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Influence of spectral characteristics inherent to cameras on color rendering in the multimedia images

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Abstract. The paper presents the research results concerning the end devices of multimedia paths. It is focused on the spectral characteristics of human vision, which are basic for the creation of light-to-signal converters. The influence of changes in the spectral characteristics of the sensitivity of the converters on the color rendition in the end-to-end multimedia path has been investigated. Changes in the spectral characteristics of the transducers caused by the refined spectral characteristics of CIE06 vision, supplemented with previously unknown characteristics of vision (ipRGC model), as well as one of the possible variants of color perception impairment (data of Prof. M. Neitz) have been considered. An algorithm has been presented, which allows calculating the spectral characteristics for new and promising light-to-signal converters, depending on the spectral characteristics of vision properties. Analytical expressions have been proposed, which makes it possible to correct the color signals of the existing light-to-signal converters to ensure the required level of color rendering quality in the end-to-end path. Estimates of the effectiveness of the proposed algorithm have been given.

Keywords: image, color space, spectral distribution, ipRGC, melatopsin.

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1. Introduction

The development of video technologies has reached the level where many practical tasks are performed using video streams, for example: driving cars, unmanned aerial vehicles, remote diagnostics and treatment of people (telemedicine), *etc*. This places high demands on image and video transmission systems. The requirements themselves lead to continuous modernization and improvement of video transmission systems. This is how high and ultra-high-definition television systems, digital cinema and photoprinting, multimedia technologies for interactive exchange and transmission of video information were created [1–4].

Many points of the end-to-end video transmission system have been significantly improved, which eliminated the appearance of unwanted changes in the transmitted video content, or their presence is imperceptible to the viewer. But at the same time, parts of the end-to-end video path remained, the influence of which was not considered, and this can lead to noticeable and sometimes unacceptable distortions. In the works [5–7], studies are presented, which reveal the degree of influence of light sources on the quality of color rendering. At the same time, there are other parts of the tract, which were not paid attention to in the works, they should include, for example, the properties of human vision [8], which are the initial data in the construction of final devices for the transmission and reproduction of images. In 2006 [9], the curves of vision sensitivity were revised, and differences were found. Some questions of the degree of influence on color rendering and interactive exchange between multimedia applications was not fully investigated.

Questions of physiological percepting information are presented in the works [10–12] that describe the CAM color perception model, which is currently the most complete analytical description of the adaptive processes of color perception. This model is based on average observer data. Consequently, the final devices of telecommunication paths, built on the basis of the characteristics of the average observer, have an error (from the viewpoint of each observer) and require further research in terms of the quality of color perception.

The aim of the work is to improve color rendering in converters “light-to-signal” and “signal-to-light”.

2. Difference between spectral characteristics of cameras based on the characteristics of CIE1931 and CIE2006

In the materials of the CIE standard [8], it is a question of clarifying the characteristics of color perception CIE1931. Refinements are related to a large extent to the blue and green regions of the spectral characteristics of vision sensitivity. If one considers changes in the context of telecommunication paths, which take as a basis the spectral characteristics of perception when designing the light-to-signal and signal-to-light converters (1), then the matrix NPM_{UHDTV} and $NPM^{-1}{}_{UHDTV}$ are applied. The direct and inverse *NPM* matrices are used to transition from the coordinates of the RGB color space to *xyz* and inverse. This is due to the fact that the data from the standard [9] are described in the *xyz* coordinate system, and telecommunication and multimedia applications operate in the RGB color space, therefore, a matrix of transition to a single coordinate system should be used.

The matrix is constructed using the algorithm presented in the ITU-R document [13] for a triangle with primary colors standardized for ultra-high-definition television [14]:

$$\begin{bmatrix} \bar{r}_\lambda \\ \bar{g}_\lambda \\ \bar{b}_\lambda \end{bmatrix} = NPM_{UHDTV} \begin{bmatrix} x\{\text{CIE1931}\}_\lambda \\ y\{\text{CIE1931}\}_\lambda \\ z\{\text{CIE1931}\}_\lambda \end{bmatrix},$$

