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Colorimetry and Dichromatic Vision

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Abstract

Normal trichromats have three types of cone photoreceptors: L, M, and S cones (most sensitive to long, medium, or short wavelengths, respectively). Therefore, standard colorimetry is based on three variables (X, Y, Z). Dichromats only have two types of functional cones due to genetic factors. The main consequences are that dichromats (1) confuse colors that can only be discriminated by the response of the type of cone they lack and (2) make errors when naming colors. Chromaticity diagrams can be used to specify dichromats' color confusions. Confusion points represent imaginary stimuli that only activate L, M, or S cones. Confusion lines radiate from confusion points and represent pseudoisochromatic stimuli (i.e., colors confused by the corresponding type of dichromat if presented at an appropriate intensity). Dichromat's color appearance models have been developed to simulate the colors supposedly seen by dichromats, and there exist color simulation tools that implement some of those models.

Keywords: dichromacy, color vision, color simulation, color naming, color preference

1. Introduction

Normal trichromats have three types of cone photoreceptors in the retina: L, M, and S cones (most sensitive to long, medium, or short wavelengths, respectively). Therefore, standard colorimetry, which was developed for normal trichromats, is based on three variables (X, Y, Z) [1], and it is not directly suitable for severe color vision deficiencies like dichromacy [2].

Dichromats only have two types of functional cones due to genetic factors [2, 3]. Protanopes, deuteranopes, and tritanopes lack L, M, or S cones, respectively. Protanopes and deuteranopes are also known as red-green dichromats and constitute the most frequent form of dichromacy, affecting about 2% of human males. Tritanopia is a much rarer disorder that affects less than 0.01% of humans. The structure of this chapter reflects the main consequences of

this physiological feature for dichromats at different levels: (1) color discrimination, (2) color appearance, (3) color naming, and (4) color preference.

Regarding color discrimination, dichromats confuse colors that can only be discriminated by the response of the type of cone they lack. How can we use standard colorimetry to characterize dichromatic color vision? Chromaticity diagrams can be used to specify dichromats' color confusions if we assume that dichromacy is a reduced version of trichromacy [4, 5]. In brief, confusion points represent imaginary stimuli that only activate L, M, or S cones. Confusion lines radiate from confusion points and represent pseudoisochromatic stimuli (i.e., colors confused by the corresponding type of dichromat if presented at the appropriate intensity). Section 1.1 will describes the rationale of this procedure in greater detail and will introduces a feature present in most part of red-green dichromats, the so-called residual red-green discrimination, which to some extent can challenge the validity of this procedure.

Although chromaticity diagrams are a powerful tool to characterize color confusions in dichromats, they do not tell us anything about the appearance of colors in this kind of observers. Dichromat's color appearance models have been developed to simulate the colors supposedly seen by dichromats, and there exist color simulation tools that implement some of those models. Section 1.2 will describe in some detail one of the most famous color appearance models in dichromats [6].

1.1. Chromaticity diagrams, confusion lines, and cone fundamentals

1.1.1. Chromaticity diagrams and confusion lines

Under the assumption that dichromacy is a reduced form of trichromacy (*reduction*, *loss*, or *König hypothesis*), it is possible to use standard chromaticity diagrams in order to characterize dichromatic color confusions [4, 5]. **Figure 1** shows confusion lines radiating from confusion points for protanopes (first row), deuteranopes (second row), and tritanopes (third row) in *CIE 1931 xy* (left panel) and *CIE 1976 u'v'* (right panel) chromaticity diagrams. Confusion or copunctal points represent imaginary stimuli that only activate a given type of cone and can be determined by the intersection of several confusion lines for a given type of dichromat. For example, the protanope confusion point, determined by the intersection of several protanope confusion lines, represents an imaginary stimulus that only activates L cones (protocones), without triggering any response in M cones (deuteracones) or S cones (tritacones).

