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ON THE CAUSES OF DIFFERENCES BETWEEN THE COLOUR-MATCHING FUNCTIONS OF PHYSIOLOGICAL SYSTEMS OF TRICHROMATS AND DICHROMATS

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ABSTRACT

The article discusses the reasons for the differences between the colour-matching functions (CMF) of the physiological trichromat system $(LMS)_{phys}$[1] and the cone fundamentals of the CIEPO06 colorimetric system and the CMF of Nyberg-Yustova colorimetric system $(LMS)_{NY}$[1]. It has been shown that the hypothesis, which has prevailed for many years, that dichromatism is caused by the absence of one of the trichromat's receptors, cannot explain the difference in spectral sensitivity of *L*-, *M*- and *S*-type cones of trichromats and dichromats. It is shown that the CIEPO06 and $(LMS)_{NY}$ functions can be obtained from the $(LMS)_{phys}$ CMF of trichromats if the algorithm for determining reference colour stimuli in dichromats is based on a dominant receptor detecting signals from a neighbouring receptor with reduced sensitivity.

The results obtained indicate that protanopes have almost no *L*-cones, and therefore the sensitivity of their long-wavelength *M*-receptors matches that of trichromats' *M*-cones. This demonstrates that the algorithm for forming the long-wavelength reference colour stimulus *M* in protanopes aligns with the hypothesis that they lack trichromats' *L*-cones. A different result was observed for deuteranopes. The contribution of *M*-cone signals to the sensitivity of deuteranope *L*-cones exceeds 40 %. This is why the measured spectral sensitivity of their *L*-receptors differs significantly from that of normal trichromat's *L*-receptors. This result suggests that using the CIEPO06 functions as spectral sensitivities for trichromats is not justified. Since the algorithms for forming reference colour stimuli in the human visual system vary among trichromats, protanopes, and deuteranopes, the authors suggest introducing three different physiological colorimetric systems: one for trichromats based on $(LMS)_{phys}$, and separate systems for protanopes and deuteranopes based on CIEPO06.

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

1. INTRODUCTION

To calculate the quantitative and qualitative characteristics of floodlighting installation, the International Commission on Illumination (CIE) introduced the *L*-, *M*-, and *S*-receptor responses on the wavelength of monochromatic radiation affecting the human visual system (HVS). Since Maxwell's work [1], dichromats have been used to define the functions of the physiological trichromat system (i.e., humans with normal colour vision). According to the Young-Helmholtz theory [2], dichromats lack one of the three cone types: *L*-cones (red-sensitive, denoted as К in Russian literature) in protanopes, *M*-cones (green-sensitive, З) in deuteranopes, or *S*-cones (blue-sensitive, С) in tritanopes. In addi-

[1] 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.

tion to this explanation of dichromacy (the "loss of receptors" hypothesis), there exists an alternative "merging" hypothesis proposed by Helmholtz in the second edition of his Physiological Optics. This hypothesis suggests that dichromacy arises from the fusion of sensitivities of adjacent receptors. However, the "merging" hypothesis is disregarded by proponents of using dichromats, as only the "loss of receptors" hypothesis allows the measurement of spectral sensitivity functions for *L*- and *M*-receptors in trichromats. This measurement can be achieved through two distinct methods.

This hypothesis suggests that dichromacy occurs when the sensitivities of adjacent receptors merge. However, proponents of the use of dichromats disregard the "merging" hypothesis, as only the "loss of receptors" allows for the measurement of spectral sensitivity functions for *L*- and *M*-cones in trichromats. These measurements can be achieved using two distinct methods.