$$\begin{bmatrix} x\{\text{CIE1931}\}_\lambda \\ y\{\text{CIE1931}\}_\lambda \\ z\{\text{CIE1931}\}_\lambda \end{bmatrix} = NPM_{UHDTV}^{-1} \begin{bmatrix} \bar{r}_\lambda \\ \bar{g}_\lambda \\ \bar{b}_\lambda \end{bmatrix},$$

$$NPM_{UHDTV} = \begin{bmatrix} 0.6369 & 0.1446 & 0.1688 \\ 0.2627 & 0.6780 & 0.0593 \\ 0.000 & 0.0280 & 1.0610 \end{bmatrix},$$

$$NPM_{UHDTV}^{-1} = \begin{bmatrix} 1.7167 & -0.3556 & -0.2533 \\ -0.6666 & 1.6165 & 0.0157 \\ 0.0176 & -0.0427 & 0.9420 \end{bmatrix},$$

where $\bar{r}_\lambda$, $\bar{g}_\lambda$, $\bar{b}_\lambda$ are the spectral characteristics of the sensitivity of the end devices of telecommunication paths within the range $\lambda \in 390\ldots720$ nm;
x, y, z\{CIE1931|CIE2006\} – spectral characteristics of the human vision apparatus presented by CIE.

The negative part of the characteristics indicates the incomplete coverage of the chromaticity diagram by the triangle of the ultra-high-definition television system. The spectral characteristics shown in Fig. 1 are idealized in one and in the other case are intended to realize the triangle of ultra-high-definition television.

Also, the presented expressions are valid for transforming the chromaticity coordinates of the image. The forward and backward transformation should be used for two options:

– the content is formed in the CIE31 system, and the transmission and reproduction systems are built on the CIE06 color space and reverse sequence; or

– the system is based on the CIE31 space and the transmission signals need to be corrected in accordance with CIE06.

The chromaticity coordinate transformations between the CIE1931 and CIE2006 spaces differ from the above and have the form (1):

$$\begin{bmatrix} \bar{r}\{\text{CIE2006}\}_\lambda \\ \bar{g}\{\text{CIE2006}\}_\lambda \\ \bar{b}\{\text{CIE2006}\}_\lambda \end{bmatrix} = NPM'_{UHDTV} \begin{bmatrix} x\{\text{CIE1931}\}_\lambda \\ y\{\text{CIE1931}\}_\lambda \\ z\{\text{CIE1931}\}_\lambda \end{bmatrix},$$

$$\begin{bmatrix} x\{\text{CIE1931}\}_\lambda \\ y\{\text{CIE1931}\}_\lambda \\ z\{\text{CIE1931}\}_\lambda \end{bmatrix} = NPM'^{-1}_{UHDTV} \begin{bmatrix} \bar{r}\{\text{CIE2006}\}_\lambda \\ \bar{g}\{\text{CIE2006}\}_\lambda \\ \bar{b}\{\text{CIE2006}\}_\lambda \end{bmatrix}. \quad (1)$$

NPM' calculated according to the formula provided in ITU-R BT.2380-2,

$$NPM' = P'_f \cdot diag\left(P'^{-1}_f \cdot W_{D65}\right),$$

$$NPM'^{-1} = P'_{inv} \cdot diag\left(P'^{-1}_{inv} \cdot W_{D65}\right),$$

where $P'_f = P \cdot k_{CIE}$ or

$$P' = \begin{bmatrix} x_r & x_g & x_b \\ y_r & y_g & y_b \\ z_r & z_g & z_b \end{bmatrix} \cdot \begin{bmatrix} x_{rk} & x_{g_k} & x_{bk} \\ y_{rk} & y_{g_k} & y_{bk} \\ z_{rk} & z_{g_k} & z_{bk} \end{bmatrix}$$

and $W_{D65} = \begin{bmatrix} x_W / y_W \\ 1 \\ z_W / y_W \end{bmatrix}$. For the inverse transformation, one should apply the formula $P'_{inv} = P \cdot k_{CIE}^{-1}$. The matrix k has a dimension of 3×3 and consists of coefficients that are determined from the expression $k = P_{UHDTV} / P_i$ for each i-th system.

Table 1. Values of the coefficient for the transition between color spaces.