Confusion lines or pseudoisochromatic lines represent stimuli that are indistinguishable for a given type of dichromat (if presented at the appropriate intensity). For example, red-green dichromats (protanopes and deuteranopes) accept the full range of mixtures of a monochromatic light of 545 nm (green) and a monochromatic light of 670 nm (red) to match a reference monochromatic light of 589 nm (orangish yellow) of adjustable intensity. As it can be seen in **Figure 1**, spectral lights of 545, 589 and 670 nm fall in protanope and deuteranope confusion lines. This match is known as Rayleigh match, and it is implemented in the Nagel anomaloscope, the most precise and reliable instruments designed to diagnose color vision deficiencies. Pseudoisochromatic plates, widely used to detect color vision deficiencies, use different combinations of surface color stimuli selected from different confusion lines (for a full description of color vision diagnose, see [7]).
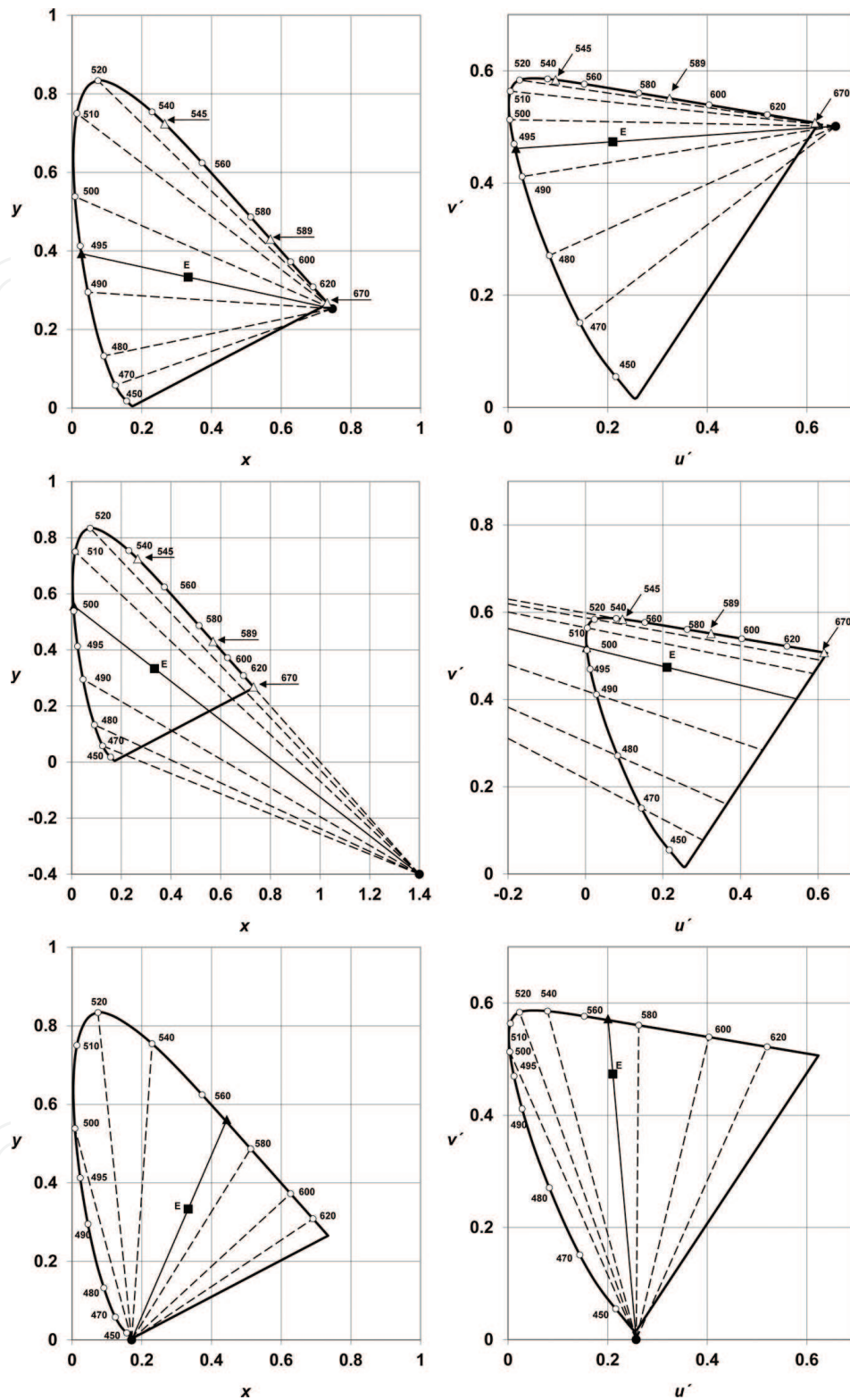
Figure 1. Confusion lines and types of dichromatism. Dichromatic confusion lines represented for protanopes (first row), deuteranopes (second row), and tritanopes (third row) in CIE *xy* 1931 (left panel) and CIE *u′v′* 1976 (right panel) chromaticity diagrams for different wavelengths (dashed lines) and the equal-energy stimulus E, represented by a black square (solid line). Black circles represent protanope (x_p = 0.747, y_p = 0.253), deuteranope (x_d = 1.40, y_d = − 0.40), and tritanope (x_t = 0.171, y_t = 0) confusion points. Black triangles represent the neutral points for dichromats (see Section 2.2). The stimuli of the Rayleigh match (white triangles) are also represented for protanopes and deuteranopes (see text for details).

Nevertheless, the use of pseudoisochromatic lines to characterize the color confusions of dichromats is limited mainly due to the following factors: (1) the existence of individual differences in relation to the spectral sensitivities of the cones in a given group of dichromats [2, 3] and (2) the existence of *residual red-green discrimination* in the major part of red-green dichromats for color stimuli over 3° of visual angle, revealed by the fact that red-green dichromats behave as anomalous trichromats for large-field stimuli ([8, 9]), as well as the existence of *residual S cone function* in some observers diagnosed as tritanopes [3].

1.1.2. Cone fundamentals derived from color matching functions and dichromatic confusion points

Cone primaries or cone fundamentals (i.e., the spectral sensitivity of the cones) derived from confusion color matching functions (CMFs) and dichromatic confusion points are known as *König fundamentals* and have been extensively pursued in color science (the interested reader can consult a large list of references, e.g., [4, 5, 10–12]). How can we use the CMFs to obtain the cone fundamentals? This can be stated as a particular case of a more general transformation: the transformation of one set of primaries to another. Since CMFs $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are theoretically linear combinations of the cone fundamentals $\bar{l}(\lambda)$, $\bar{m}(\lambda)$, and $\bar{s}(\lambda)$, using matrix algebra we have:

$$\begin{pmatrix} \bar{x}(\lambda) \\ \bar{y}(\lambda) \\ \bar{z}(\lambda) \end{pmatrix} = \begin{pmatrix} K_p x_{pc} & K_d x_{dc} & K_t x_{tc} \\ K_p y_{pc} & K_d y_{dc} & K_t y_{tc} \\ K_p z_{pc} & K_d z_{dc} & K_t z_{tc} \end{pmatrix} \begin{pmatrix} \bar{l}(\lambda) \\ \bar{m}(\lambda) \\ \bar{s}(\lambda) \end{pmatrix} \tag{1}$$

where x_{pc}, y_{pc}, and z_{pc} represent the chromaticity coordinates of the protanope confusion point; x_{dc}, y_{dc}, and z_{dc} represent those of the deuteranope confusion point; and x_{tc}, y_{tc}, and z_{tc} represent those of the tritanope confusion point (K_p, K_d, and K_t are constant factors that scale the cone fundamentals). From this linear equation, we can get the cone fundamentals from the confusion points obtained from dichromatic observers:

$$\begin{pmatrix} \bar{l}(\lambda) \\ \bar{m}(\lambda) \\ \bar{s}(\lambda) \end{pmatrix} = \begin{pmatrix} K_p x_{pc} & K_d x_{dc} & K_t x_{tc} \\ K_p y_{pc} & K_d y_{dc} & K_t y_{tc} \\ K_p z_{pc} & K_d z_{dc} & K_t z_{tc} \end{pmatrix}^{-1} \begin{pmatrix} \bar{x}(\lambda) \\ \bar{y}(\lambda) \\ \bar{z}(\lambda) \end{pmatrix} \tag{2}$$

A more detailed description can be found in Section 8.2.5 of Ref. [4] and in Appendix, Part III of Ref. [5]. **Figure 2A** represents the set of cone fundamentals of normal trichromats proposed by Smith and Pokorny in 1975 [13] that was derived using this procedure. The spectral sensitivity of L, M, or S cones has been eliminated in **Figure 2B–D** to illustrate protanopia, deuteranopia, and tritanopia, respectively. More recently, Stockman and Sharpe [11, 14] have proposed a set of cone fundamentals based on the Stiles and Burch 10° CMFs (adjusted to 2°) and on direct measurements of the spectral sensitivity of dichromats, which has become the basis of the CIE proposal for physiologically relevant CMFs (http://www.cvrl.org/).