1.1. The First Method

The first method is based on establishing luminance matching monochromatic comparison fields under special adaptation conditions. Within the daylight vision, the rod signals maintain a consistent level due to their saturation state. Therefore, during measurements, the *S*-cones must also be driven into saturation. This is achieved by illuminating the comparison fields with monochromatic radiation at a wavelength λ_s, to which the *S*-cones are sufficiently sensitive, while the dichromat's remaining receptors are practically insensitive. Under these conditions, the dichromat perceives two monochromatic comparison fields, Fig. 1, *(a)*, and can adjust their luminance to equality with threshold precision. The spectral sensitivity of the investigated receptor, in relative units, is determined by the ratio:

$$S_0(\lambda) = \frac{\Phi(\lambda)}{\Phi(\lambda_{ref})},$$

where $\Phi(\lambda_{ref})$ is the constant monochromatic radiant flux at wavelength λ_{ref} incident on the right comparison field, and $\Phi(\lambda)$ is the monochromatic radiant flux at wavelength λ incident on the left comparison field at the moment of luminance equality.

This method for determining $S_0(\lambda)$ relies on von Kries' hypothesis, which posits that receptor adaptations occur independently. Thus, adaptation of the blue receptor does not affect the sensitivity of other HVS receptors. This hypothesis has been experimentally confirmed by numerous authors [2].

1.2. The Second Method

The second method is based on colour matching of comparison fields by dichromats under natural HVS adaptation and deriving the chromaticity coordinates of the HVS reference colour stimuli from these results, Fig. 1, *(b)*.

In [3], a key expression for basic photometry is derived, forming the foundation of this method. Let the authors write the colour equation for a trichromat:

$$\boldsymbol{\Phi} = L\mathbf{L} + M\mathbf{M} + S\mathbf{S},$$

where **L, M, S** are the reference stimuli of the colour space, and *L, M, S* are the colour coordinates.

The spectral sensitivity of a dichromat (protanope or deuteranope) can generally be expressed as the sum of the sensitivities of the *L*- and *M*-receptors:

$$A = \alpha L + \beta M, \qquad (1)$$

where A is the colour coordinate of the dichromat's second colour-perceiving mechanism (in addition to ***S***), and α, β are weighting coefficients ($\alpha + \beta = 1$).

For the dichromat's two-dimensional colour space, the colour equation takes the form:

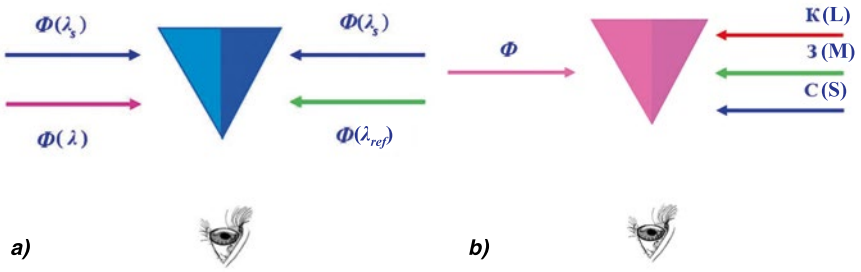

Fig. 1. Basic diagrams of equalization of comparison fields by lightness *(a)* and by colour *(b)*

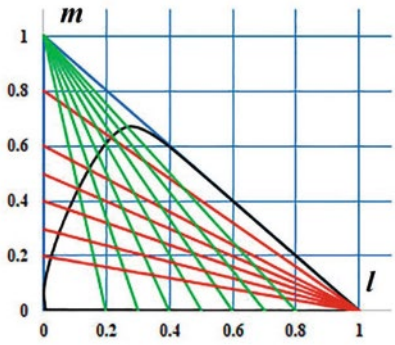

Fig. 2. Bundles of lines on the chromaticity diagram (black) of a trichromat, indistinguishable by protanopes (red lines, α = 0) and deuteranopes (green lines, $\beta = 0$)

$$\boldsymbol{\Phi} = S\mathbf{S} + A\mathbf{A}, \tag{2}$$

where **A** is the unit vector of the dichromat's second colour-perceiving mechanism (in addition to ***S***).

For a classical protanope, who lacks *L*-receptors, the coefficients α and β in Equation (1) are set to 0 and 1, respectively. For a deuteranope, who lacks *M*-receptors, the coefficients are reversed: $\alpha = 1$, $\beta = 0$.

