

## Towards a Model To Predict Macular Dichromats' Naming Errors: Effects of CIE Saturation and Dichromatism Type

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Thirty macular dichromat children (12 protanopes + 18 deuteranopes) and 29 controls, between 5 and 9 years old, participated in a monolexic denomination task. Their clinical status was determined after a repeated application of a chromatic test set (Ishihara, CUCVT, and TIDA). The stimuli to be named were 12 tiles from the Color-Aid set belonging to the green, blue, and purple basic categories. Results showed that: (a) Dichromats made more naming errors when low saturation stimuli were used; (b) protanopes made more errors than deuteranopes; and (c) pseudoisochromatic lines predicted accurately the type of most frequent naming errors but they underestimated macular dichromats' functional capacity to name colors. Results are consistent with a model of macular dichromats' vision that hypothesizes a residual third type of cone in the periphery of the retina. Implications of this fact for everyday use of colors by macular dichromats' and for the validity of standard clinical diagnoses are discussed.

*Key words:* color blindness, color categorization, clinical diagnosis, dichromatism

Treinta niños dicromáticos maculares (12 protanopes + 18 deuteranopes) y 29 controles, con edades comprendidas entre los 5 y 9 años, participaron en una tarea monolexémica de denominación de colores. Su categoría clínica se estableció partiendo de los resultados obtenidos tras la doble aplicación de una batería de tests cromáticos (Ishihara, CUCVT y TIDA). Los estímulos a nombrar fueron doce muestras del conjunto del Color-Aid, pertenecientes a las categorías básicas verde, azul y morado. Los resultados mostraron que: (a) los dicromáticos tuvieron más errores cuando se utilizaron estímulos de baja saturación; (b) los protanopes cometieron más errores que los deuteranopes; (c) las líneas de pseudoisocromaticidad fueron adecuadas para predecir cuáles fueron los errores de nombramiento más frecuentes, pero fueron menos eficaces de lo esperado a la hora de predecir la capacidad funcional de los dicromáticos maculares en el nombramiento de colores. Los resultados concuerdan con un modelo de la visión de los dicromáticos maculares que asume la existencia en la periferia de un tercer tipo de cono. Se discuten las implicaciones de este hecho para comprender el uso cotidiano que hacen estos observadores de los colores y la validez del procedimiento habitual de diagnóstico clínico.

*Palabras clave:* ceguera a los colores, categorización cromática, diagnóstico clínico, dicromatismo

Color is not a property of objects or surfaces, but an attribute of the perceptual response produced by the brain as a result of the light that hits the retina. As the phenomenon of metamer colors show, in order to produce the perception of the same chromatic experience, two stimuli need not be physically identical, but only need to produce the same response pattern in the three cone types.

People with only two cone types in the macular retina are diagnosed as dichromats (Fletcher & Voke, 1985). When, as in red-green pathologies (daltonisms), the affected cone is the protocone (the most sensitive to long wavelengths) or the deuteracone (most sensitive to medium wavelengths), a specific diagnosis of protanopia or deuteranopia, respectively, is made.

As protanopes and deuteranopes have only two types of cone, they have more metamers than common trichromats. Moreover, it is easy to indicate which stimuli will be metamers for dichromats but not for common trichromats: those (pseudoisochromatic stimuli) that the common observer only differentiates using the cone type that the dichromat does not possess. As we will see, CIEu'v' chromacity diagram provides an easy way of identifying pseudoisochromatic stimuli.

Figure 1 shows the chromacity diagram established by the Commission Internationale de l'Eclairage (CIE) in 1976. To the right, a black triangle ( $u' = 0.65$ ;  $v' = 0.50$ ) shows the protanope convergence point in the position determined by Pitt in 1935 (this position is the one usually reproduced in the literature; see, for example, Fletcher & Voke, 1985,