1.2. Color appearance: What are the colors seen by dichromats?

Each point represented in a chromaticity diagram represents metameric stimuli for normal trichromats, that is, color stimuli that presented at the appropriate intensity are perceptually
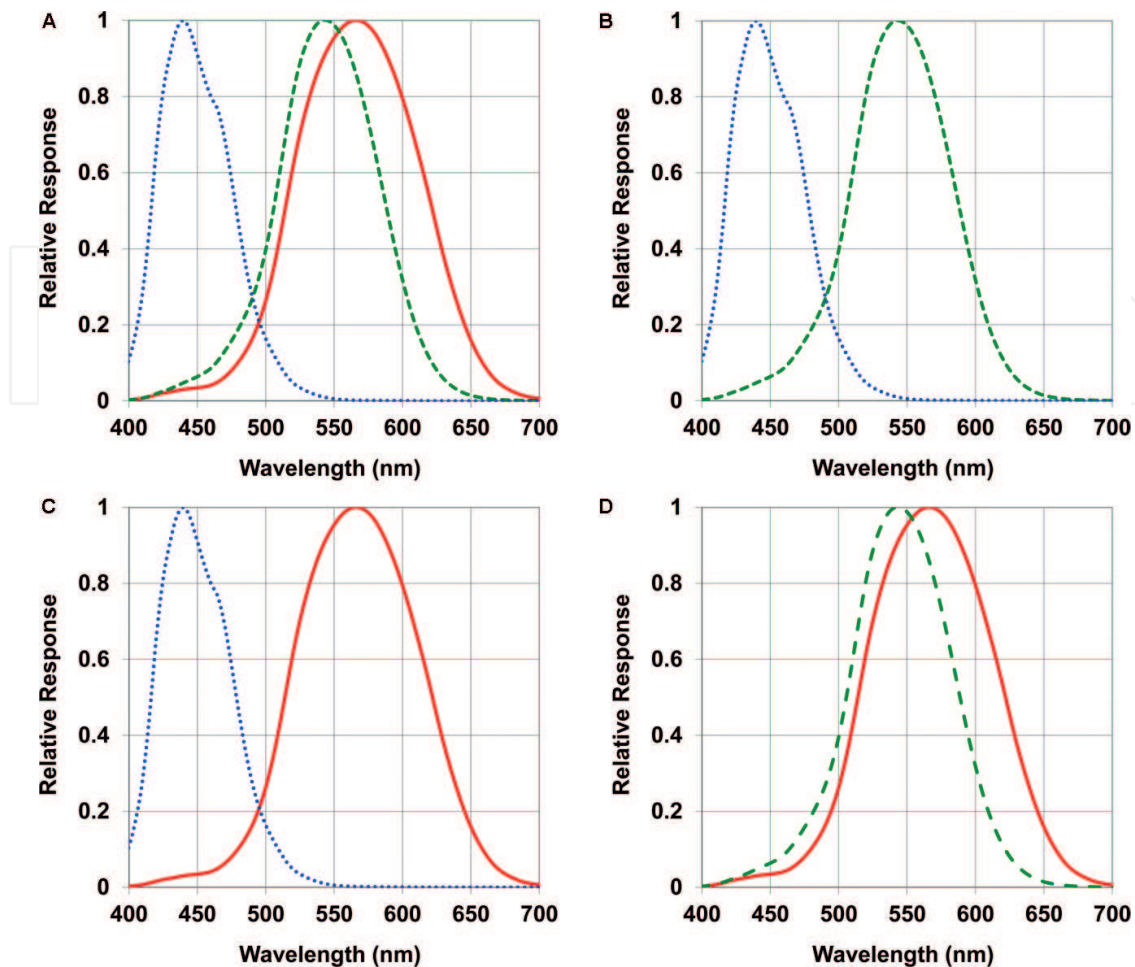
Figure 2. Cone fundamentals in normal trichromats and dichromats. **Figure 2A** represents the Smith and Pokorny cone fundamentals established in 1975 [13] normalized separately to peak at unity (these fundamentals were derived from the Judd CMFs published in 1951, a corrected version of the CIE 1931 CMFs that was later improved by Vos in 1978; see, e.g., Ref. [14]). L (solid red line), M (dashed green line), or S (dotted blue line) spectral sensitivity has been eliminated in **Figure 2B–D** to illustrate protanopia, deuteranopia, and tritanopia, respectively.

identical despite being physically different. As explained in Section 1.1.1, dichromats have more metamers than normal trichromats: for a given stimulus, the corresponding confusion line represents all the pseudoisochromatic stimuli that, if presented at the appropriate intensity, are metamers for a given type of dichromat. One of the most interesting and controversial aspects in color science has been the quest for an answer to this question: Which are the colors seen by dichromats? [2, 5]. More specifically, for a given color stimulus, which of all the possible metamers represents the actual color seen by a given type of dichromat?

In 1995, Viénot, Brettet, Ott, Ben M'Barek, and Mollon published a paper trying to respond to this question. Although the authors were aware that the quality of the sensations of other people cannot be fully known (page 128 in Ref. [15]), they described the rationale of an algorithm designed to simulate the chromatic appearance for a dichromat, in order to allow a normal trichromat to experience the same colors as a type of dichromat when looking at the same scene. The algorithm used to obtain this kind of simulations is described in more detail in Ref. [6]. The main assumption of the simulation is the aforementioned König hypothesis, that is, that dichromacy is a reduced version of normal trichromacy. On the basis of this assumption, the algorithm establishes, for a

given color stimulus **Q**, and for a given type of dichromat, a stimulus **Q′** which is indistinguishable from **Q** and that produces the same color experience both in normal trichromats and dichromats of the specified type. In this way, it is possible to simulate the appearance of any scene, no matter how complex it is, for each type of dichromat, as it can be observed in **Figure 3**.

The algorithm proposed by Brettel et al. [6] does not use chromaticity diagrams to implement the simulation but LMS colorimetry (in which each tristimulus value represents the response of L, M, or S cones). Specifically, the authors used the cone fundamentals proposed by Stockman, MacLeod, and Johnson in 1993 [16]. In this physiologically based cone color space, **Q** and **Q′** stimuli are defined as $Q = (L_Q, M_Q, S_Q)$ and $Q' = (L_{Q'}, M_{Q'}, S_{Q'})$.

