

## ANALYSIS OF PHYSIOLOGICAL COLORIMETRIC SYSTEMS OF TRICHROMATS

George V. Boos, Andrei A. Grigoryev\*, and Victoria A. Rybina

*National Research University Moscow Power Engineering  
Institute (NRU MPEI), Moscow, Russia  
E-mail: \*aag.2010@yandex.ru*

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### ABSTRACT

Criteria for determining whether a physiological colorimetric system<sup>1</sup> belongs to the colour space of basic colorimetry have been formulated. A method for assessing the correspondence of an arbitrary colour space to the physiological space of the CIE 1931 standard colorimetric observer is presented. Studies of CIE-recommended colorimetric spaces – CIEPO06, Judd, Mac-Adam, and several other well-known systems – revealed that they are non-physiological for the CIE standard observer. The error in the colour-matching functions of the physiological  $LMS_{\text{phys}}$  system, caused by the uncertainty in the position of the reference colour stimulus  $S$  within the Nyberg triangle, has been quantified.

**Keywords:** colour-matching functions, colorimetric systems, dichromats, trichromats, protanopes, deuteranopes, statistical theory, comparison fields

### 1. INTRODUCTION

All existing methods for evaluating the quantitative and qualitative characteristics of floodlighting installations and their components (light sources and luminaires) rely on experimental studies to establish colour equality between two comparison fields. These experiments are essential for determin-

ing the colour-matching functions (CMFs) of colorimetric systems, which form the basis of all lighting engineering calculations.

According to Schrödinger [1, 2], the task of defining CMFs for any colorimetric systems is addressed within basic colorimetry, which is grounded in the Young – Helmholtz theory and Grassmann’s laws [3]. The work of Maxwell and Schrödinger demonstrated that the colour space (CS) of basic colorimetry is a three-dimensional affine space where the coordinates of points, directed segments, and their lengths are defined, but neither distances nor angles between these segments are specified. For visual representation, Grassmann and later Schrödinger introduced a vector colour space, which is widely used in colorimetry.

Basic colorimetry is founded on the theory that the human visual system, under photopic vision, perceives responses from three types of cone photoreceptors with partially overlapping spectral sensitivity curves, Fig. 1, (a). This overlap makes it impossible to measure even the relative spectral sensitivities of the three cone types through direct colour-matching function assessment experiments. Indirect methods, such as using dichromats instead of trichromats [4, 5], inducing artificial colour blindness in receptors [6], and others, rely on hypotheses with limited applicability. These approaches have led to discrepancies in the measured sensitivity distributions of  $L$ -,  $M$ -,  $S$ - cones reported by different authors. Despite these variations, the colour spaces constructed from these  $L$ ,  $M$ , and  $S$  sensitivity functions are termed as “physiological” by their authors.

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<sup>1</sup> In Russia, there is a concept of a physiological colorimetric system in which the colour-matching functions correspond to the spectral sensitivities of the  $L$ -,  $M$ - and  $S$ -cone types.

Since the vector colour space (CS) constructed from the basic colorimetry CS is linear [2], Grassmann's laws [3] imply that the number of equivalent colorimetric systems is infinitely large. This property of CS is erroneously extended to the physiological CS of basic colorimetry. According to Meisel [7], a physiological CS is defined as one where the spectral sensitivities of the three receptors in the average human eye with normal vision of trichromat coincide with the CMFs of that CS.

As demonstrated in [8], individual spectral sensitivity curves of  $L$ -,  $M$ -,  $S$ - receptors vary significantly among trichromats. Consequently, their averaged values differ across observer groups and deviate from the reference  $L$ ,  $M$ ,  $S$  sensitivities, established for reference receptors. In our view, this is one reason for the proliferation of distinct physiological CS proposed by various authors. A second cause lies in the use of dichromats to derive spectral sensitivity functions for trichromats. As shown in [8], this approach introduces substantial errors in determining the  $\bar{l}(\lambda)$  function.