From equation (2), it follows that dichromats perceive two radiations as identical if the ratio $n = SA$ remains constant:

$$\frac{S}{\alpha L + \beta M} = n. \tag{3}$$

Rewriting Equation (3) in terms of chromaticity coordinates

$$\left(l = \frac{L}{L+M+S},\ m = \frac{M}{L+M+S},\right.$$
$$\left. s = \frac{S}{L+M+S}\right): \frac{s}{\alpha l + \beta m} = n. \tag{4}$$

Given that $s = 1 - l - m$, equation (4) leads to the equation of colours indistinguishable to dichromats in the trichromat's colour space:

$$l(1+\alpha n) + m(1+\beta n) - 1 = 0. \tag{5}$$

Equation (5) defines a bundle of lines passing through a common point with coordinates:

$$\left.l = \frac{\beta}{\beta - \alpha},\ m = -\frac{\alpha}{\beta - \alpha}\right\}.$$

As shown in Fig. 2, the pole of this bundle equation (5) constructed for varying *n* and $\alpha = 0$ coincides with the chromaticity of the reference stimulus ***L***. When $\beta = 0$, it coincides with the chromaticity of the reference stimulus ***M***.

2. PROBLEM STATEMENT

Both measurement methods assume that:

– The algorithm for establishing colour equality of comparison fields,

– The algorithm for perceiving reference colour stimuli,

– The spectral sensitivities of receptors are identical for trichromats and dichromats.

While the latter condition can be satisfied by selecting dichromats via DNA tests, and the validity of the first condition was verified in [4], the second hypothesis remains unsubstantiated. Its validity has long been questioned in colorietry, prompting a series of articles in the mid-20th century [4, 5]. In our view, claims about the hypothesis' correctness are not based on experimental evidence but rather on the absence of alternative methods for determining the spectral sensitivities of trichromat eye receptors under natural (or near-natural) adaptation.

In [7], this assumption is challenged. A statistical theory of HVS function was developed, explaining the origin of colour thresholds, along with a mathematical model for calculating their magnitude. This enabled the creation of a method to determine the spectral sensitivities of trichromats with varying visual deviations. Experimental results from this work, combined with findings from [8], led to the development of the physiological colorimetric system $\boldsymbol{(LMS)_{phys}}$ [9], fully aligned with the standard CIE ***XYZ*** colorimetric system:

$$\left(\bar{l}_{\text{ph}}(\lambda), \bar{m}_{\text{ph}}(\lambda), \bar{s}_{\text{ph}}(\lambda)\right) = \left(\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)\right) \times$$
$$\times \begin{pmatrix} 6.116466\text{e-}01 & -5.077397\text{e-}01 & 7.143363\text{e-}07 \\ 5.137178\text{e-}01 & 1.40609\text{e+}00 & -1.978225\text{e-}06 \\ -1.253644\text{e-}01 & 1.016469\text{e-}01 & 1.000001\text{e+}00 \end{pmatrix}.$$

The spectral sensitivities of the developed system differ significantly from their counterparts in the CIE-recommended CIEPO06 system, Fig. 3. The reasons for this discrepancy require clarification.

3. METHODOLOGY

The CIEPO06 model is largely based on the work of A. Stockman and L.T. Sharpe [10–12]. Their experimental studies employed a method

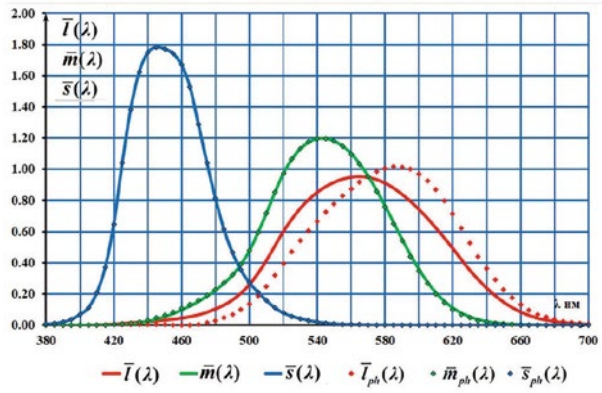

Fig. 3. Spectral sensitivities of receptors CIEPO06 $\left(\bar{l}(\lambda), \bar{m}(\lambda), \bar{s}(\lambda)\right)$ and $\boldsymbol{(LMS)_{phys}}$ $\left(\bar{l}_{ph}(\lambda), \bar{m}_{ph}(\lambda), \bar{s}_{ph}(\lambda)\right)$

to isolate "blue" cones (*S*-cones), using dichromats as observers instead of trichromats. Dichromats were selected via DNA tests.