Figure 3. Dichromatic color appearance simulations. (A) Original Joaquin Sorolla's painting *Saliendo del baño* ("Coming out of the bath"); (B) protanopia simulation; (C) deuteranopia simulation; and (D) tritanopia simulation. The simulations were performed using the color simulation tool named "Vischeck" (http://www.vischeck.com/). Note that the great changes in hue from the pinkish colors in the original image (A) toward yellowish colors in the protanopia (B) and deuteranopia (C) simulation do not occur in the tritanopia simulation (D) (according to the model of Brettel et al. [6], reddish and greenish blue are identical for tritanopes and normal trichromats). Because of possible errors in reproduction, the actual colors could present some differences with the original images.

In a three-dimensional representation of this space, each axis represents the response of one of the three types of cones, and confusion lines are easily determined as parallel lines to one of the axes, since they represent all the stimuli that only vary in the response of the cone that is absent for a given type of dichromat, keeping constant the response of the two remaining cones: confusion lines for protanopes are parallel to L axis ($M_{Q'} = M_Q$ and $S_{Q'} = S_Q$), confusion lines for deuteranopes are parallel to M axis ($L_{Q'} = L_Q$ and $S_{Q'} = S_Q$), and confusion lines for tritanopes are parallel to S axis ($L_{Q'} = L_Q$ and $M_{Q'} = S_Q$).

But only one of the stimuli contained in a given confusion line, the one defined by the vector **Q′**, would fulfill the requirement of producing the *same* experience (according to the authors) in dichromats and normal trichromats. Which one is the correct stimulus for each type of dichromat ($L_{Q'}$, $M_{Q'}$, and $S_{Q'}$ in protanopes, deuteranopes, and tritanopes respectively)? Given this uncertainty, Brettel et al. [6] drew on data collected from unilateral dichromats (observers who are dichromats in one eye and supposedly normal trichromats in the other) in order to establish the stimuli that cause common chromatic experiences both for dichromats and normal trichromats. Which are the stimuli that serve as perceptive anchors to translate the colors of any image to the colors supposedly seen by dichromats? In brief:

1. It is assumed that equal-energy stimulus **aE** ($0 \leq a \leq 1$) produces the same perceptual response both in dichromats and normal trichromats, regardless of its intensity (the authors defined **E** as the metamer of the equal-energy stimulus with the maximum reproducible intensity in the screen where the simulation was run). Therefore, the origin **O** ($L_O = M_O = S_O = 0$) and the equal-energy stimulus **E** define the neutral axis *OE*, perceived as achromatic.

2. The three-dimensional LMS space of normal trichromats is reduced to two hemiplanes in dichromats, each one of them associated with the perception of one hue. Which are the hues equally perceived by dichromats and normal trichromats? From the published studies on unilateral dichromats, it was inferred that:

    2.1. The hues produced by spectral stimuli of 575 nm (yellow) and 475 nm (blue) are identical for protanopes, deuteranopes, and normal trichromats. This inference was based on several studies on unilateral dichromats of genetic origin.

    2.2. The hues produced by spectral stimuli of 660 nm (red) and 485 nm (greenish blue) are identical for tritanopes and normal trichromats. This inference was based on one study on a case of acquired unilateral tritanopia.

The hemiplanes that contain the LMS coordinates related to the chromatic experiences common to dichromats and normal trichromats are defined by the achromatic axis *OE* and by the LMS coordinates of 575 and 475 nm in the case of protanopes and deuteranopes or by the achromatic axis *OE* and by the LMS coordinates of 660 and 485 nm in the case of tritanopes. Stimulus **Q′** is defined by the intersection of the confusion line of **Q** and the corresponding hemiplane. This procedure can be applied to all the elements of any image in order to translate its original colors to the colors supposedly seen by dichromats according to the aforementioned assumptions of the model.

Despite the reservations expressed by the authors concerning the validity of the method, they defended its utility for normal trichromats to evaluate the chromatic variety experienced by dichromats when looking at any scene.

1.3. Dataset

After the previous theoretical and technical background, the following sections will present some empirical data relating colorimetric variables with dichromatic experiences. In Section 2, we will present an experimental method developed to evaluate the accuracy of color simulation tools in relation to dichromats [17]. Section 3 gives an overview of two competitive models developed to describe and predict the confusions made by red-green dichromats when naming colors [18, 19]. Both models are based on colorimetric variables. Model A is based on the activity of the yellow-blue and the achromatic mechanisms. Model B includes a third variable: the aforementioned residual red-green discrimination. Section 4 deals with an emotional aspect related to color, describing color preferences in red-green dichromats and comparing them to the preferences of normal trichromats [20]. Finally in Section 5, we will summarize the most important conclusions of our research on red-green dichromats.

2. Evaluation of color appearance simulation tools

2.1. Color appearance simulation tools

Several color appearance simulation tools are available. All of them take an original image as input and apply some image processing algorithm or optical filtering to get a processed or filtered image that represents the colors supposedly seen by observers with different types of color vision deficiencies. For example, dichromatic color appearance simulation tools translate any image into versions of that image to simulate protanopia, deuteranopia, and tritanopia, as illustrated in **Figure 3**. Simulation tools also can be used to create systems for avoiding color combinations difficult to discriminate by color anomalous observers [21]. Our research on color appearance simulation tools, to be described in Section 2.2, has been focused on color appearance simulation tools for the most common types of dichromatic color vision: protanopia and deuteranopia.

2.2. Simulcheck: A method to evaluate the accuracy of dichromatic color appearance simulation tools

Figure 3 shows four versions of the famous masterpiece *Saliendo del baño* ("Coming out of the bath") painted by the Spanish painter Joaquin Sorolla in 1915. The one at the upper left (**Figure 3A**) is the original image. **Figure 3B–D** is three versions of that image created to mimic how the original picture is seen by the three types of dichromats, protanopes, deuteranopes, and tritanopes, respectively. The simulation was performed by means of the Internet available color simulation tool named "Vischeck" (which is based on the algorithm of Brettel et al. [6] described in Section 1.2) (http://www.vischeck.com/). **Figure 3C** is reproduced again in **Figure 4A** to facilitate

its comparison with the simulation of deuteranopia provided by "Coblis" (**Figure 4B**), another color simulation tool (http://www.color-blindness.com/coblis-color-blindness-simulator/). It is easy to appreciate some important differences between both deuteranopia simulations. For example, the **Figure 3A** whites (i.e., the woman's shirt, the towel or the waves' crest) become light pinks in **Figure 4B** but not in **Figure 4A**. It means that the same input (**Figure 3A**) produced different colors (**Figure 4A** and **B**) when using different tools to mimic the same type of dichromatic color vision (deuteranopia). Obviously, it can be concluded that at least one of the tools is not performing accurately.