Based on the Young – Helmholtz theory, Grassmann's laws, and visual physiology data [3], it's possible to formulate criteria that should be met by the physiological CS of an arbitrary set of trichromat's observers. All trichromatic CSs in basic colorimetry are related by means of linear transformations, which makes their analysis most convenient within the framework of the standardized CIE colorimetric system [9]. The XYZ system is particularly advantageous, as colour luminance is defined by a single coordinate,  $Y$ .

### 1.1. Criteria for Belonging of a Physiological Colorimetric System to the Colour Space of Basic Colorimetry

There are next criteria to belong to CS of basic colorimetry:

1. In the photopic vision range (luminance  $L_v \geq 10 \text{ cd/m}^2$ ) signals from all  $L$ ,  $M$ ,  $S$  receptors in the physiological colour space must be greater than zero. This criterion is uncontested among lighting engineers, and many proposed physiological systems satisfy it.

2. The luminance sensation elicited by positive  $L$ ,  $M$ ,  $S$  receptor signals cannot be negative. Thus, the luminance coefficients of the physiological CS must also be positive.

3. A physiological CS must account for the positive luminance sensations of real colours in individuals with colour vision deficiencies. Specifically, it must explain the experimentally confirmed fact that protanopes, deutanopes, and tritanopes exhibit distinct but always positive spectral luminous efficiency.

4. Since the transformation of a chromaticity diagram from one colorimetric system to another is projective, the chromaticity coordinates of all real colours must lie within the reference colour stimuli triangle (RCST) in both the physiological CS and any other colorimetric system derived via projective transformation.

The authors of "physiological" colorimetric systems analysed the obtained functions in relation to only some of the requirements mentioned above, what is not enough for a truly physiological system. Experimental data in [8] demonstrate that even when trichromats analysing, the formulated criteria are not always met in the reference colorimetric system.

This discrepancy arises because CMFs derived from specific trichromatic observer groups may differ markedly in shape and peak positions from those of the Guild and Wright observer set, which the CIE established as the reference for constructing the RGB and XYZ systems. Consequently, a colorimetric system deemed "physiological" for an author's observer group may not qualify as such for the CIE reference trichromats.

The value of developing niche "physiological" CS is limited unless they align with the reference RGB and XYZ systems. Thus, defining a CS that is truly physiological for these CIE-standardized systems is critical. Only such a CS can be universally recognized as the physiological colour space of trichromats.

The significance of determining CMFs for a trichromat's physiological colorimetric system lies in its ability to account for chromatic adaptation of  $L$ ,  $M$ ,  $S$  receptors in a physiologically valid manner. This is critical for modern colour difference spaces such as OSA-UCS, DIN99d, CAM02-UCS, CAM16, and others, which rely on these principles.

## 2. RESEARCH METHOD

In accordance with CIE recommendations, authors of physiological colour spaces typically characterize their systems using transition matrices that