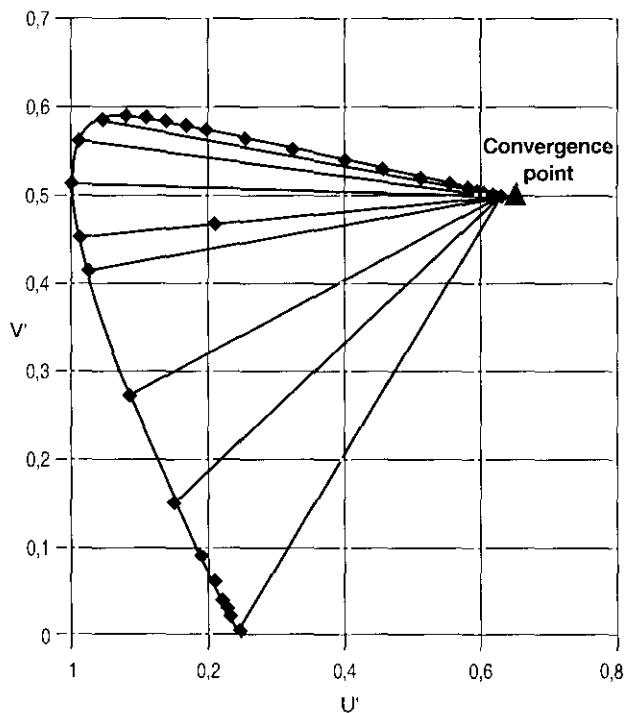


Figure 1. CIEu'v' chromacity diagram and pseudoisochromatic lines. All stimuli that can be represented on the same pseudoisochromatic line are metamers for protanopes.

p. 159; Birch, 1993, p. 37), and corresponds to an imaginary stimulus that only activates the protocones. Given the convergence point, protanope pseudoisochromatic stimuli can be determined in the following way:

(1) A pseudochromatic line can be determined by two points, the convergence point and the point corresponding to a specific color (for example, an achromatic color).

(2) Perfect metamerism is foreseen when two stimuli are presented on the same pseudochromatic line and are of equivalent reflectances.

(3) Smith and Pokorny's cone function fundamentals can be used to establish the reflectances for protanopes and deuteranopes. If we know the standard reflectance and the chromacity coordinates corresponding to a specific stimulus (for example,  $R = 22.6$ ;  $x = 0.269$ ;  $y = 442$ ), matrix algebra may be used (for example, Travis, 1991, chap. 3; Lillo, 2000, chap. 7) to estimate the magnitude of the relative response (from zero to 100) that the stimulus produces in protocones (20.92) and deuteracones (25.93). The value of the former indicates the reflectance corresponding to deuteranopes, whereas that of the latter corresponds to protanopes.

#### Basic Colors and CIE<sub>x</sub>y Chromacity Diagram: Model 1 Predictions

CIE colorimetric measurements offer an objective way to determine which stimuli should be similar for normal trichromats (the ones with the same chromatic coordinates), and for dichromats (the ones with coordinates in the same pseudochromatic lines). They also provide information about some psychophysical properties, such as the dominant wavelength ( $\lambda_D$ ) or the CIE saturation ( $S_{u'v'}$  - see Hunt, 1987; Lillo, 2000 for a detailed description). However, they do not offer direct information about the way that color names are used in colloquial language.

Several methods can be used to decide when a word (such as yellow or green) corresponds to a basic chromatic category (Corbet & Davies, 1997; Crawford, 1982). Some studies (Kay & McDaniel, 1978) have shown that in Berlin and Kay's (1969) level-6 languages (such as English or Spanish), there are 11 basic categories: red, green, yellow, blue, orange, purple, pink, brown, white, black, and gray. Extensive research carried out at the University of California (Boynton & Olson, 1987, 1990; see also Sturges & Whitfield, 1997), while providing additional information confirming the basic character of the eleven categories in English, also obtained results that can be used to specify the volumes occupied by every basic category in CIE spaces. More specifically, using the stimuli of the Optical Society of America (OSA) Atlas that received the same denomination by, at least, four of the seven participants in the Boynton and Olson (1987) naming task, we determined these volumes as is specified in Table 1.