As noted in [7], the CMF of the human visual system are determined not only by cone sensitivity (trackable via DNA tests) but also by neural signal processing. The perception of luminance and colour arises not at the receptor output but after the brain processes these signals. This signal processing algorithm may be fundamentally different for trichromats, who have three types of receptors, and dichromats, who lack one of the receptors but still have the ability to perceive colour and luminance.

In our opinion, the difference between the measured LMS receptor sensitivities in CIEPO06 and $\boldsymbol{(LMS)_{phys}}$ stems from the differences in HVS signal processing algorithms between trichromats and dichromats. Analysis of the results in [9] showed that even trichromats have variability in the threshold-level colour differences. However, this variability has a minimal impact on the spectral sensitivity determination for LMS receptors, as the signal levels during colour matching far exceed the thresholds. The main factor is the difference in the reference colour stimuli identification algorithms: trichromats use three reference stimuli, while dichromats use only two. According to a hypothesis repeatedly proposed since the last century, when the maximum sensitivity of one trichromat receptor drops below a threshold (due to colour anomaly), the brain ceases to interpret its signal as originating from a distinct receptor. Instead, it merges (sums) this signal with that of an adjacent, dominant receptor. This creates a dichromat's colour space based on two receptors, each with its own spectral sensitivity curve. Thus, a person with defective colour vision becomes a dichromat. Until recently, confirming or refuting this hypothesis was impossible, as it required knowledge of the "true" spectral sensitivities of trichromat's receptors. Since the $\boldsymbol{(LMS)_{phys}}$ system [9] was derived solely from trichromat data, the authors suggest that it's $\bar{l}_{ph}(\lambda)$, $\bar{m}_{ph}(\lambda)$, $\bar{s}_{ph}(\lambda)$ values represent "true" sensitivities. This enables the authors to test the receptor-merging hypothesis in dichromats.

4. RESULTS

Let us consider the first method to determining the addition functions of dichromats, as previously discussed.

In [11], a matrix of coefficients is provided for converting the relative spectral sensitivities of *L*-, *M*-, *S*-receptors from CIEPO06 to the ***XYZ*** system. This matrix is not a direct transformation matrix between CIEPO06 and ***XYZ***. However, following CIE recommendations that the chromaticity coordinates of an equa*l*-energy illuminant (CIE standard illuminant E) should lie at the centre of the colour triangle (a principle used in developing ***XYZ***), forward and inverse transformation matrices between ***XYZ*** and CIEPO06 can be derived. The inverse transformation is expressed as:

$$\left(\bar{l}(\lambda), \bar{m}(\lambda), \bar{s}(\lambda)\right) = \left(\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)\right) \times \times \begin{pmatrix} 0.205244 & -0.497222 & 0 \\ 0.833449 & 1.403485 & 0 \\ -0.038693 & 0.093737 & 1 \end{pmatrix}, \quad (6)$$

Calculations using equation (6) and the $\left(\bar{l}_{ph}(\lambda), \bar{m}_{ph}(\lambda), \bar{s}_{ph}(\lambda)\right)$ function of $\boldsymbol{(LMS)_{phys}}$ are shown in Fig. 3. Significant discrepancies are evident between the dependencies $\bar{l}(\lambda)$ and $\bar{l}_{ph}(\lambda)$.

Rewriting equation (1) for these functions yield:

$$\bar{a}(\lambda) = \alpha \bar{l}(\lambda) + \beta \bar{m}(\lambda), \quad (7)$$

where $\bar{a}(\lambda)$ is the spectral sensitivity of a protanopia or deuteranopia, measured via comparison matching field.