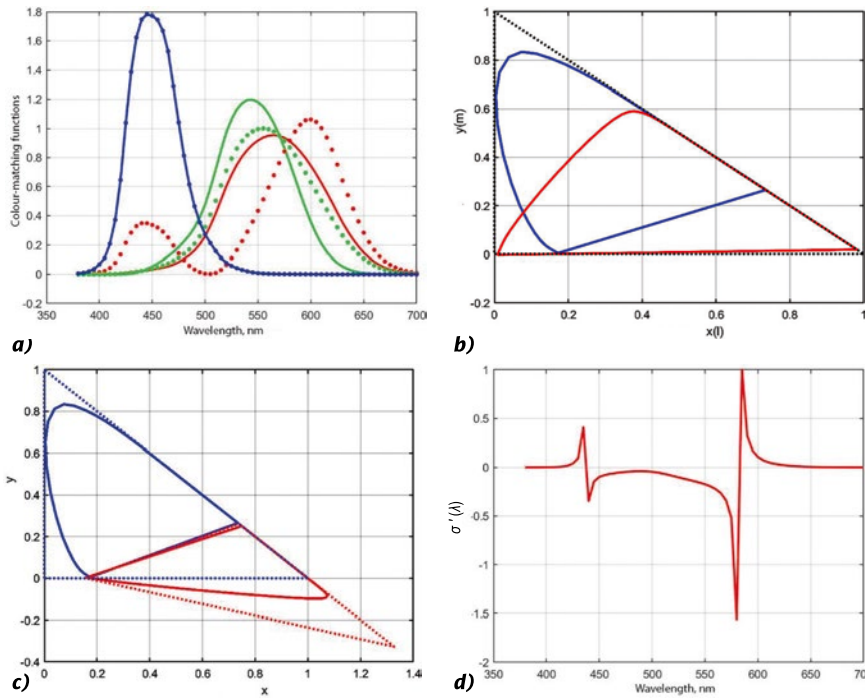


Fig. 1. Plots for the CIEPO06 and XYZ colorimetric systems: a) colour-matching functions; b) chromaticity diagram in the reference colour space; c) chromaticity diagram of CIEPO06 (red) within the XYZ (blue); d)  $\sigma'(\lambda)$ .

convert their CS's CMFs into the standard XYZ system. However, full specifications of physiological CS, including CMFs, transition matrices, and luminance coefficients, are rarely provided.

Furthermore, instead of transition matrices from physiological CS to XYZ system, authors often provide coefficient matrices that convert the relative spectral sensitivities of the physiological CS receptors into colour-matching functions of XYZ system. While there is no inherent issue with this approach, since the equal-energy illuminant "E" is centred in the chromaticity diagram (a principle used in constructing the XYZ system), it remains straightforward to derive forward and inverse transition matrices between the physiological CS and XYZ system using these coefficients.

The critical problem lies in the fact that deriving such transition matrices does not validate the physiological nature of these CS. According to Grassmann's laws, infinitely many equivalent colorimetric systems exist, but only one corresponds to the physiological colour space of the reference trichromat. For example, the CIE 1931 RGB system is undeniably a trichromat colorimetric systems, yet it fails to describe a physiological colour space because receptor responses in this system assume negative values, violating Criterion 1. Similarly, the XYZ system cannot qualify as physiological, as "dichromats" lacking the "X" or "Z" receptors exhib-

it unchanged relative luminous efficiency compared to trichromats, contradicting experimental data and Criterion 3.

The core of the proposed methodology involves analysing known physiological CS for compliance with the criteria outlined above. If any criterion, evaluated in the reference XYZ system, is not satisfied, the colorimetric system in question cannot represent the physiological colour space of the standardized trichromat adopted as the reference.

### 3. RESULTS

In 2006, CIE Technical Committee 1–36 published a report [10], recommending the use of the physiological colour space (cone fundamentals) CIEPO06, for which the following matrix, converting the relative  $L, M, S$  colour-matching functions to the XYZ system, was provided in 2019 [5]:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 1.9473 & -1.4144 & 0.3647 \\ 0.6899 & 0.3483 & 0 \\ 0 & 0 & 1.9348 \end{pmatrix} \begin{pmatrix} L \\ M \\ S \end{pmatrix}. \quad (1)$$

This transformation (1) enables the derivation of transition matrices from the LMS system to XYZ system and vice versa, as well as the chromaticity coordinates of the  $L, M, S$  reference colour stimuli in  $X, Y, Z$ :

