} \tag{20}$$

using the values of unique hues shown in Table 2 below. Here $h' = h + 360$ if $h < h_1$, and $h' = h$ elsewise.

Table 2 – Unique hue data for the calculation of hue quadrature

	Red	Yellow	Green	Blue	Red
i	1	2	3	4	5
h_i	20.14	90.00	164.25	237.53	380.14
e_i	0.8	0.7	1.0	1.2	0.8
H_i	0.0	100.0	200.0	300.0	400.0

If i=3 and $H = 241.2116$ for example, then H is between H_3 and H_4 (see Table 2). Compute $P_L = H_4 - H = 58.7884$; $P_R = H - H_3 = 41.2116$ and round P_L and P_R values to values to integers 59 and 41. Thus, according to Table 2, this samples considered as having 59 % of Green and 41 % of Blue, which is the H_c and can be reported as 59G41B or 41B59G.

Calculate the achromatic response

$$A = p'_2 N_{bb}. \tag{21}$$

Calculate the correlate of lightness

$$J = 100 \cdot \left(A / A_W \right)^{c \cdot z}. \tag{22}$$

Calculate the correlate of brightness

$$Q = \left(4/c \right) \cdot \sqrt{J/100} \cdot \left(A_W + 4 \right) \cdot F_L^{0.25}. \tag{23}$$

Calculate the correlates of chroma (C), colorfulness (M), and saturation (s)

$$t = \frac{\left(50000/13 \right) \cdot N_C \cdot N_{cb} \cdot e_t \cdot \sqrt{a^2 + b^2}}{u + 0.305}; \tag{24}$$

$$\alpha = t^{0.9} \left(1.64 - 0.29^n \right)^{0.73}; \tag{25}$$

$$C = \alpha \sqrt{J/100}; \tag{26}$$

$$M = C \cdot F_L^{0.25}; \tag{27}$$

$$s = 100 \cdot \sqrt{M/Q}. \tag{28}$$

CAM16 includes three attributes in relation to the chromatic content: chroma (*C*), colourfulness (*M*) and saturation (*s*). These attributes together with lightness (*J*) and hue angle (*h*) can form three colour spaces J, a_C, b_C, J, a_M, b_M and J, a_s, b_s, where:

$a_C = C \cdot \cos(h)$	$a_M = M \cdot \cos(h)$	$a_s = s \cdot \cos(h)$
$b_C = C \cdot \sin(h)$	$b_M = M \cdot \sin(h)$	$b_s = s \cdot \sin(h)$

Inverse conversion equations

Initial data

Different combinations of perceived correlates, that is, *J* or *Q*; *C*, *M*, or *s*; and *H* or *h*.

Calculate J from Q
(if input is Q):

$$J = 6.25 \left(\frac{cQ}{\left(A_W + 4 \right) F_L^{0.25}} \right)^2. \tag{29}$$

Calculate t

If input is M:

$$C = M / F_L^{0.25}. \tag{29}$$

$$\alpha = \begin{cases} 0 & \text{if } J = 0; \\ \dfrac{C}{\sqrt{J/100}} & \text{otherwise} \end{cases}; \tag{30}$$

if input is s:

$$\alpha = \left(\frac{s}{50} \right)^2 \frac{A_W + 4}{c}; \tag{31}$$

$$t=\left(\frac{\alpha}{\left(1.64-0.29^{n}\right)^{0.73}}\right)^{1/0.9}. \tag{32}$$

Calculate h from H (if input is H)

Use the Table 2. Choose $i\in\{1,2,3,4\}$ such that $H_i\le H\le H_{i+1}$. Compute:

$$h'=\frac{\left(H-H_i\right)\left(e_{i+1}h_i-e_ih_{i+1}\right)-100h_ie_{i+1}}{\left(H-H_i\right)\left(e_{i+1}-e_i\right)-100e_{i+1}}; \tag{33}$$

$$h=\begin{cases}h'-360^\circ & \text{if } h'>360^\circ\\ h' & \text{otherwise}\end{cases}. \tag{34}$$