Lillo et al. created and developed in 2014 [17] a method named "Simulcheck" to evaluate ("-check") the accuracy of color simulation ("Simul-") tools. This method is based on the measurement of two colorimetric variables, h_{uv} (hue angle) and L_R (relative luminance). Each one of these variables is related to a relevant feature of dichromatic color vision, respectively (see below): the existence of pseudoachromatic colors and the differences in the lightness perception for those colors.

h_{uv}, a standard colorimetric variable specified in the *CIE 1976 u'v´* chromaticity diagram that correlates with hue [1], was used to measure the accuracy of color simulation tools in relation to pseudoachromatic colors. The hue angle of a stimulus is simply calculated as the angle formed by an imaginary horizontal line passing through the reference white and the line defined by the reference white and the stimulus chromaticity coordinates. As it was previously commented, **Figure 1** right panel shows several *CIE 1976 u'v´* chromaticity diagrams including some confusion lines that represent pseudoisochromatic stimuli. One of these lines (the solid line) passes through the chromaticity of the equal-energy stimulus (the point labeled with the letter E). It means that for the specific type of dichromacy considered (protanopia in the upper diagram, deuteranopia in the central diagram, and tritanopia in the bottom diagram) every stimuli represented by a point in this line must be perceived as an achromatic color (white, gray, or black) like the one seen when looking at an equal-energy stimulus. Because these stimuli are achromatic for a type of dichromat but not for normal trichromats, they are frequently named "pseudoachromatics" [7].
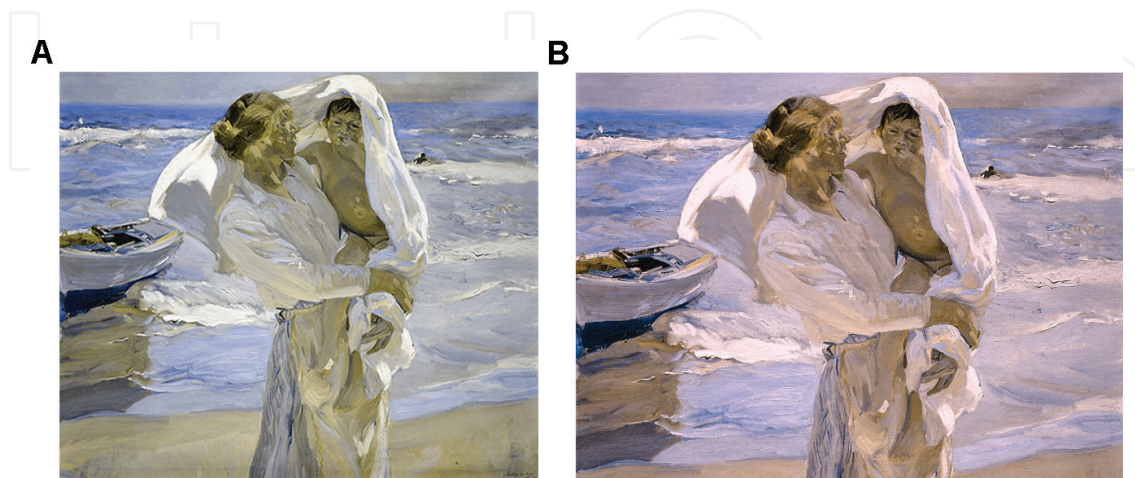

Figure 4. Two color appearance simulations for deuteranopia of a Joaquin Sorolla's painting. (A) Vischeck simulation and (B) Coblis simulation.

Let us use the right panel of the first row in **Figure 1** (representing confusion lines for prota-nopes in the *CIE 1976 u'v'* chromaticity diagram) to make an intuitive explanation on how the hue angle (h_{uv}) is used by Simulcheck to measure the accuracy of color simulation tools in rela-tion to pseudoachromatic colors. The pseudoachromatic line for protanopes intersects with the chromaticity diagram (1) between 490 and 495 nm (the so-called neutral point for protanopes, represented by a black triangle, see, e.g., Ref. [12]) and (2) in the purple line near 700 nm. The corresponding h_{uv} values are (1) near 184° that corresponds to stimuli usually perceived as green (bluish green, actually) by normal trichromats, so these stimuli can be named "protanope pseudoachromatic greens," and (2) near 4° that corresponds to stimuli usually perceived as red or pink by normal trichromats, so they can be named "protanope pseudoachromatic reds."

Regarding the differences in lightness perception for pseudoachromatics, such differences derive from fact that the spectral sensitivity of protanopes and deuteranopes differs from that of normal trichromats (see, e.g., Ref. [2]). As a consequence, their lightness perception is also different (see next section). For protanopes, reds are darker and greens are lighter than for normal trichromats. For deuteranopes the pattern is exactly the reverse.

2.2.1. Methods

Participants. Ten normal trichromats and 10 dichromats (5 protanopes, 5 deuteranopes) were participated. Their color vision was assessed with a set of pseudoisochromatic tests and a Nagel anomaloscope (Tomey AF-1, Tomey, Nagoya, Japan). All were native Spanish speakers.

Stimuli. Two chromatic stimulus sets and an achromatic stimulus set were used. Each chro-matic set included 40 stimuli evenly spaced in h_{uv}. The first set included stimuli with varying chroma and lightness (maximum chroma set), whereas the second set included stimuli with equal chroma and lightness (constant chroma set). The achromatic set included 20 achromatic stimuli evenly spaced in lightness from black to white.