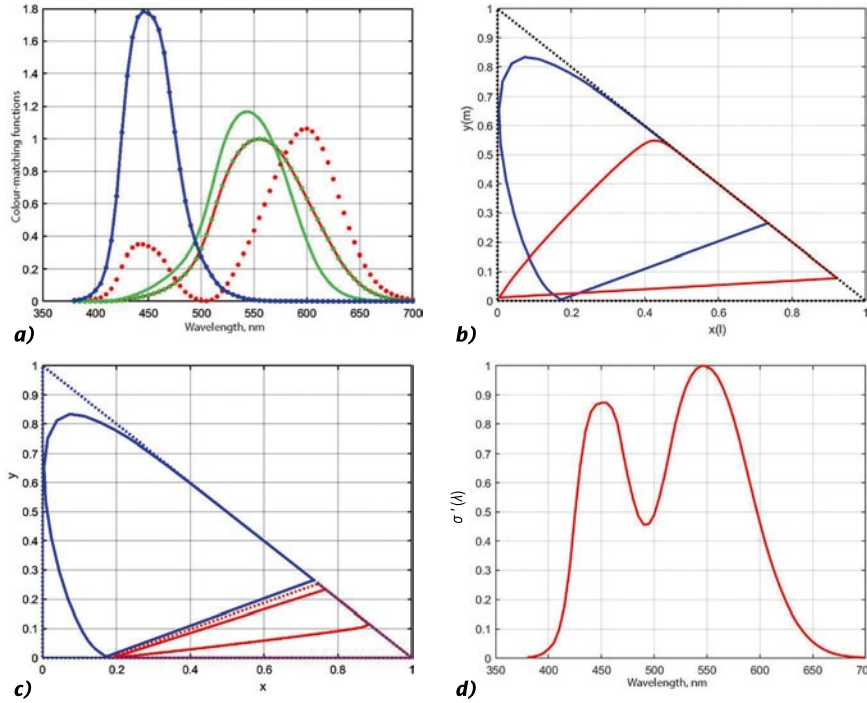


Fig. 2. Plots for the Judd and XYZ colorimetric systems: a) colour-matching functions; b) chromaticity diagram in the reference colour space; c) chromaticity diagram (red) within the XYZ (blue); d)  $\sigma'(\lambda)$

$$\begin{aligned}
 (L M S) &= (X Y Z) \begin{pmatrix} 0.205244 & -0.497222 & 0 \\ 0.833449 & 1.403485 & 0 \\ -0.038693 & 0.093737 & 1 \end{pmatrix}, \\
 (X Y Z) &= (L M S) \begin{pmatrix} 1.997938 & 0.707823 & 0 \\ -1.18646 & 0.292177 & 0 \\ 0.188522 & 0 & 1 \end{pmatrix}, \quad (2) \\
 \begin{pmatrix} x_L & y_L & z_L \\ x_M & y_M & z_M \\ x_S & y_S & z_S \end{pmatrix} &= \begin{pmatrix} 0,738401 & 0,261599 & 0 \\ 1,326716 & -0,326716 & 0 \\ 0,158619 & 0 & 0,841381 \end{pmatrix}.
 \end{aligned}$$

Fig. 1, (a) shows the colour-matching functions of the XYZ system (dashed curves) and CIEPO06 LMS systems (solid curves), while Fig. 1, (b) displays their chromaticity diagrams in the reference colour space. Using the methodology from [3, 8, 11], the  $l, m$  chromaticity diagram for CIEPO06 was calculated, Fig. 1, (c). In the XYZ system, the luminance coefficient of the  $Y$  reference colour stimulus is 1, while those of the other two reference colour stimuli are zero. Thus,  $Y$  coordinate of the sum of the tristimulus values,  $\sigma'(\lambda)$  [23], transformed into XYZ system from CIEPO06 (or another system), must remain positive for all real colours, as it is proportional to the perceived luminance. This  $Y$  coordinate can be calculated based on the known values of the converted in CS  $X, Y, Z$  chromaticity coordinates  $Y'(\lambda)$  for real colours  $l, m$  in the CIEPO06 CS, Fig. 1, (c), and the CMF  $\bar{y}(\lambda)$  derived

via the transition matrix (2) for the LMS system of CIEPO06, Fig. 1, (a).

$$\begin{aligned}
 y'(\lambda) &= \frac{Y'(\lambda)}{\sigma'(\lambda)}, \\
 \sigma'(\lambda) &= \frac{Y'(\lambda)}{y'(\lambda)},
 \end{aligned}$$

where  $Y'(\lambda)$  represents the wavelength-dependent  $Y$  coordinate of monochromatic radiation, obtained by using equation (2).

Since matrix (2) was designed by the CIEPO06 authors to ensure  $Y'(\lambda) = \bar{y}(\lambda)$ ,

$$\sigma'(\lambda) = \frac{\bar{y}(\lambda)}{y'(\lambda)}.$$

Fig. 1. (d) plots  $\sigma'(\lambda)$  for CIEPO06.