Conversion type	**Correction factors, CIE1931 ⇒ CIE2006**	**Inverse correction factors, CIE2006 ⇔ CIE1931**
CIE1931 ⇔ CIE2006	$k_{CIE} = \begin{bmatrix} 1.0226 & 0.4761 & 1.0009 \\ 1.0361 & 1.3868 & 0.4909 \\ 0.6736 & 1.2264 & 1.1031 \end{bmatrix}$	$k_{CIE}^{-1} = \begin{bmatrix} 0.9779 & 2.1005 & 0.9991 \\ 0.9651 & 0.7211 & 2.0372 \\ 1.4845 & 0.8154 & 0.9065 \end{bmatrix}$

3. Physiological features of perception

The works of Prof. M. Neitz [15, 16] focus on the physiological characteristics of color perception, which can be one of the possible cases of color blindness, differing from the average characteristics, on the basis of which the spectral characteristics CIE1931 and CIE2006. As a result, the spectral characteristics of the sensitivity of vision have changes: the center of the blue region is shifted to the wavelength 415 nm; green region – to 530 nm, red – to 560 nm, as shown in [17]. It should also be noted that the green and red regions have deviations within 20…40 nm, as shown in Fig. 1.

Fig. 1 shows the characteristics of the end devices that should be implemented for undistorted color rendering with the characteristics presented in [17]. First of all, the concept of "undistorted" is considered from the viewpoint of an observer with limited visual abilities. It should be understood that the features of physiological perception can be much more, which will lead to a change in characteristics.

The statements made by N.D. Nyuberg [18], G. Wyszecki and W. Stiles [19], S.S. Patterson *et al.* [20], as well as F. Webler [21] indicate that perception is not only a physiological process, but also a psycho-physiological one. Consequently, a person perceives the distances between colors both in absolute values and in relative ones. This leads to the fact that the image transmitted by the multimedia paths can be adapted to the viewer, who has a limited visual ability, by applying the expressions presented in Table 2. As a result, perception of the number of colors in the image will be limited only by the observer's ability to distinguish color differences:

$$P_f' = P \cdot k_{CVD} \,. \qquad (2)$$

Based on transformation Table 2 and the condition that the viewer perceives the relative difference in colors, one can conclude that the transmission of shades will be greater than without applying the coefficient k_{CVD}^{-1}. In this case, there is no direct conversion, because there is no need to produce light-to-signal converters that would implement a limited color rendering area.

To evaluate the efficiency of the algorithm, it is proposed to use the number of colors that can be transmitted by the system. The input data is the number of colors present in the test image in Fig. 2. The output values are two conditions – reproduction on the final condition without proposed correction and with correction. The results are presented in Table 3.

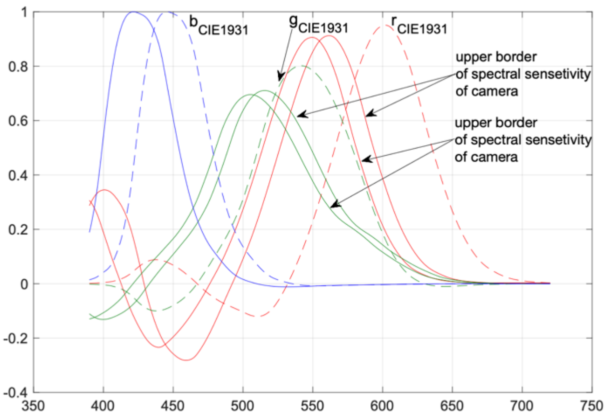


Fig. 1. Calculated spectral characteristics of the sensitivity inherent to the final device of the path, built on the basis of Prof. M. Neitz's data.

Table 2. Values of the coefficient for the transition between color spaces.