For protanopes, the system of equations (7) across different wavelengths becomes:

$$\left.\begin{aligned} \bar{m}_p(\lambda_1) &= \alpha_p \bar{l}_{ph}(\lambda_1) + \beta_p \bar{m}_{ph}(\lambda_1) \\ \bar{m}_p(\lambda_2) &= \alpha_p \bar{l}_{ph}(\lambda_2) + \beta_p \bar{m}_{ph}(\lambda_2) \\ &\cdots\cdots \\ \bar{m}_p(\lambda_n) &= \alpha_p \bar{l}_{ph}(\lambda_n) + \beta_p \bar{m}_{ph}(\lambda_n) \end{aligned}\right\}. \quad (8)$$

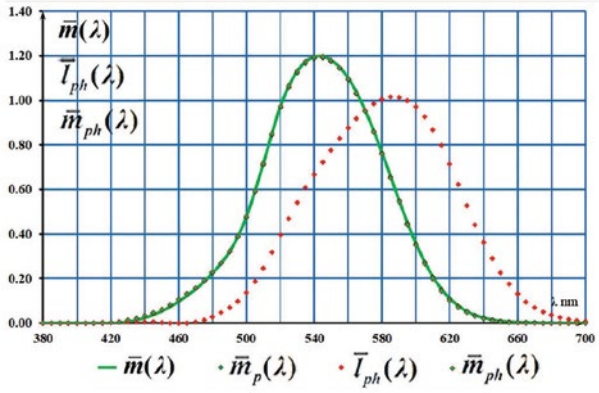

Fig. 4. Spectral sensitivities of receptors ***CIEPO06*** $\bar{m}(\lambda)$, $\bar{m}_p(\lambda)$ and $(LMS)_{phys}$ $\bar{m}_{ph}(\lambda)$, $\bar{l}_{ph}(\lambda)$

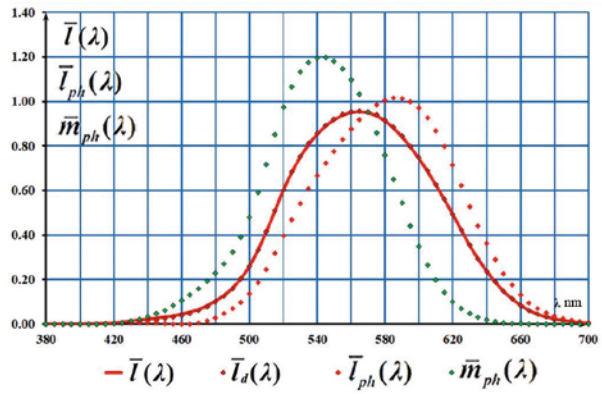

Fig. 5. Spectral sensitivities of receptors ***CIEPO06*** $\bar{l}(\lambda)$), $\bar{l}_d(\lambda)$ and $(LMS)_{phys}$ $\bar{m}_{ph}(\lambda)$, $\bar{l}_{ph}(\lambda)$

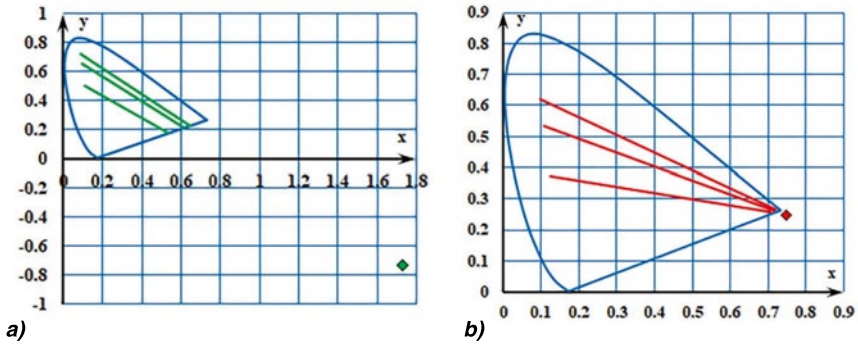

Fig. 6. To determine the coordinates of reference stimuli $(LMS)_{NY}$: *a* – colour M_{NY}, *b* – colour L_{NY}