Table 1  
*Chromatic (Dominant Wavelength and Saturation) and Reflectance Ranges for each Basic Category*

| Category | Range Dominant Wavelengths (in nm) | Saturation Range (CIEu'v')       | Reflectance Range |               |               |
|----------|------------------------------------|----------------------------------|-------------------|---------------|---------------|
|          |                                    |                                  | Standard          | Protanope     | Deutanope     |
| Red      | 610.5 – 496.5                      | Partial (1.14–2.14)              | 4.73 – 17.28      | 3.44 – 13.11  | 5.56 – 19.94  |
| Green    | 494.0 – 575.5                      | All except very near (0.28–1.25) | 3.94 – 65.89      | 4.17 – 66.18  | 3.79 – 65.70  |
| Yellow   | 572.5 – 585.5                      | All except very near (0.43–1.25) | 27.51 – 74.93     | 25.06 – 73.22 | 28.74 – 76.03 |
| Blue     | 476.0 – 495.5                      | All except very near (0.34–1.66) | 3.30 – 61.83      | 3.78 – 67.74  | 3.00 – 58.05  |
| Orange   | 586.5 – 614.0                      | Partial (0.92–2.45)              | 12.74 – 63.50     | 9.12 – 43.89  | 15.06 – 76.03 |
| Purple   | –529.0 – 472.5                     | All except very near (0.26–1.42) | 3.51 – 32.05      | 3.50 – 31.78  | 3.51 – 32.23  |
| Pink     | 598.0 – –555.0                     | All (0.08–1.64)                  | 17.89 – 60.22     | 15.69 – 56.70 | 19.30 – 62.47 |
| Brown    | 579.5 – –503.5                     | All (0.14–1.60)                  | 3.77 – 20.23      | 3.59 – 19.20  | 3.89 – 20.89  |
| White    | —                                  | 0–0.08                           | 50 – 100          | 50 – 100      | 50 – 100      |
| Black    | —                                  | 0–0.08                           | 0 – 15            | 0 – 15        | 0 – 15        |
| Gray     | —                                  | 0–0.08                           | 5.75 – 70.86      | 5.75 – 70.86  | 5.75 – 70.86  |

Note. Saturation values were computed according the standard equation (see Hunt, 1987, p. 198; Wyszecki, 1986, pp. 9-57; Lillo, 2000, p. 169):

$$S = 13 \sqrt{(u' - u'_n)^2 - (v' - v'_n)^2}$$

These values must be divided by 13 in order to be transformed into CIEu'v' chromacity diagram distances.

The first parameter to consider is the *chromatic area*. That is, the portion of CIE chromaticity diagram where stimuli belonging to a basic category are represented. To specify chromatic areas, Table 1 uses two parameters: (1) The *range of dominant wavelengths* and (2) the *saturation range*. For the latter parameter, the maximum values indicated correspond to the most saturated stimuli presented by the OSA Atlas.

Reflectance is the second parameter to consider for the delimitation of basic category volumes. In Table 1, three kinds of reflectances are specified. The first is the standard one. The other two are transformations required to make predictions related to the use of basic categories by dichromats. As mentioned, transformations were carried out using the Smith and Pokorny (1975) fundamentals, so that the well known lightness alterations shown by dichromats are compensated for (see, for example, Fletcher & Voke, 1985, pp. 167-169; Lillo, Collado, Vitini, Ponte, & Sánchez, 1998).

Using the data from Table 1, the basic categories predicted by Model 1 as naming responses to a specific stimulus can be determined in the following way:

1. The coordinates of the stimulus and the convergence point are used to trace a pseudoisochromatic line.
2. There is *chromatic concordance* between the stimulus and a basic category when the pseudoisochromatic line intersects with the basic category chromatic area.
3. There is *reflectance concordance* when the stimulus is included in the range corresponding to a basic category.
4. A basic category will be a predicted response only when it has *chromatic* and *reflectance* concordance with the presented stimulus.

Figure 2 uses one of the tiles (green) employed in our research to provide a graphic example of the four steps we have just described. The two large squares with a plus sign inside indicate the positions of both stimuli required to trace protanopes' pseudoisochromaticity line for the specific tile: the convergence point ( $u' = 0.65$ ;  $v' = 0.50$ ) and the point corresponding to the target tile ( $u' = 0.14$ ;  $v' = 0.51$ ). Larger round points indicate the tiles that were consistently categorized as red in Boynton and Olson's work (1987). Triangles, small gray squares, and small points provide the same kind of information for the orange, yellow, and green categories, respectively. Because the pseudoisochromaticity line crosses the areas corresponding to these categories (which also occurs for gray, pink, and brown, but is not shown to avoid graphic confusion in the figure), these categories have *chromatic concordance* with that tile. Although tile standard reflectance is 22.6%, the use of matrix algebra and the fundamentals of Smith and Pokorny (1975) provides a 25.93% protanope reflectance. As Table 1 indicated, this value falls within the ranges of transformed reflectance of the following categories: green (4.17-66.18), yellow (25.06-73.22), and orange (9.12-43.89). Consequently, these categories fulfil the *reflectance concordance* requisite. Table 1 also reveals that the red category does not fulfil this requisite because its reflectance range (3.44-13.11) does not include the 25.93% value.