Calculate e_t, A, p_1', p_2' **and** γ

$$e_t=\frac{1}{4}\left(\cos\left(h\pi/180^\circ+2\right)+3.8\right); \tag{35}$$

$$A=A_W\left(J/100\right)^{1/(cz)} \tag{39}$$

$$p_1'=e_t\frac{50000}{13}N_cN_{cb} \tag{36}$$

$$p_2'=A/N_{bb}; \tag{37}$$

$$\gamma=\frac{23\left(p_2'+0.305\right)t}{23p_1'+11t\cos\left(h\right)+108t\sin\left(h\right)}. \tag{38}$$

Calculate a and b

$$a=\gamma\cos\left(h\right); \tag{40}$$

$$b=\gamma\sin\left(h\right); \tag{41}$$

Calculate R_a', G_a', B_a'

$$\begin{pmatrix}R_a'\\G_a'\\B_a'\end{pmatrix}=\frac{1}{1403}\begin{pmatrix}460 & 451 & 288\\460 & -891 & -261\\460 & -220 & -6300\end{pmatrix}\begin{pmatrix}p_2'\\a\\b\end{pmatrix}. \tag{42}$$

Calculate R_c, G_c, B_c

$$R_c=\operatorname{sign}\left(R_a'\right)\frac{100}{F_L}\left(\frac{27.13\left|R_a'\right|}{400-\left|R_a'\right|}\right)^{1/0.42}; \tag{43}$$

$$G_c=\operatorname{sign}\left(G_a\right)\frac{100}{F_L}\left(\frac{27.13\left|G_a\right|}{400-\left|G_a\right|}\right)^{1/0.42}; \tag{44}$$

$$B_c=\operatorname{sign}\left(B_a\right)\frac{100}{F_L}\left(\frac{27.13\left|B_a\right|}{400-\left|B_a\right|}\right)^{1/0.42}; \tag{45}$$

Calculate $\boldsymbol{R_c, G_c, B_c}$

$$R = R_c / D_R; G = G_c / D_G;\ B = B_c / D_B. \tag{46}$$

Calculate $\boldsymbol{X, Y, Z}$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = M_{16}^{-1} \begin{pmatrix} R \\ G \\ B \end{pmatrix} \tag{47}$$

2 Uniform colour space: CAM16-USC

Colorimetric assessments may be expressed in J, C, h or Q, M, h and J, M, h spaces.

As it was shown [3], usage of J, M, h space gives more accurate predictions of colour appearance, and this space is proposed in [2] for use. The UCS based on CAM16 is given by next Equations:

$$J' = \frac{1.7J}{1 + 0.007J}; \tag{29}$$

$$M' = \ln(1 + 0.0228M)/0.0228; \tag{30}$$

$$a'_M = M' \cos(h'); \tag{31}$$

$$b'_M = M' \sin(h'); \tag{32}$$

$$h' = h, \tag{33}$$

where J, M, h – correlates of lightness, colorfulness and hue, computed with CAM16.

The color difference between two samples can be computed as the Euclidean distance between them in CAM16-UCS:

$$\Delta E' = \sqrt{(\Delta J')^2 + (\Delta a'_M)^2 + (\Delta b'_M)^2}, \tag{34}$$

where $\Delta J', \Delta a'_M, \Delta b'_M$ are the J', a'_M, b'_M differences between the pair of samples, respectively.

The results of testing published to date have shown that predictions obtained by using CAM16-based colour space best match all available colour appearance data and can be considered to become a possible base for further research work on development of TV and related video systems, and on the development of colour appearance models for implementation as the part of image quality assessment systems, particularly colorimetric quality assessment. CAM16-UCS can be further improved by the use of the power correction function, equation proposed by Huang et al [6]:

$$\Delta E = 1.41(\Delta E')^{0.63}. \tag{35}$$

3 CAM16-UCS (a'_M, b'_M) chromaticity diagram

CAM16-UCS (a'_M, b'_M) chromaticity diagram is presented in Figures 1 and 2. The figures demonstrate the dependence of colour appearance on adaptation level L_A and on surround conditions (dark, dim, average) in CAM16-UCS space.

These changes of colour appearance can be critical for video applications in that viewing conditions substantially differ on transmitting and receiving ends, which results in impairments of colour rendition.