Procedure. Simulcheck includes two tasks: the "pseudoachromatic stimuli identification task" and the "minimum achromatic contrast task." The first task measures the h_{uv} values of the pseudoachromatic stimuli selected by the observers from a set of colors spanning the whole hue circle (see above): participants are required to select the stimulus more similar to gray. Simulcheck includes a "minimum achromatic contrast task" to measure L_R (relative lumi-nance), a psychophysical variable directly related to lightness perception. This task estimates L_R (relative luminance), a psychophysical variable directly related to lightness perception. The pseudoachromatic stimulus selected in the first task is presented as text over the 20 stimuli of the achromatic set. Participants are required to select the stimulus which makes it more difficult to read the text which is the one with minimum contrast with the pseudoachromatic stimuli. L_R is computed as the ratio between L_T (the luminance of the achromatic background selected) and L (the standard luminance values of the pseudoachromatic stimuli).

2.2.2. Results and conclusions

We compared the results obtained by real red-green dichromats and simulated dichromats (i.e., normal trichromats performing the tasks with the transformed stimuli). Mann-Whitney

U tests were performed and *p* values lower than .05 indicated significant differences between real and simulated dichromats (see Figures 9 and 10 in Ref. [17]). Hue angle values were very similar for real red-green dichromats (protanopes and deuteranopes) and for those simulated by Vischeck, but not for those simulated by Coblis. As it happened for h_{uv}, the L_R values of the colors simulated by Vischeck were very much more accurate than their Coblis' equivalents. Therefore we concluded [17] that Vischeck is a much more accurate tool than Coblis to simulate red-green dichromacy.

3. Color naming models in dichromats

Much of the modern work on color and language [22–24] has been inspired by the seminal work of Berlin and Kay [25] about the basic color terms (BCTs). These terms are monolexemic, known and used by all members of the language community and can be used to communicate about the color of any type of object. The general limitations in color naming of red-green dichromats [26] also appear for using BCTs [18].

Two models based on transformed colorimetric variables were developed by Moreira et al. in 2014 [19] to predict the confusions made by red-green dichromats when naming colors using basic color terms (BCTs). Castilian Spanish BCTs are 11 (English equivalents after hyphen): rojo-red, verde-green, amarillo-yellow, azul-blue, blanco-white, negro-black, naranja-orange, morado-purple, marrón-brown, rosa-pink, and gris-gray. Model A is based on the activity of the yellow-blue and the achromatic mechanisms. Model B includes a third variable: residual red-green discrimination.

In essence, Model A departs from the *reduction hypothesis*; therefore, it shares the main assumption of the model of Brettel et al. [6] described previously (see Section 1.2). More specifically, Model A is based on the same assumptions of the model of Brettel et al. [6] regarding the chromatic experiences shared by dichromats and normal trichromats, but it uses standard colorimetric variables instead of LMS colorimetry to describe and predict the use of BCTs (see below). In contrast, Model B includes residual *red-green discrimination*, given the great amount of research that evidences that the major part of red-green dichromats behaves as anomalous trichromats for large-field stimuli (over 3°) both in psychophysical tasks [8, 9] and color-naming tasks [27–32]. In fact, as it was stated before that the existence of residual red-green discrimination can challenge the use of confusion lines to predict the confusions made by red-green dichromats and casts serious doubts on the assumptions on which Model A is based (a critical reexamination can be seen in Ref. [33]).

A full description of Models A and B can be found in Ref. [19]. Here we will only present the essential features of both models. Model A is entirely based on the activity of the yellow-blue and the achromatic mechanisms, specified in terms of variables *s'* and L^*_T, respectively. Both of these variables are related to standard colorimetric variables derived from CIELUV space and its chromaticity diagram (*CIE 1976 u'v'*). Like standard variables, which do not consider individual differences within normal trichromats, Model A variables do not take into account individual differences within protanopes or deuteranopes.

The first variable of Model A, s', identifies hue and quantifies saturation for protanopes (s'_p) and deuteranopes (s'_d) using the *1976 CIE u'v'* chromaticity diagram. Specifically, s' is computed from the projection of the 2D chromaticity diagram onto a 1D representation of chromaticity related to the chromatic experiences shared by dichromats and normal trichromats according to the model of Brettel et al. [6]. **Figure 5** shows how s'_p identifies hue (yellow or blue) and quantifies saturation for protanopes using the *CIE 1976 u'v'* chromaticity diagram as follows (the same rationale applies to deuteranopes):

1. There is a biunivocal relation between confusion lines and variable s'_p. For example, $s'_p = 0$ only for the pseudoachromatic confusion line for protanopes, i.e., the protanopic confusion line passing through the chromaticity of the reference white (thick solid line in **Figure 5**; see Section 2.2). This confusion line includes all the stimuli that protanopes perceive as achromatic according to Model A. Any other confusion line intersects either with the "blue line" ($\lambda_D = 475$ nm) or with the "yellow line" ($\lambda_D = 575$ nm) at a given intersection point.

2. Variable s' is simply computed as the distance between the achromatic point and the intersection point (except for a scalar, this distance coincides with the value of the standard colorimetric variable, s_{uv} [1] for the intersection point). We arbitrarily decided s' to be positive for intersection points located on the "yellow line" and negative for those located on the "blue line."
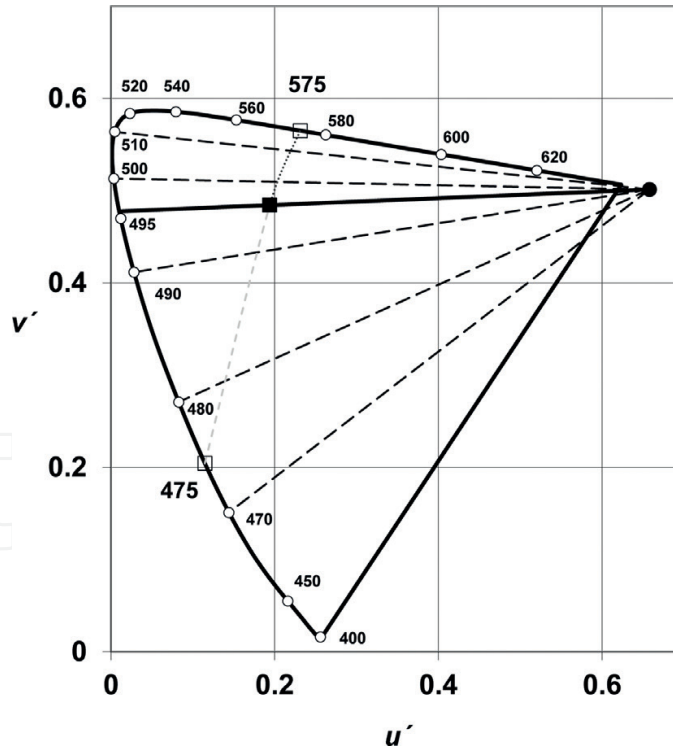

Figure 5. Intersection between confusion lines for protanopes and the "yellow" (black dotted line) or "blue" (grey dashed line) lines according to Model A. Every confusion line (dashed line) radiates from the protanopic confusion point (black circle, $u' = 0.658$, $v' = 0.501$) and intersects with either the yellow or the blue line (white squares show the chromatic coordinates of 475 and 575 nm). The solid line crossing the achromatic point (black square, sample S 0500-N of NCS atlas in our study, $u' = 0.19$, $v' = 0.48$; see Appendix A in Ref. [18]) includes pseudoachromatic stimuli (achromatic for protanopes). The s' variable was defined as the distance from the achromatic point to the intersection point between the confusion line of a given stimulus and either the yellow or the blue line (see text for details).