Seemingly, there is a contradiction between our previous statement about the confusion between reds and greens being very common among color-blind people, and our subsequent statement about the green tile used as an example, where the red category did not fulfil the reflectance concordance requisite and, consequently, was not a predicted response

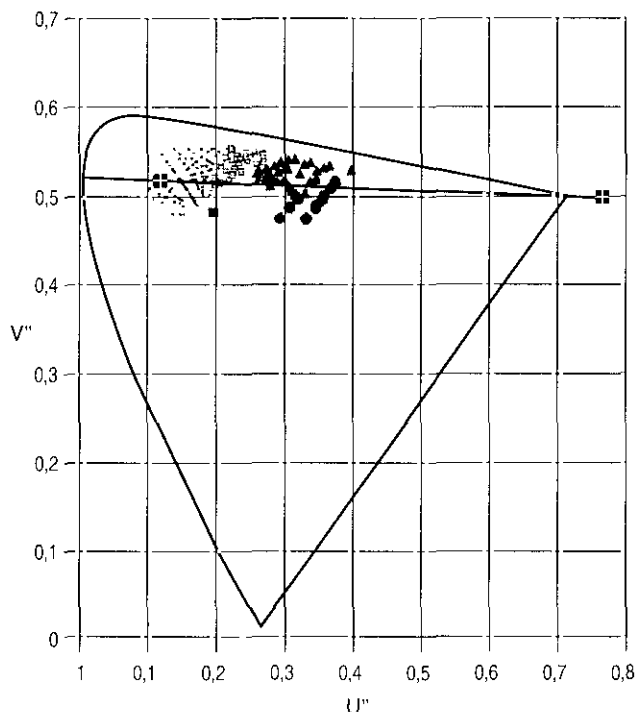


Figure 2. Chromatic concordance and pseudoisochromatic lines. Several chromatic areas are shown (thick points = red; triangles = orange; squares = yellow; small points = green). As these are crossed by the isochromatic line, the chromatic concordance requisite is fulfilled.

when presenting the target. However, there is no contradiction, considering that for some green tiles, the red category would be one of the expected responses: for the greens whose transformed reflectance is among the reflectances corresponding to the red category (3.44-13.11). In conclusion, Model 1 predicts that dark greens, but not medium or light greens, may be called reds by protanopes.

#### *Limitations of Model 1: Towards a new Predictive Model (Model 2)*

Model 1 would be accurate if, as we have assumed till now, clinically diagnosed dichromats were real dichromats. The evidence we shall now comment on suggests that this assumption is not fully tenable.

At the turn of the century, Nagel (1904, cited in Fletcher & Voke, 1985) designed the clinical anomaloscope which is still "the undisputed queen of all color vision test instruments" (Kaiser & Boynton, 1996, p. 429). Nagel was aware that his anomaloscope projected onto a visual field restricted to the macula and, most important, he was the first (Nagel, 1905, as cited in Nagy, 1980 and in Nagy & Boynton, 1979) to discover that most macular dichromats become anomalous trichromats when color stimulation strikes the peripheral retina. This discovery, however, was forgotten until it was finally rediscovered (Boynton & Scheibner,

1967; Scheibner & Boynton, 1968; Smith & Pokorny, 1977).

Despite research suggesting that rods have some influence on macular dichromats' trichromaticity (Montag & Boynton, 1987; Nagy, 1980; Smith & Pokorny, 1977), this cannot be a full explanation of a phenomenon that appears when rods are saturated. In these circumstances, results obtained from high intensity Rayleigh matches (Nagy, 1980), selective adaptation (Scheibner & Boynton, 1968), fluctuation colorimetry (Frome, Piantanida, & Kelly, 1982) and color naming (Montag, 1994; Nagy & Boynton, 1979) agree that macular dichromats have a third type of cone, which is like an anomalous version of the cone that is absent in their macula.

The data described in this paper were obtained using a monolexic color naming task and can be considered as an extension of previous work (Lillo, et al., in press; Montag, 1994; Montag & Boynton, 1987) using the same task to study the trichromaticity of macular trichromats.