It is possible to give more complete quantitative evaluation of possible colour appearance changes with change of adapting luminance and surround, by an evaluation of the change of chromaticity coordinates in CAM16-UCS space as distance ΔE between points on the plane of coordinates a'_M, b'_M for different combinations of adapting luminance L_A and of surround for the compared stimuli.

The dependence of perceived colours on L_A may be shown with use the criterion:

$$\Delta E'_{20-200} = \sqrt{\left(\Delta J'_{20-200}\right)^2 + \left(\Delta a'_{M\ 20-200}\right)^2 + \left(\Delta b'_{M\ 20-200}\right)^2}\,, \tag{36}$$

where $\Delta J'_{20-200}$, $\Delta a'_{M\ 20-200}$, $\Delta b'_{M\ 20-200}$ – differences of coordinates of colour space J', a'_M, b'_M for adapting luminance levels $L_A = 20$ cd/m^2 and $L_A = 200$ cd/m^2.

The values of ΔE_{20-200} are shown in the Table 1. Data, presented on Table 1 and on Figure 2, are comparable with this evaluation. A comparison of evaluations confirms that conditions of independently changing surround of image and adapting luminance at the transmitting side and on a receiving side can result in distortions of colour rendition from a level unnoticeable or barely noticeable to the level of unacceptable impairment of image colorimetric quality.