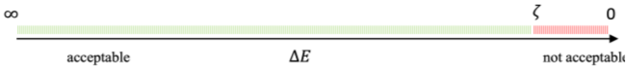
Conversion type	**Inverse correction factors, CIE1931 ⇒ CVD**
CVD_{upper} ⇔ CIE1931	$k_{CVD}^{-1} = \begin{bmatrix} 1.0567 & 0.4438 & 1.0661 \\ 1.0348 & 1.3771 & 0.3964 \\ 0.3927 & 1.6668 & 1.1104 \end{bmatrix}$
CVD_{under} ⇔ CIE1931	$k_{CVD}^{-1} = \begin{bmatrix} 2.2227 & 0.3873 & 1.1018 \\ 2.4740 & 1.4481 & 0.3014 \\ 0.0516 & 8.8411 & 1.1788 \end{bmatrix}$

Table 3. Comparison of the number of colors reproduced on the screen for options with and without correction. (The number of colors transmitted by ultra-high-definition television in absolute values $\sum C$ and in relative *p*, %)

	UHDTV, $\sum C_{UHDTV}$	$\sum C_{upper}$	*p*, %	$\sum C_{under}$	*p*, %
Test image – Fig. 2 (not correct)	495528	336219	67.8	291914	58.9
Test image – Fig. 2 (correct)		476624	96.1	384308	77.5

Definition 1. *Whatever the set of existing image colors* $\left(\sum C\right)$ *you can always find matrix coefficients* k^{-1}_{CVD} *using which you can transfer colors in a predetermined region of perceived colors.*

Provided that the color difference parameter is located in the area $\Delta E \in (\infty, \varsigma)$ and $\Delta E \in (\varsigma, 0)$ – the area of indistinguishability of colors.



The expression ΔE can be calculated using the presented expressions in [5].

4. Peculiarities of color transmission through the tract when taking into account ipRGC characteristics

The well-known three-component theory of vision, apparently, should be revised, given that the appearance of studies [17, 20–22] indicates the importance of the existence of another light-sensitive cell with a substance based on melanopsin (a component of the chemical composition of a light-sensitive cell responsible for maximum sensitivity to light energy at 485 nm). In [21, 22], the spectral characteristics of melanopsin sensitivity are presented; it can be seen that the prevailing part of the sensitivity belongs to the blue-green region.

But the problem remains: how to consider the emergence of new data on the photosensitive cell, which ultimately introduces changes in the traditional three-component spectral characteristics of vision. From the works of Prof. Tsujimura, as well as [21], it follows that melanopsin affects the perception of color. It is noted that these cells enhance the signal coming through them from light-sensitive blue and green cells, and the amplification process depends on the color of the stimulus in question. It should be understood that not in all possible cases do the same spectral distribution fall on light-sensitive cells. For the cases where an object has many colors, the amount of additions made by cells based on melanopsin is an open question and, most likely, will directly depend on the size of the stimulus.

Therefore, the spectral characteristics of transmitting and reproducing devices of multimedia and broadcast paths must take these features into account. Applying Eqs (1), (2), it is possible to determine the spectral characteristics of an ideal camera to ensure color rendition in the area of the color triangle of ultra-high-definition television. Fig. 2 shows the spectral characteristics of the camera calculated on the spectral response characteristics of CIE31. From previous works, it follows that with the prevailing blue color in the stimulus, the presence of cells with melanopsin complements the sensitivity of the blue area of the visual characteristics, which is reflected in the curve (b_{10} + melanopic); with the prevailing green color, three components of the spectral characteristics are supplemented (g_{10} + melanopic); in addition to blue and green (b_{10} + g_{10} + melanopic).

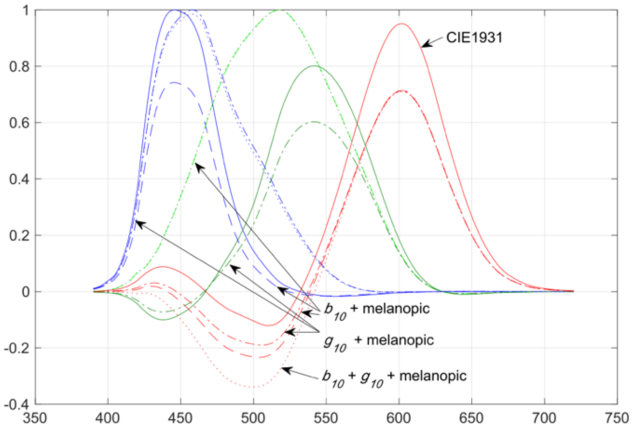


Fig. 2. Spectral characteristics of end devices with account of the spectral characteristics of melanopsin sensitivity.