The second variable of Model A, transformed lightness, L^*_T, is computed as standard lightness (L^* [1]), but instead of using the standard luminance factor, it takes into account that protanopes lack L cones and deuteranopes lack M cones. Transformed protanope and deuteranope lightness, L^*_p and L^*_d, were computed as follows:

1. Transformed luminance factor for protanopes (Y_p) and deuteranopes (Y_d) was computed on the assumption that the luminance factor of the reference white is exactly the same for normal trichromats and dichromats, which makes it possible to compute a scaling factor for protanopes and other for deuteranopes. We used Stockman and Sharpe $L_2(\lambda)$ and $M_2(\lambda)$ cone spectral sensitivities [14] and derived the relative contribution of L and M cones to luminosity from $V_2^*(\lambda) = 1.5\,L_2(\lambda) + M_2(\lambda)$ (Eq. 7 in Ref. [14]).

2. Finally, the corresponding transformed lightness values for protanopes and deuteranopes (L^*_p and L^*_d) were computed.

Model B includes s' and L^*_T variables as Model A but also includes a third variable, ΔRG_{res}, to take residual activity in the R-G channel into account. According both to Model A and Model B, the probability of using a given BCT decreases insofar as a stimulus differs from the best exemplars of the corresponding category in terms of s' and L^*_T. But only according to Model B, this probability also decreases as the stimulus moves away from the focal color of that category in terms of incremental distance along the corresponding confusion line, ΔRG_{res}.

3.1. Methods

Participants. 32 normal trichromats (17 females, 15 males) and 17 dichromats (8 protanopes, 9 deuteranopes) were participated. All were native Spanish speakers, and they were assessed with a set of color vision tests and a Raleigh match on a Nagel anomaloscope (Tomey AF-1, Tomey, Nagoya, Japan).

Stimuli. 102 stimuli from the NCS color atlas were used. They included (1) the best exemplar of each basic color category in Spanish (a detailed description on the equivalent basic color terms can be found in Section 3), (2) stimuli in the boundary of neighboring basic color categories, and (3) stimuli halfway between a boundary and the best exemplar of a basic color category.

Procedure. Stimuli were presented simultaneously, and participants were asked to select instances (mapping task) or to select the prototype (best exemplar task) of a given basic color term. Both tasks were performed independently.

3.2. Results and conclusions

The comparison of the predictions of Models A and B and the observed responses of protanopes and deuteranopes showed that Model B was more accurate than Model A in predicting the use of BCTs, indicating that *residual red-green discrimination* must be taken into account in order to explain the use of BCTs by red-green dichromats, besides the yellow-blue and the achromatic mechanisms. For example, for the use of green by protanopes, the proportion of variance (R^2) accounted for by Model A was 56%, whereas the proportion of variance

accounted for by Model B was 96% (i.e., the increment in the proportion of variance accounted for by using Model B instead of Model A was $\Delta R^2 = 40\%$) (see Table VI in Ref. [19] for a systematic comparison of both models).

4. Color preference in dichromats

Color preference in normal observers [34] has been explained considering object-color associations [35], emotional factors [36], and the responses in the chromatic opponent mechanisms [37]. For the last case, standard colorimetric measurements have been used to estimate the response magnitudes in the three retinal cones (L, M, and S) and the two opponent mechanisms (red-green, L-M, and yellow-blue, S-(L + M)). Álvaro et al. [20] studied color preferences in dichromats and compared them to the preferences of normal trichromats (**Figure 6**; see also Schloss [38]).

4.1. Methods

Participants. 32 normal trichromats (17 females, 15 males) and 32 dichromats (15 protanopes, 17 deuteranopes) were participated. All were assessed with a set of color vision tests and a Nagel anomaloscope (Tomey AF-1, Tomey, Nagoya, Japan), and they were native Spanish speakers.

Stimuli. Three stimulus sets were saturated, light and dark versions of red, orange, yellow, chartreuse, green, cyan, blue, and purple. Those stimuli were approximations of the Berkley Color Project set [39].

Procedure. Participants were required to rate their preference (color-preference task) or to name aloud (color-naming task) the color individually presented. Preference rating scale
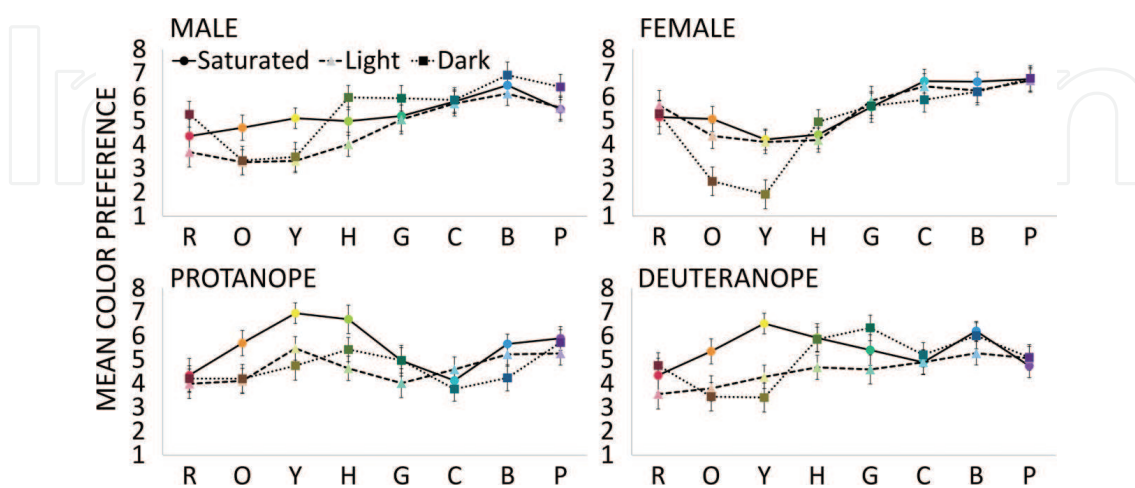