Adult dichromats participated in the experiments of Montag (1994; Montag & Boynton, 1987), which allowed for systematic evaluation of their denomination of the full set of surface colors contained in the OSA atlas with different presentation types. CIEu'v' centroids were computed for every basic category, allowing the author to conclude that: (a) Macular dichromats always exhibited a red-green compression in their responses; that is, their centroids were closer than those of common trichromats' for categories such as purple and blue, that are differentiated in terms of the red-green response mechanism. (b) Macular dichromats' categorization was more similar to that of common observers' (normal trichromats) when relatively large (4 degrees instead of 1) and continuous (more than 2 seconds) stimuli were used.

The research by Lillo et al. (in press) can be considered as an extension of the work of Montag (1994), applied to children. As in Montag's experiments, this group of researchers used large stimuli and long exposure times in a naming task. In order to accommodate the experimental procedure to children, the number of participants was increased and a smaller stimulus sample was used. As the main target was to evaluate the way macular dichromat children use the eleven basic chromatic categories, a set of just 11 prototypes was used. The results led to the following conclusions: (a) Macular dichromats achieved almost 100 % correct responses when naming primary basic categories (red, green, yellow, and blue), but made significantly more errors than controls when naming all the secondary chromatic categories (purple, orange, pink, brown); (b) Macular dichromats made fewer errors than predicted by Model 1, although most errors were of the types predicted by the model; and (c) Protanopes tended to make more errors than deuteranopes but, except for the pink prototype, these differences were not statistically significant.

Altogether, the studies by Montag (1994) and Lillo et al. (in press) suggest that in macular dichromats' peripheral retina, there are cones of a type similar to those missing

from their macula. As with normal trichromats (Abramov, Gordon, & Chan, 1991; Nagy & Doyal, 1993), these cones must have a scattered distribution; therefore, they can only provide information when continuous, saturated, and large stimuli are projected onto the periphery. In this case, the red-green opponent mechanism will give a diminished response (compared to that of common observers' macula) and macular dichromats' perception will be similar, but never identical, to that of common observers.

What will be called Model 2 from now on, is the result of assuming that in macular dichromats' peripheral retina, a cone type that is absent from macula is operating and, consequently, that these are anomalous trichromats when responding to large stimuli. From this model, the following predictions are made:

1. The identity of the erroneously employed basic categories can be predicted from the postulates of Model 1 (chromatic and reflectance concordance).

2. Due to the third cone availability, Model 2 predicts fewer naming errors than Model 1.

3. Due to the scattering of the cone distribution at periphery, it is assumed that, for macular dichromats, the third cone type has less informative capacity than that of common trichromats in their macula. Consequently, it is predicted that macular dichromats will produce more naming errors in response to low saturation stimuli, because in this situation, the third cone's activity will not be informative.

4. Considering the ample evidence (for example, Alpern & Torii, 1968a, 1968b; Heath, 1958; Kinnear, 1986; Lillo et al., 1998; De Marco et al., 1992) about both the existence of lightness-perception alterations in macular dichromats, and how these alterations are more severe in protanopes than in deuteranopes, more naming errors are predicted for protanopes.

To evaluate the accuracy of Model 2, we selected a sample of 12 stimuli that, in previous pilot works, had received consistent naming responses by normal children. Specifically, the children named seven of these stimuli *green*, three of them *blue*, and two of them *purple*. Each category included at least one relatively high- and one relatively low-saturation stimulus. The total number of stimuli was similar to the one used in previous research (Lillo et al., in press), and facilitates administering the naming task to children. One of the stimuli contained in each of the three categories employed was its prototype. A relatively high number of *green* samples (seven) was included in the sample: (a) to confirm the surprisingly accurate results obtained in previous research (Lillo et al., in press); and (b) to increase the number of errors computed for every observer (otherwise, it would be not possible to obtain significant differences). As the category *blue* includes both dark and light stimuli, and these two types are categorized differently in some languages (see Davies & Corbett, 1994), we used one sample of light and another of dark blue.

## Method

### Participants

There were three groups of subjects: protanopes ( $n = 12$ ), deuteranopes ( $n = 18$ ), and controls ( $n = 29$ ). Their mean age was 7.17 years ( $SD = 1.58$ ). All of them lived in Alcorcón, a city near Madrid (Spain), and their mother tongue was Spanish. They were chosen from 1,631 boys, aged 5-9 years, who were screened for color-blindness.