Calculations  $\sigma'(\lambda)$  reveal that, according to CIEPO06, monochromatic radiation at  $\lambda$  in range (440–580) nm is perceived by the standard trichromat with negative luminance. Fig. 1, (c) further shows that non-monochromatic colours with chromaticity coordinates below the alychne ( $x$ -axis) also exhibit negative luminance. This confirms that the CIEPO06 CS is not a physiological colorimetric system for the trichromat, corresponding to the CIE 1931 XYZ and RGB systems.

The best results among the analysed systems were obtained for Judd's colorimetric system [3], with reference colour stimuli's chromaticity coordinates in XYZ system:

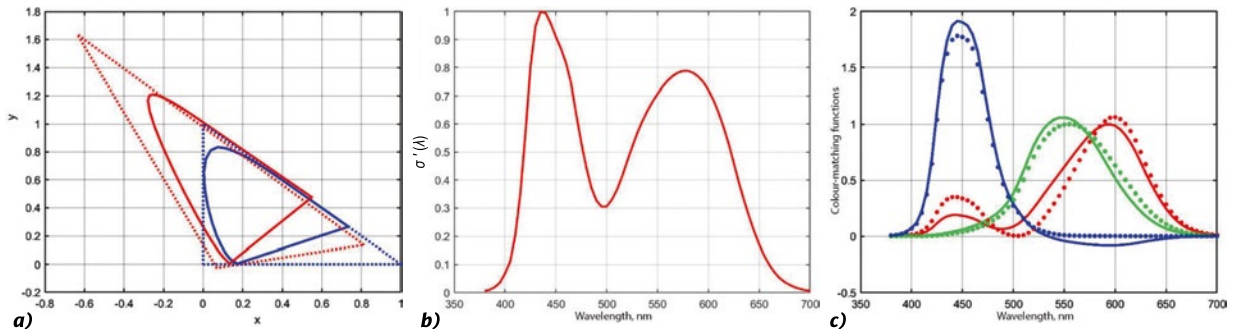


Fig. 3. Plots for the König and Dieterici colorimetric system: *a*) chromaticity diagram of the König and Dieterici colorimetric system (red) within the XYZ system (blue); *b*)  $\sigma'(\lambda)$ ; *c*) colour-matching functions for the König and Dieterici colorimetric system