Solving equation (8) over the visible spectrum using the least squares method gives coefficients $\alpha_p = 0.012$, $\beta_p = 0.988$. Calculations of $\bar{m}_p(\lambda)$ using these coefficients in equation (7) closely match the ***CIEPO06*** $\bar{m}(\lambda)$ values, Fig. 4, with an integral difference of just over 1 % [7]. The negligible value of α_p compared to β_p indicates a practically complete absence of sensitivity in "red" receptors (*L*-cones) for protanopes. This explains why the $\bar{m}(\lambda)$ function, derived in [11] and assuming total *L*-receptor absence in protanopes, aligns closely with $\bar{m}_{ph}(\lambda)$ for trichromats, showing an integral difference of ≤1.5 %, Fig. 4.

A different scenario arises for deuteranopes. Rewriting the system of equations (8) for deuteranopes yields:

$$\left.\begin{aligned} \bar{l}_d(\lambda_1) &= a_d \bar{l}_{ph}(\lambda_1) + \beta_d \bar{m}_{ph}(\lambda_1) \\ \bar{l}_d(\lambda_2) &= \alpha_d \bar{l}_{ph}(\lambda_2) + \beta_d \bar{m}_{ph}(\lambda_2) \\ &\cdots\cdots \\ \bar{l}_d(\lambda_n) &= \alpha_d \bar{l}_{ph}(\lambda_n) + \beta_d \bar{m}_{ph}(\lambda_n) \end{aligned}\right\}. \qquad (9)$$

Solving equation (9) gives coefficients $\alpha_d = 0.641$, and $\beta_d = 0.359$. Calculations of $\bar{l}_d(\lambda)$ using these coefficients in equation (7) closely match the $\bar{l}(\lambda)$, Fig. 5, with an integral difference of less than 0.8 %.

Here, α_d and β_d are comparable, differing by a factor of 1.79. This indicates a substantial contribution (up to 44 %) from "green" receptors (*M*-cones), presumed absent in deuteranopes, to their long-wavelength "red" spectral sensitivity. According to the hypothesis of combining receptor reactions in dichromats, this sensitivity can be achieved for deuteranopes when they are used as observers to equalize the comparison fields in terms of lightness.

Let us now consider the second method, which is based on colour matching between comparison fields and involves the use of dichromats as observer.

In the works of Yustova and Nyberg [4, 6], dependencies were constructed using data from 4 protanopes and 3 deuteranopes following the scheme in Fig. 1, *(b)*. A subset of these dependencies is shown in Fig. 6. The intersection points of the bundles of lines enabled the derivation of a transformation matrix from the ***XYZ*** system to the Nyberg-Yustova LMS system $(LMS)_{NY}$:

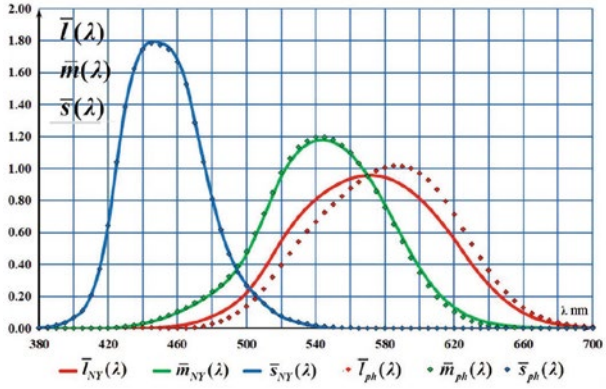

Fig. 7. Spectral sensitivities of receptors $(\boldsymbol{LMS})_{\mathbf{NY}}$ $\left(\bar{l}_{\mathrm{NY}}(\lambda), \bar{m}_{\mathrm{NY}}(\lambda), \bar{s}_{\mathrm{NY}}(\lambda)\right)$ and $(\boldsymbol{LMS})_{\mathbf{phys}}$ $\left(\bar{l}_{\mathrm{ph}}(\lambda), \bar{m}_{\mathrm{ph}}(\lambda), \bar{s}_{\mathrm{ph}}(\lambda)\right)$