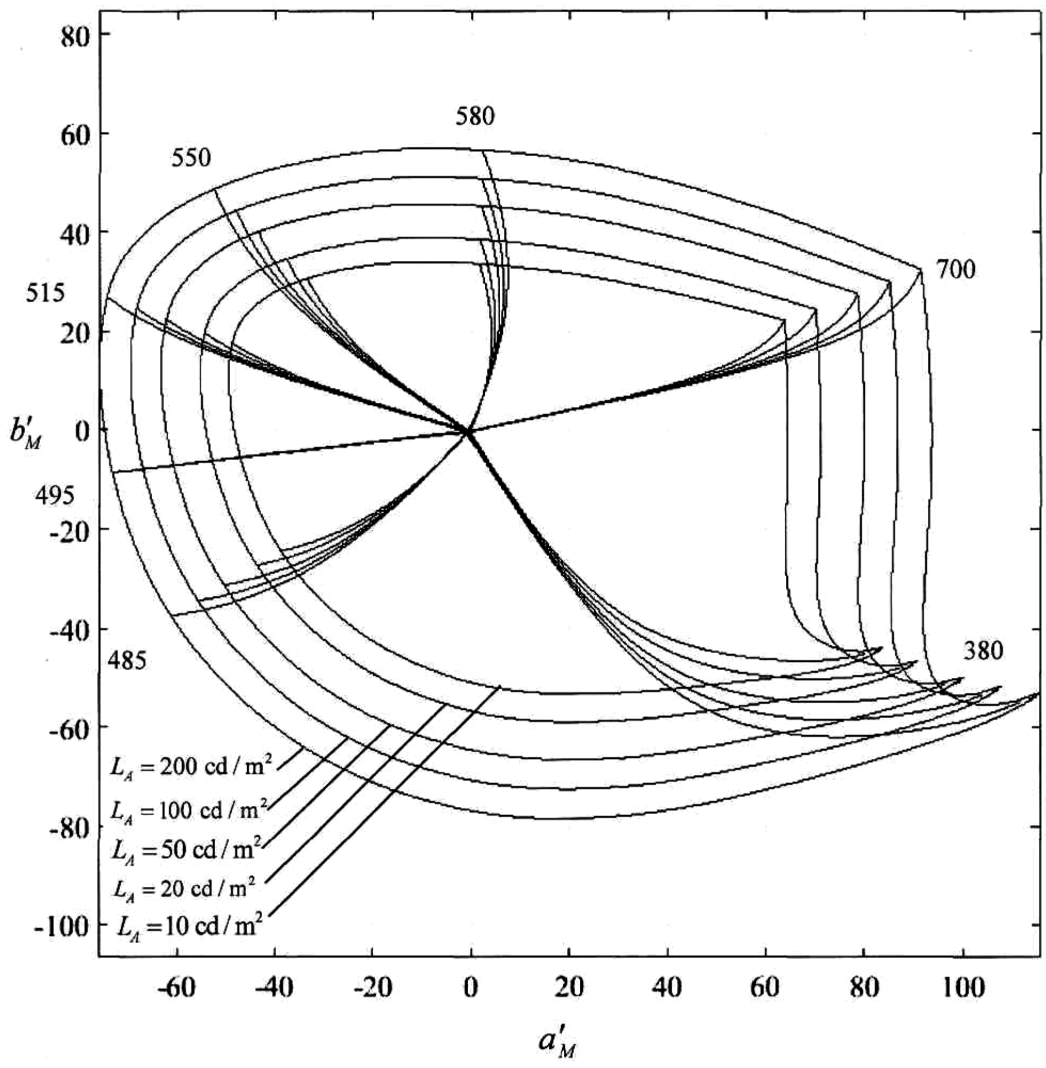

Figure 1 – Chromaticity diagram CAM16-UCS $(a'_M, b'_M), Y_W = 100, Y = 10$

Table 1 – Values of distance ΔE between position of points of monochromatic colours of chromaticity diagram for combined adapting luminance and surround conditions for stimulus luminance equal 10 cd/m^2

Conditions of viewing (adapting luminance (L_{A1}, L_{A2}) and surround) on capturing and reproduction ends		λ, nm						
		380	485	495	515	550	580	700
$L_{A1} = 200$ cd/m^2 – average	$L_{A2} = 20$ cd/m^2 – dim	12.39	8.51	8.4	8.51	8.53	8.59	9.55
$L_{A1} = 200$ cd/m^2 – average	$L_{A2} = 20$ cd/m^2 – dark	18.16	13.18	13.01	13.07	13.02	13.02	13.89
$L_{A1} = 20$ cd/m^2 – average	$L_{A2} = 200$ cd/m^2 – dim	9.34	9.12	9.01	9.15	9.03	8.63	9.12