It is not an easy task to physically realize this spectral composition. Moreover, in multimedia and broadcast systems, where the spectral composition of a scene object changes over time, it is not possible to apply only one of the spectral components. Based on this, to consider the properties of melanopsin perception, a variant of the correction factors presented in Table 1 can be Table 3.

Therefore, using the coefficients presented in Table 3, the ideal spectral characteristics of the light-to-signal converters can be calculated. One should also use P'_f for color correction in the case of image formation with traditional systems with spectral characteristics adduced in Fig. 1 or close to them.

$$P'_f = P\cdot k_{\{b_{10}, g_{10}, bg_{10}\}}, \quad P'_{inv} = P\cdot k^{-1}_{\{b_{10}, g_{10}, bg_{10}\}}. \qquad (3)$$

For the cases where the system has a transmitting device or a reproducing device built on the basis of CIE31 and CIE06 characteristics, the color rendition should be corrected using the formula (4):

$$P'_f = P\cdot k_{\{b_{10}, g_{10}, bg_{10}\}}\cdot k_{CIE}, \quad P'_{inv} = P\cdot k^{-1}_{\{b_{10}, g_{10}, bg_{10}\}}\cdot k^{-1}_{CIE}. \qquad (4)$$

It is necessary to understand that Eqs (3) and (4) are valid only for a certain set of colors. The use of one of the sets of correction factors can be expressed by the condition obtained from Fig. 3. Also, Fig. 3 shows the degree of influence of melanotropin on the spectral sensitivity of the chromaticity channels of the "light-to-signal" converter. The values of the influence on the blue-red and green-red channels of the transducer are presented. The interval of wavelengths for which the indicated in Table 3 matrix correction factors should be determined from Fig. 3 along the line reflecting the effect of melanopsin sensitivity on the sensitivity of all three-color channels of the cameras. Dots in this figure indicate areas where the curve passes through zero, which in turn indicates changes in the degree of influence. In the case

Table 3. Correction factors that take into account color perception based on the characteristics of melanopsin.

Conversion type	**Correction factors, ipRGC ⇒ CIE1931**	**Inverse correction factors, CIE1931 ⇒ ipRGC**
b_{10} + melanopic	$k_{b_{10}} = \begin{bmatrix} 1.0587 & 1.3977 & 1.3399 \\ 0.9901 & 1.6305 & 1.1307 \\ 0.0275 & 0.0847 & 0.9553 \end{bmatrix}$	$k^{-1}_{\bar{b}_{10}} = \begin{bmatrix} 0.9446 & 0.7155 & 0.7463 \\ 1.0100 & 0.6133 & 0.8844 \\ 36.318 & 11.804 & 1.0468 \end{bmatrix}$
g_{10} + melanopic	$k_{g_{10}} = \begin{bmatrix} 1.0587 & 1.3977 & 1.3399 \\ 0.9681 & 1.6305 & 1.1307 \\ 0.0275 & 0.0847 & 0.9553 \end{bmatrix}$	$k^{-1}_{\bar{g}_{10}} = \begin{bmatrix} 0.9446 & 0.7155 & 0.7463 \\ 1.0329 & 1.0439 & 7.3991 \\ 29.628 & 1.4058 & 0.6827 \end{bmatrix}$
b_{10} + g_{10} + melanopic	$k_{bg_{10}} = \begin{bmatrix} 1.0658 & 1.8773 & 1.7415 \\ 0.9746 & 1.2867 & 1.1757 \\ 0.0277 & 0.1138 & 1.2415 \end{bmatrix}$	$k^{-1}_{\bar{b}\bar{g}_{10}} = \begin{bmatrix} 0.9383 & 0.5327 & 0.5742 \\ 1.0261 & 0.7772 & 5.6930 \\ 36.076 & 8.7888 & 0.8055 \end{bmatrix}$

of positive values of the plot, the complex influence is reflected in the color rendering of all three spectral characteristics inherent to the camera r_{10}, g_{10}, b_{10}, and the negative ones – only on b_{10}, r_{10} or g_{10}, r_{10}.