Figure 6. Mean preference ratings averaged for trichromatic males and females and dichromatic protanopes and deuteranopes. Mean preference ratings (± SEM) are shown as a function of hue, given by the x-axis: red (R), orange (O), yellow (Y), chartreuse (H), green (G), cyan (C), blue (B), and purple (P). Separate lines represent colors from the saturated (solid with circles), light (dashed with triangles), and dark (dotted with squares) sets. Marker colors are only an approximation of those in the experiment. This figure is a reproduction of **Figure 1** from Álvaro et al. [20].

ranged from 1 to 10. Color names were restricted to the 11 Spanish basic color terms (see Section 3). Both tasks were performed independently.

4.2. Results and conclusions

We compared the color preference ratings of dichromats and normal trichromats (**Figure 6**) by means of a mixed-model ANOVA with set (saturated, light, and dark) and color (red, orange, yellow, chartreuse, green, cyan, blue, and purple) as within-subject factors and group (trichromat males, trichromat females, protanopes, and deuteranopes) as the between-subjects factor (p values lower than .05 indicated significant differences). While normal trichromats' preference peaks at blue and hits bottom at yellow-green [35, 37, 39], red-green dichromats' preference peaks at yellow and the preference for blue is weaker than normal trichromats'. Protanope's preference was more affected than deuteranope's preference. In relation to the underlying mechanisms to color preference, we entered cone contrasts (between color stimuli and background; see **Figure 7**) as predictors in linear regressions analyses with average color preference ratings (**Figure 6**) as the dependent variable. Cone contrast partially explained normal trichromat's preference with the yellow-blue system being the most important. Variations of cone-contrast theory partially explained protanope's preference with again a special relevance of the yellow-blue system activation (bottom of **Figure 7**) but showing evidence of red-green residual activity in deuteranopes
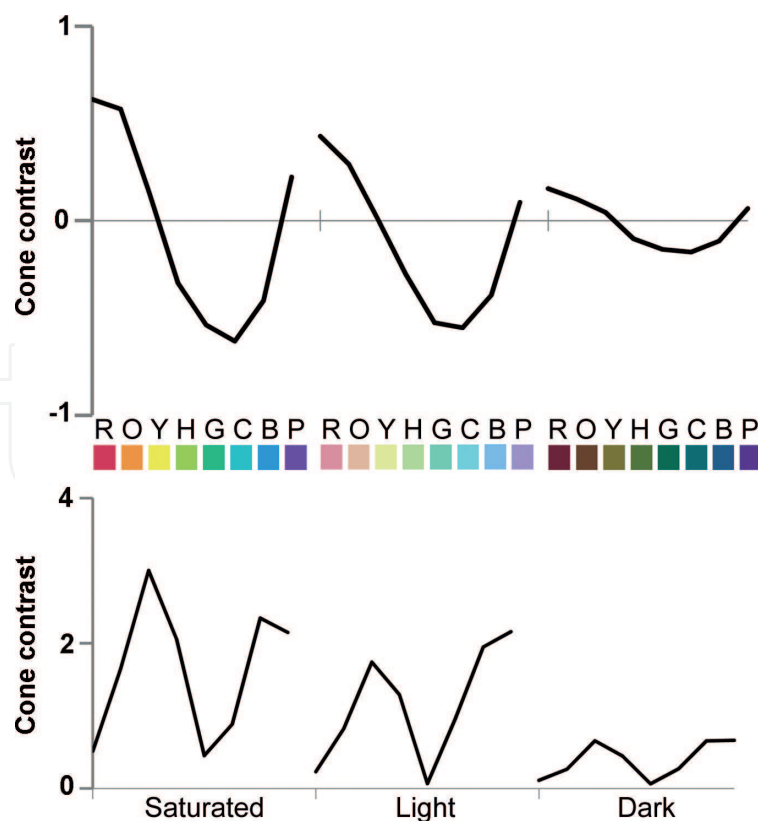

Figure 7. Cone contrast of the stimulus sets used to evaluate color preference in normal trichromats and red-green dichromats. Red-green (L − M, top panel) and yellow-blue activation (|S−(L + M)|, bottom panel) stimulus-background cone-contrast values for the saturated, light, and dark set of colors used in Ref. [20]: red (R), orange (O), yellow (Y), chartreuse (H), green (G), cyan (C), blue (B), and purple (P). This figure has been adapted from **Figure 3** in Álvaro et al. [20].

(top of **Figure 7**). For example, the activation of the yellow-blue system was a significant predictor and explained almost two thirds of the variance (R^2 = .61) in protanopes' preference for the full color set and more than three quarters of the preference for saturated (R^2 = .76) and light (R^2 = .88) colors (see Table 1 in Ref. [20]). Besides, this novel study demonstrated that the fluency of processing also underlies males' preference (either normal trichromats or dichromats): there was a higher preference for the colors named more accurately, quicker, more consistently and with greater consensus in normal trichromatic males and dichromatic males but not in normal trichromatic females.

5. Conclusions

The main conclusions of our research on red-green dichromacy related to colorimetry can be stated as follows:

1. Simulcheck is a valid method to evaluate color simulation tools in relation to dichromacy [17]. Hue angle and relative luminance are the two colorimetric dependent variables measured by the two psychophysical tasks included in the method. The similarity of the pattern of results obtained by simulated and real dichromats is a good indicator of the validity and the accuracy of color simulation tools.

2. Residual red-green discrimination must be taken into account to explain the use of basic color terms (BCTs) by red-green dichromats, as well as yellow-blue and achromatic mechanisms [19]. For most part of dichromats, distance along confusion lines (besides yellow-blue and achromatic mechanisms) is a relevant colorimetric variable for the use of BCTs.

3. Color preference of red-green dichromats is different from color preference of normal trichromats [20]. Yellow-blue cone contrast (computed from colorimetric variables) accounts for dichromats' pattern of preference, with some evidence for residual red-green activity in deuteranopes' preference.

Acknowledgements

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