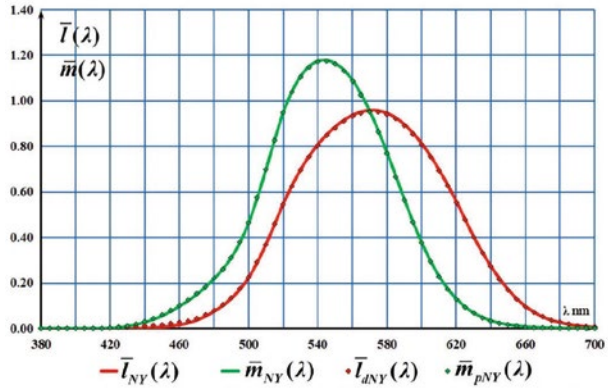

Fig. 8. Spectral sensitivities of receptors $(\boldsymbol{LMS})_{\mathbf{NY}}$ $\bar{l}_{\mathrm{NY}}(\lambda)$, $\bar{m}_{\mathrm{NY}}(\lambda)$ and $\bar{l}_{\mathrm{dNY}}(\lambda)$, $\bar{m}_{\mathrm{pNY}}(\lambda)$

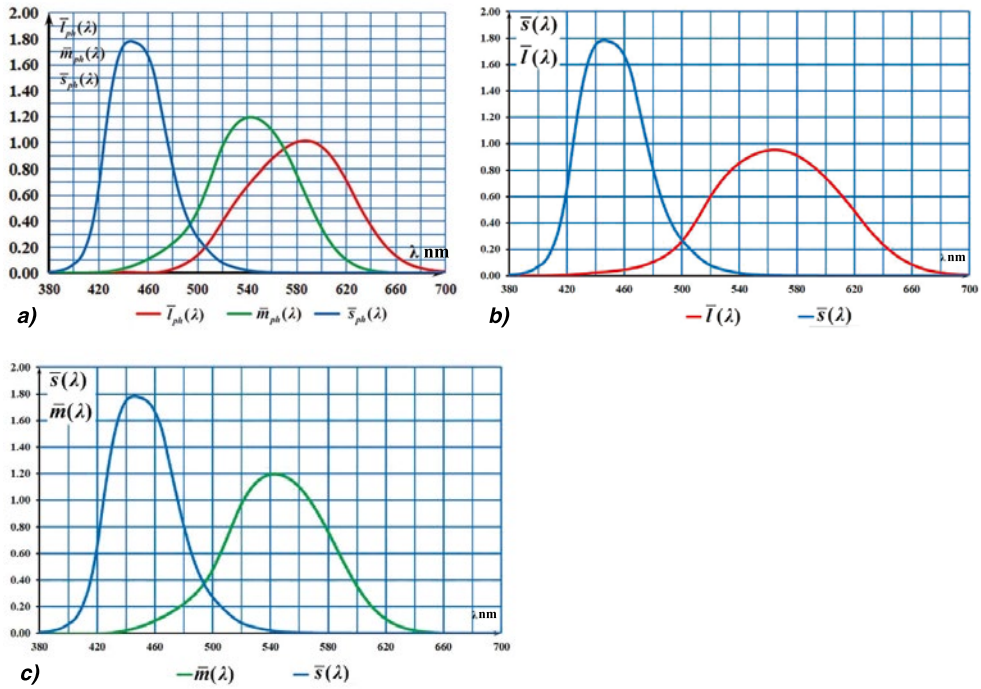

Fig. 9. Spectral sensitivities of receptors: trichromat *(a)*, deuteranope *(b)*, and protanope *(c)*

$$\left(\bar{l}_{\mathrm{NY}}(\lambda), \bar{m}_{\mathrm{NY}}(\lambda), \bar{s}_{\mathrm{NY}}(\lambda)\right) = \left(\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)\right) \times \times \begin{pmatrix} 0.747 & 0.25 & 0.003 \\ 1.74 & -0.73 & -0.01 \\ 0.174 & 0.005 & 0.821 \end{pmatrix}. \quad (10)$$

Fig. 7 compares the results of calculations using equation (10) with the $\left(\bar{l}_{\mathrm{ph}}(\lambda), \bar{m}_{\mathrm{ph}}(\lambda), \bar{s}_{\mathrm{ph}}(\lambda)\right)$ curves.