Dots in this figure indicate areas where the curve passes through zero, which in turn indicates changes in the degree of influence. In the case of positive values of the plot, the complex influence is reflected in the color rendering of all three spectral characteristics inherent to the camera r_{10}, g_{10}, b_{10}, and the negative ones – only on b_{10}, r_{10} or g_{10}, r_{10}.

The condition for using the correction matrices for direct and inverse transformations can be written as

$$k_m = \begin{cases} k_{\{br\}_{10}} & \text{if } \lambda \in 390...473 \\ k_{\{rgb\}_{10}} & \text{if } \lambda \in 473...517 \\ k_{\{gr\}_{10}} & \text{if } \lambda \in 517...720 \end{cases} \quad (5)$$

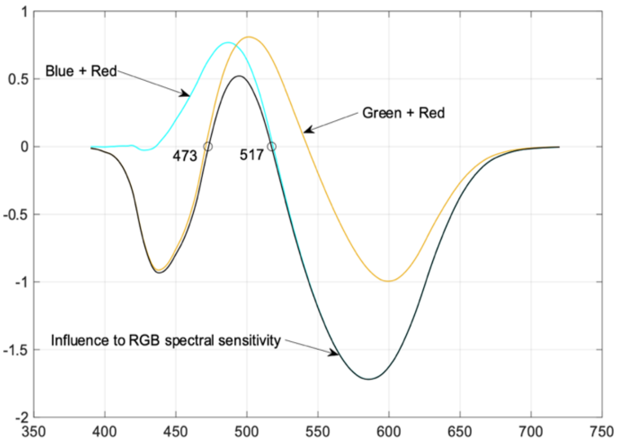


Fig. 3. The magnitude of the influence of sensitivity of the spectral characteristics of the final devices of TV and multimedia paths.

From the presented data, *we can make the statement that no matter what the spectral distribution of the image object P(λ), it will always be possible to find a matrix of coefficients k, applying which it will be possible to reduce the color rendering error to a minimum.*

The expression (5) denotes the effect of the correction factor in the range of wavelengths related to the locus (to the line of monochromatic colors). For coordinates with a relative saturation less than unity, one should determine the areas within which one of the three correction factors could be applied. Based on the presented expression (5), the condition for the existence of k coefficients can be written in the form

$$k_{\{br\}_{10}} = \begin{cases} y_1 > 2.338x + 0.402 \text{ for } 0.174 < x < 0.313 \\ y_2 < 1.270x + 0.068 \text{ for } 0.115 < x < 0.313 \end{cases}$$

$$k_{\{rgb\}_{10}} = \begin{cases} y_2 > 1.270x + 0.068 \text{ for } 0.115 < x < 0.313 \\ y_3 < -1.905x - 0.925 \text{ for } 0.052 < x < 0.313 \end{cases}$$

$$k_{\{gr\}_{10}} = \begin{cases} y_3 > -1.905x - 0.925 \text{ for } 0.052 < x < 0.313 \\ y_4 < -0.151x - 0.376 \text{ for } 0.313 < x < 0.735 \end{cases}$$

$$\left\{ k_{\{br\}_{10}}, k_{\{gr\}_{10}} \right\}_{magenta} = \begin{cases} y_1 > 2.338x + 0.4025 \\ \text{for } 0.174 < x < 0.313, \\ y_4 < -0.151x - 0.376 \\ \text{for } 0.313 < x < 0.735 \end{cases}$$

The specified conditions are presented for the coordinates of the reference white color of the D65 type, the equations for an arbitrary color temperature can be calculated using the following expression

Table 4. The relative areas of transmitted colors, considering the properties of vision, in comparison with the locus and the ultra-high-definition television system.

	Locus	**UHDTV**	**Upper, prof. Neitz**	**Under, prof. Neitz**	**ipRGC**
S_x / S_{locus}	1.00	0.63	0.26	0.14	0.63
$S_x / S_{triangle}$	–	1.00	0.41	0.23	1.00

S_{locus} is the area of the locus, $S_{triangle}$ – area of colors transmitted by the chromaticity triangle, S_x – area of colors perceived by a person with different spectral characteristics of perception.