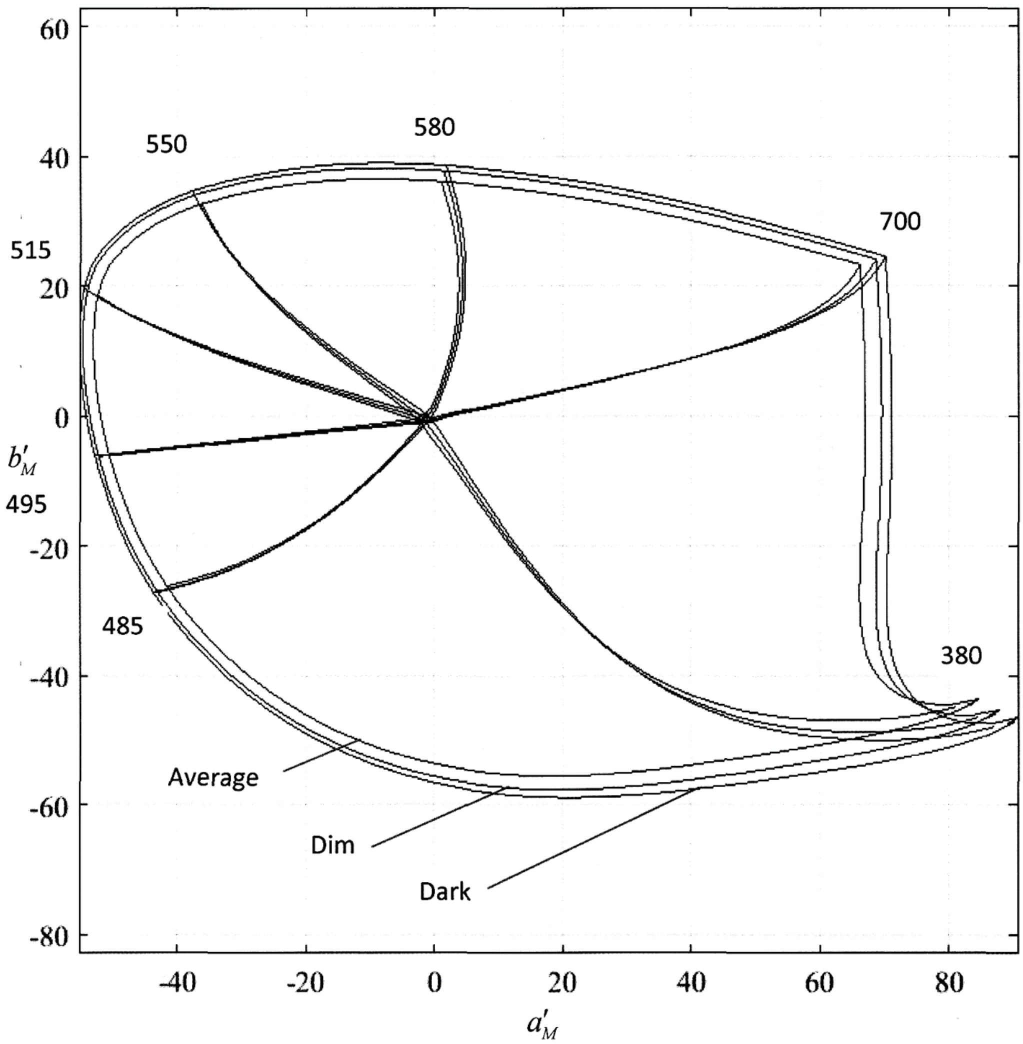

Figure 2 – Chromaticity diagram CAM16-UCS (a'_M, b'_M), $L_A = 20$ cd/m^2, $Y_W = 100$, $Y = 20$

Table 2 – Correlation of distance ΔE and colour rendition impairment

ΔE, CIE units	Image impairment evaluation
3	Unnoticeable
5	Barely noticeable
10	Bad
15	Unacceptable

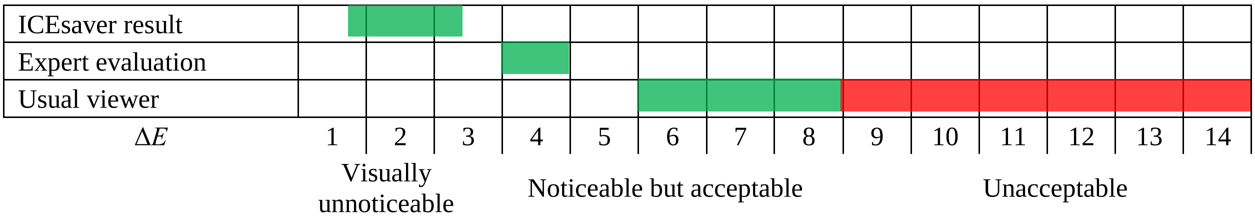

Figure 3 – Occurrence of image impairment in dependence of colour deflection levels ΔE

References

1 CIE Technical Report. *A colour appearance model for colour management systems: CIECAM02*. CIE 159: 2004

2 Changjun Li, Zhiqiang Li, Zhifeng Wang, Yang Xu, Ming Ronnier Luo, Guihua Cui, Manuel Melgosa, Michael H. Brill, Michael Pointer *Comprehensive color solutions: CAM16, CAT16, and CAM16-UCS* Color Res. Appl. 2017; 1–16. DOI: 10.1002/col.22131

3 M. Ronnier Luo, Guihua Cui, Changjun Li *Uniform Colour Spaces based on CIECAM02 Colour Appearance Model* – Colour Research and Application, Volume 31, Issue 4, May 2005

4 Nico Schlömer, Algorithmic improvements for the CIECAM02 and CAM16 color appearance models https://arxiv.org/abs/1802.06067

6 Gofaizen O.V., Pilyavskiy V.V. TV image colour appearance characteristics: Perception adaptive properties/Digital Technologies, 2011, No. 10, Pp. 86–105

7 Min Huang, Guihua Cui, Manuel Melgosa, Manuel Sánchez-Marañón, Changjun Li, M. Ronnier Luo, and Haoxue Liu Power functions improving the performance of color-difference formulas / Optics Express Vol. 23, Issue 1, pp. 597-610 (2015) https://doi.org/10.1364/OE.23.000597