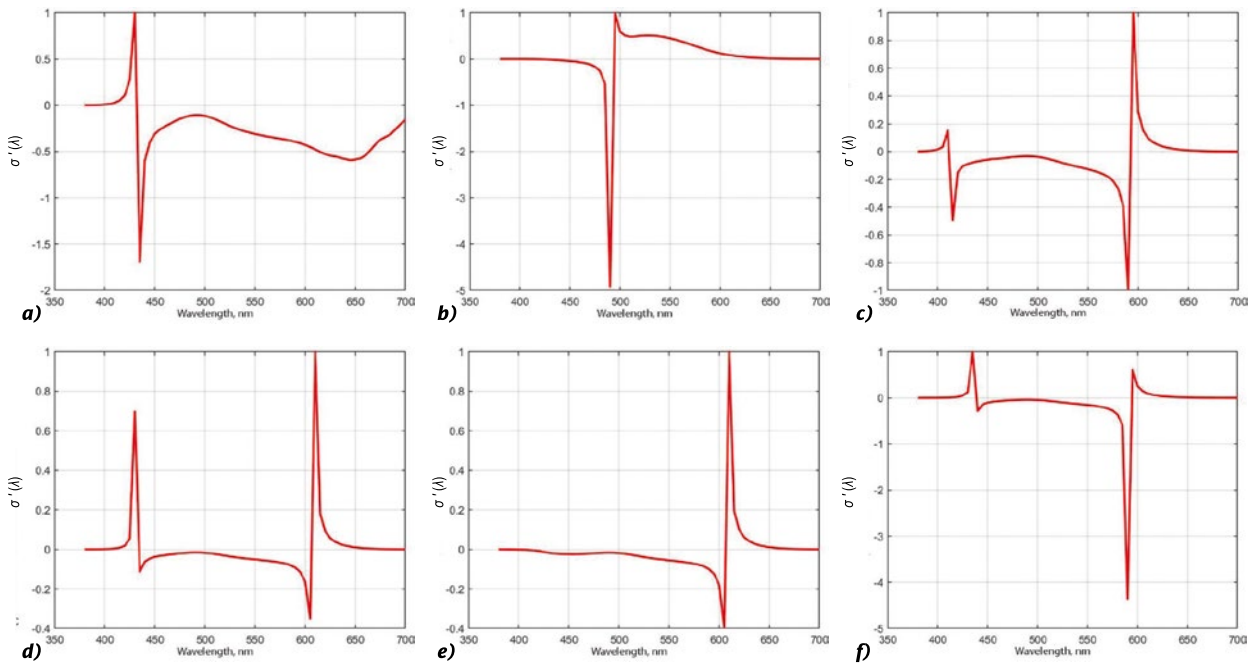


Fig. 4. Transformation of  $\sigma'(\lambda)$  into the XYZ colorimetric system for the colorimetric systems of: *a*) Pitt [14], *b*) Stiles [15], *c*) Szekeres [16], *d*) Yustova [4], *e*) Mac-Adam [17], *f*) Kustarev [18]

$$(L, M, S) = \begin{pmatrix} 2,96 & -2,17 & 0,22 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

these yield the following transition matrices between  $X, Y, Z$  and  $L, M, S$  CMFs:

$$(L, M, S) = (X, Y, Z) \left. \begin{pmatrix} 0 & -0,46 & 0 \\ 1 & 1,36 & 0 \\ 0 & 0,1 & 1 \end{pmatrix} \right\} \\ (X, Y, Z) = (L, M, S) \left. \begin{pmatrix} 2,95 & 1 & 0 \\ -2,17 & 0 & 0 \\ 0,22 & 0 & 1 \end{pmatrix} \right\}.$$

Results for Judd’s colorimetric system, analogous to those for CIEPO06, are shown in Fig. 2.

Judd’s colorimetric system satisfies all physiological criteria except Criterion 3, placing the  $S$  and  $M$  reference colour stimuli on the alychne renders protanopes (lacking  $L$  receptors) blind in this system. Additionally, Judd’s colorimetric system implies identical luminous efficiency for deuteranopes and trichromats, contradicting experimental data in Judd’s own work [3]. Thus, Judd’s colorimetric system is also non-physiological for the CIE 1931 standard observer.

Similar calculations chromaticity diagrams and  $\sigma'(\lambda)$  were performed for 10 other colorimetric systems, Table 1.

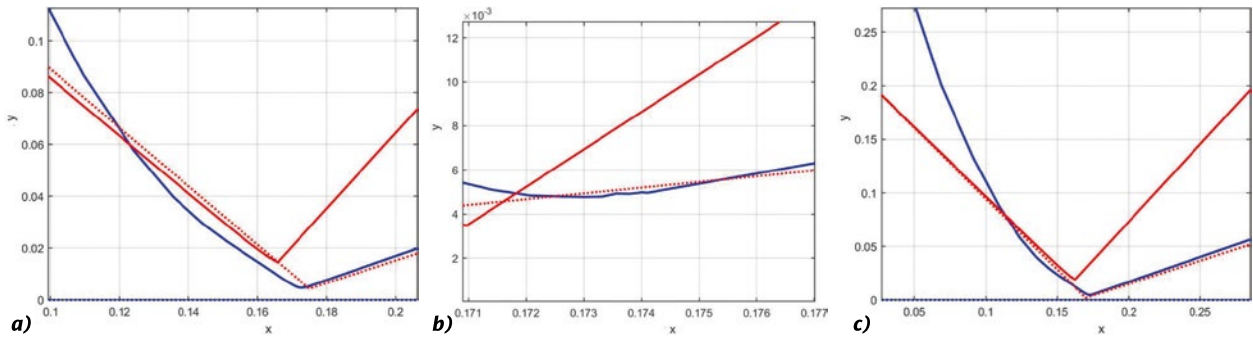


Fig. 5. Chromaticity diagrams (solid curves) and reference colour stimuli triangle (dashed curves), magnified for the colorimetric systems of: a) Thomson and Wright [19], b) Fedorov [6], c) Sperling [20]