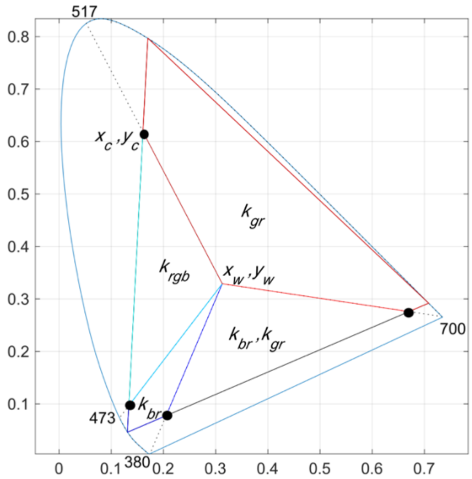


Fig. 4. The area of existence of correction matrices for ultra-high-definition television.

$$y_i = \frac{y_W - y_c}{x_W - x_c} x_i - \frac{x_c \left(y_W - y_c \right)}{x_W - x_c} + y_c ,$$

where y_i, x_i are coordinates of the i point of the segment $W \rightarrow$ c(chroma); y_W, x_W – coordinates of the reference white color; y_c, x_c – coordinates of the monochromatic color. Separation into the areas of colors is shown in Fig. 4.

5. Comparison of color rendering

If the areas of transmitted colors for different systems are compared, you can get the data presented in Table 4.

6. Conclusions

The materials presented in the article allow the expansion of understanding of the spectral characteristics of color perception. The presented expressions (2)–(4) allow the characteristics of perception to be considered, and the correcting coefficients built on their basis can be applied to the transmitted and reproduced image without changing the spectral characteristics of the latter. Therefore, corrective factors should be used for error-free color reproduction.

Applying Eqs (1)–(4), the author has obtained the corrected color values in ultra-high-definition television in accordance with the viewer's perception properties. The use of correction factors and the given quantitative indicators for the conversion of CIE1931 and CIE2006 does not seem possible to achieve significant indicators, which is caused by small differences in the spectral characteristics of the sensitivity. An increase in the number of transmitted colors by 18–28% is achieved by applying the expression (2), while the key is the condition reflected in Definition 1. It is understood that the result may vary depending on the transmitted image.

Studies of the influence of melanopsin and the use of correcting matrices did not allow increasing the area of transmitted colors formed earlier using a three-component ultra-high-definition television system. This is primarily related to the fact that the area of perceived colors, considering the properties of melanopsin, is larger than the area of ultra-high-definition television. Therefore, the transmitted image is deliberately limited in the area of colors, and it is difficult for an observer to identify the appearance of additional colors. Expansion of the range of transmitted colors is possible when constructing new spectral characteristics. In this case, the use of the expression (4) made it possible to correct the colors in four zones, as a result of experiments. To correct, four values of the coefficients should be applied; to achieve the accuracy of results, variable coefficients should be used, the values of which will change depending on the area of their existence.

As shown in the studies, the process of color perception and color rendering is related and more complex than it was previously imagined in multimedia systems and related applications, which means that it requires further research, since it does not have an unambiguous solution.

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Вплив спектральних характеристик камер на передавання кольору мультимедійних зображень

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Анотація. У статті представлено результати досліджень кінцевих пристроїв мультимедійних шляхів. Основну увагу приділено спектральним характеристикам людського зору, які є основними для розробки перетворювачів світло-сигнал. Досліджено вплив змін спектральних характеристик чутливості перетворювачів на передавання кольору в наскрізному мультимедійному тракті. Зміни спектральних характеристик перетворювачів через уточнені спектральні характеристики зору CIE06 доповнено раніше невідомими характеристиками зору (модель ipRGC), а також одним із можливих варіантів порушення сприйняття кольору (дані проф. М. Нейца). Наведено алгоритм, який дозволяє обчислювати спектральні характеристики для нових і перспективних перетворювачів залежно від спектральних властивостей зору. Запропоновано аналітичні вирази, які дають можливість корегувати кольорові сигнали існуючих перетворювачів, щоб забезпечити необхідний рівень якості передачі кольорів у наскрізному шляху. Наведено оцінки ефективності запропонованого алгоритму.

Ключові слова: зображення, кольоровий простір, спектральний розподіл, ipRGC, мелатопсин.