Solving equation (8) for the $\bar{m}_{\mathrm{pNY}}(\lambda)$ function yields coefficients $\alpha_p = 0.045$, and $\beta_p = 0.955$. For equation (9), applied to $\bar{l}_{dNY}(\lambda)$ the coefficients are $\alpha_d = 0.74$ and $\beta_d = 0.26$.

Fig. 7 shows the calculated values of $\bar{m}_{\mathrm{pNY}}(\lambda)$ and $\bar{l}_{\mathrm{dNY}}(\lambda)$ using equation (7), alongside experimental values derived from equation (10).

The results show that calculations of $\bar{l}_{\mathrm{dNY}}(\lambda)$ using equation (7) with $\alpha_d = 0.74$, and $\beta_d = 0.26$ closely match Yustova's experimental values $\bar{l}_{NY}(\lambda)$. Similarly, values of $\bar{m}_{\mathrm{NY}}(\lambda)$ and $\bar{m}_{\mathrm{pNY}}(\lambda)$, calculated with $\alpha_p = 0.045$ and $\beta_p = 0.955$, align nearly perfectly, Fig. 8, with integral differences of <0.5 % for $\bar{m}_{\mathrm{pNY}}(\lambda)$ and ~1 % for $\bar{l}_{\mathrm{dNY}}(\lambda)$.

These findings demonstrate that protanopia involves the loss of sensitivity in *L*-receptors of trichromats, while deuteranopia results from the merging of trichromat *L*- and *M*-receptors into a single *L*-receptor in deuteranopes.

5. DISCUSSION AND CONCLUSIONS

A comparison of the spectral sensitivity curves of dichromats, obtained via different methods, demonstrates that these curves are defined with sufficient accuracy, Figs. 3 and 7. The reasons for the differences between the results of different studies can be found in the different sets of observers, the number of observers, and the experimental methods used. The cone fundamentals, which relate to the HVS of a dichromat, are considered to be more reliable, explaining the discrepancy with the $(LMS)_{phys}$ functions derived from studies of trichromats. This study reveals that ***using dichromats to determine trichromat colorimetric characteristics introduces significant errors***, as trichromats and dichromats employ distinct algorithms for associating receptor signals with colour perception.

The authors propose three distinct physiological colorimetric systems:

1. Trichromats are based on $(LMS)_{phys}$,

2. Protanopes and Deuteranopes are based on CIEPO06**,** Fig. 9.

Mapping the two-dimensional CMF of deuteranopes and protanopes into the three-dimensional $(LMS)_{phys}$ or ***XYZ*** colour spaces is akin to reconstructing a 3D image from a 2D sketch. The chromaticity diagrams of dichromats, projected into the trichromat's 3D space, form bundles of lines, equation (5), and cannot approximate the full trichromat chromaticity diagram. Combining two dichromat systems (as in CIEPO06) fails to replicate trichromat functions, as their reference colour stimuli formation algorithms differ fundamentally.

This issue has both fundamental and practical implications. For example, calculating the colour rendering index R_a [13] for light sources with low correlated colour temperatures (< 3000 K) yields differences of 2.5 units between CIEPO06 and $(LMS)_{phys}$. For special indices R_1– R_8 discrepancies reach 7 units and for R_9 they exceed 14 units. These differences are significant for evaluating the colour rendering quality of LED light sources.

The proposed framework also explains the existence of deuteranomalous and protanomalous trichromats, whose brains process signals from three receptors even when one receptor's sensitivity is reduced. The range of defective colour vision spans from normal trichromat sensitivity to the signal capture threshold, where the dominant receptor subsumes the weakened receptor's signal. Below this threshold, the person with defective colour vision becomes a dichromat.

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