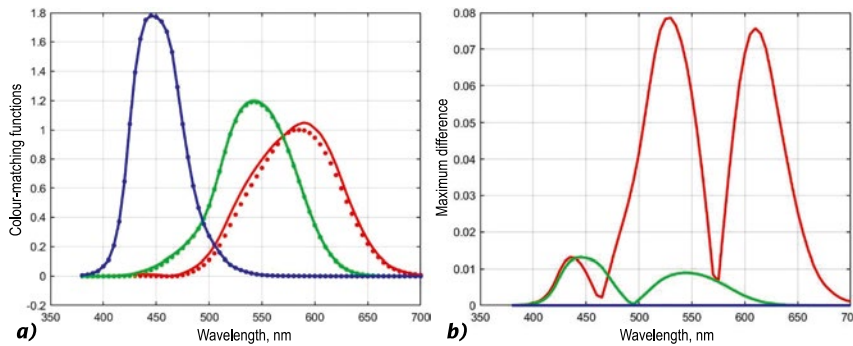


Fig. 6. Maximum (solid curves) and minimum (dashed curves) values of the colour-matching functions of the  $LMS_{phys}$  colorimetric system – a, maximum differences between the CMFs – b

For König and Dieterici colorimetric system [13], negative values of the  $\bar{s}(\lambda)$  function at  $\lambda > 535$  nm, Fig. 3, indicate its non-physiological property for the trichromat in XYZ system.

#### 4. DISCUSSION

Fig. 4 shows  $\sigma'(\lambda)$  calculations for six colorimetric systems from the Table 1, including MacAdam’s colorimetric system [17], recommended by the CIE and Russian standard [12] for evaluating light source colour rendering. Negative luminance values for some real colours indicate that, from the reference XYZ system perspective, none of these systems qualify as physiological.

The last three colorimetric systems in the Table 1, like König and Dieterici, have a positive  $y$ -coordinate for the  $M$  reference colour stimulus, ensuring  $\sigma'(\lambda) > 0$  across the visible spectrum. However, they cannot be fully deemed physiological, as their CMFs assume negative values at certain wavelengths.

Fig. 5 magnifies the chromaticity diagrams of the XYZ system (solid blue curves) and three colorimetric systems from the table (solid red curves).

Since all three colorimetric systems RCST (red dashed lines) intersect the  $X, Y, Z$  chromaticity dia-

gram, their colour-matching functions exhibit negative values at specific wavelengths:

- Thompson and Wright’s colorimetric system:  $\bar{l}(\lambda) < 0$  at  $\lambda < 470$  nm.
- Fedorov’s colorimetric system:  $\bar{m}(\lambda) < 0$  at  $\lambda = (400–405)$  nm.
- Sperling’s colorimetric system:  $\bar{l}(\lambda) < 0$  at  $\lambda = (495–540)$  nm.

#### CONCLUSIONS

The conducted study demonstrates that the analysed colorimetric systems are not physiological for the CIE 1931 standard colorimetric observer. Reference [8] presents the development of the  $LMS_{phys}$  colorimetric system, which eliminates the shortcomings of the reviewed systems. The chromaticity coordinates of its reference colour stimuli are listed in the table’s final row, with the following distinguishing features:

1.  $L$  reference colour stimulus in  $LMS_{phys}$  system is a real colour with  $x, y, z$  chromaticity coordinates  $(0.7346657271, 0.2653342729, 0)$  [21].
2. Positive luminance coefficients: All reference colour stimuli in the XYZ system have strictly positive luminance coefficients, as their  $y$  coordinates lie above the alychne.

**Table 1. The Chromaticity Coordinates of the Reference Colour Stimuli of Ten Colorimetric Systems within the XYZ System**

№	Authors	L		M		S	
		$x_l$	$y_l$	$x_m$	$y_m$	$x_s$	$y_s$
1	König, A., & Dieterici, C [13]	0.814	0.136	-0.636	1.636	0.069	-0.026
2	Pitt, F. H. G [14]	0.745	0.257	10.991	-9.74	0.16	0.004
3	Stiles, W. S [15]	0.788	0.213	1.118	-0.115	0.175	-0.017
4	Szekeres, G. A [16]	0.736	0.264	1.458	-0.456	0.174	0.002
5	Yustova, E. N [4]	0.748	0.252	1.65	-0.65	0.174	0.002
6	MacAdam, D. L [17]	0.747	0.253	1.75	-0.759	0.178	0
7	Kustarev, A. K [18]	0.737	0.2653	1.43	-0.43	0.173	0.0045
8	Thomson, L. C., Wright, W. D [19]	0.747	0.253	-5.94	6.91	0.175	0.0044
9	Fedorov, N. T [6]	0.825	0.175	-1.22	2.22	0.156	0.0005
10	Sperling, H. G [20]	0.746	0.252	-5.66	7.713	0.17	0.002
	<b>LMS<sub>phys</sub> system [8]</b>	<b>0.7347</b>	<b>0.2653</b>	<b>-5.2457</b>	<b>6.2457</b>	<b>0.1692</b>	<b>0.0011</b>

3. Reference colour stimuli triangle: The LMS<sub>phys</sub> system RCST fully encloses the XYZ system chromaticity diagram without intersecting it, ensuring positive colour-matching functions for all real colours perceived by trichromats.

The aforementioned features of the LMS<sub>phys</sub> system enable the description of all known colour-matching phenomena for the XYZ system trichromat within the framework of basic colorimetry, the Young-Helmholtz theory, and Grassmann's laws. However, it cannot be asserted that the CMFs of LMS<sub>phys</sub> system precisely align with the physiological system of Guild and Wright's observers. The reason lies in the inability to definitively determine the position of the *S* reference colour stimulus from Guild and Wright's experimental data. Nyberg [22] proposed a method to define the region of possible chromaticity coordinates for the *S* reference colour stimulus, based on Criteria 1–3 outlined earlier in this article. This region forms a triangle of very small area. As shown by calculations in [4, 21], the position of the *S* reference colour stimulus has negligible impact on the  $\bar{m}(\lambda)$ ,  $\bar{s}(\lambda)$  colour-matching functions and only weakly affects  $\bar{l}(\lambda)$ , though deviations remain. The work in [8] reduced the area of the Nyberg triangle by more than half, enabling a more precise estimation of the maximum deviation between LMS<sub>phys</sub> system CMFs and those of the physiological system corresponding to the RGB and XYZ systems. Fig. 6, (a) illustrates, for each wavelength, the maximum (solid curves) and minimum (dashed curves) values of the CMFs

across all possible positions of the *S* reference colour stimulus. Fig. 6, (b) shows the absolute differences between these values, providing an assessment of the maximum calculation errors.

Differences in Fig. 6 stem from *S*-reference colour stimulus uncertainty, not discrepancies with XYZ system. All colorimetric systems with *S* within the Nyberg triangle align with XYZ system calculations to 5–6 decimal places. That is sufficient to ensure physiological colorimetric systems errors are negligible compared to experimental noise. Except for points on the alychne, any *S* position within the Nyberg triangle satisfies all criteria. Placing *S* reference colour stimulus at the triangle's geometric centre (as in LMS<sub>phys</sub> system) is statistically justified.

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**George V. Boos,**

Ph. D. and Member of the Russian Academy of Natural Sciences. In 1986, he graduated from the Moscow Power Engineering Institute (MPEI). At present, he is the President of MSK BL

GROUP, Head of the Light and Engineering subdepartment of NRU MPEI. He is Recipient of the State Prize of the Russian Federation for Architectural Lighting of Moscow, the Chairman of the Science and Engineering Board Svetotekhnika and of the editorial board of the Svetotekhnika/Light & Engineering Journal



**Andrei A. Grigoryev,**

Doctor of Technical Sciences, Professor. In 1981, he graduated from the Moscow Power Engineering Institute (MPEI). At present, he is the Professor of the Lighting Engineering subdepartment

of NRU MPEI, the Head of the Vision Functions Research Group at Sergey Vavilov Russian Lighting Research Institute (VNISI)



**Viktoria A. Rybina,**

Ph. D. In 2018, she graduated from NRU MPEI. At present, she is a Associate Professor of the Light and Engineering subdepartment of NRU MPEI and researcher of the Vision Functions Research

Group of Sergey Vavilov Russian Lighting Research Institute (VNISI)