### Materials

The test battery consisted of the Ishihara Test (1917, see, for example, Birch, 1993, or Fletcher & Voke, 1985, pp. 276-278), the City University Color Vision Test (CUCVT; Fletcher, 1980), and the "Test para Identificación de los Daltonismos" (TIDA [Test to Identify Color-Blindness]; Lillo, 1996). A child was considered a dichromat if the following three criteria were met: (a) anomalous responses on more than 90% of the Ishihara tiles, (b) six or more out of ten *red-green* responses (protan or deutan responses) on the CUCVT, and (c) they were rated *severe* on the TIDA. Pilot work with adult observers showed that these are conservative criteria: All adults meeting these criteria were confirmed as dichromats by the anomaloscope, although some adults diagnosed as dichromats by the anomaloscope failed to meet the triple criteria.

The classical Ishihara test uses a series of tiles on which certain numbers can be identified (e.g., "seven" or "forty-two"), provided the figures and the background on which they are presented are perceived as being of different colors. Given that some of the younger children had difficulties in identifying the two-figure numbers verbally, they were allowed to emit their "number-response" figure-by-figure ("one and four" instead of fourteen). In some cases, moreover, children were allowed to trace with their finger the form of the number they said they recognized (if they were unable to identify it verbally).

The second of the tests employed, the CUCVT, consists of 11 tiles (1 training + 10 diagnostic), on which is presented a central reference pattern (a colored circle) and around it, four alternatives from which the children are asked to indicate (verbally or signaling with a finger) which is more similar to the central pattern. In all of the diagnostic tiles, one of the alternatives corresponds to that which a person with normal chromatic vision would select, whereas the three remaining figures correspond to the three classic types of alteration ("protan," "deutan," and "tritan").

The TIDA is a test that employs pseudoisochromatic illustrations especially designed for children. It has two parts. The first part allows detection of red-green color-vision anomalies (daltonisms) and starts the process of specific diagnosis. All the tiles show two groups of monkeys (3 larger ones on the top row and 4 smaller ones on the

bottom row) with different functions. The function of the top-row monkeys is to act as reference elements for the type of stimuli the child should look for in the bottom row ("gray" or "colorless"). The function of the illustrations on the bottom row is to present the alternatives from which the child is requested to select those that he or she perceives as achromatic. The second part of the TIDA should only be administered to observers detected as color blind, and affords a specific red-green diagnosis. All tiles of this part show three monkeys to the children. One acts as reference. From the other two, the children are requested to select the most similar to the reference.

The stimuli for the color-naming task consisted of twelve 5-centimeter square colored tiles, presented on a neutral gray background. They projected a visual angle of 8°. The colors were from the Color-Aid range. Table 2 shows their Color-Aid identification (number and code), chromatic category, CIEu'v' chromaticity coordinates, dominant wavelength ( $\lambda_D$ ), standard (control) reflectance, and protanope and deuteranope reflectances. The basic colorimetric measurements (Y, x, y) of the tiles were carried out with a Minolta CS-100 colorimeter. Starting with these measurements, all the parameters shown in Table 2 were computed. Specifically, to adequately compute the standard reflectance values, all the measurements with the colorimeter were carried out after fixing it onto a tripod and always pointing it at a spatial position that prevented the possible effects of specular reflection. First, a sample (N 0500), from the NCS color atlas (Hård, Sivick, & Tonquist, 1996) and

of known reflectance (84.66 %), was placed in this position and its luminance (Y) was measured. From the same position, the tiles used as stimuli in the naming task were measured successively, and the reflectance of a specific stimulus was deduced from the proportion between the luminances of the reference sample and the specific stimulus.

### Procedure

Testing was carried out where possible using natural light with an illuminance level between 250-400 lux and a correlated color temperature between 4000-6500 Kelvin. These two parameters were measured with a Gossen Colormaster 3F termocolorimeter. If light parameters fell outside of the desired values, natural light from the windows was mixed with light from a blue incandescent light bulb (its correlated color temperature was 3210 K), from a conventional adjustable table lamp. Although no direct measurements of this parameter were taken, in all cases, the CIE Color Rendering index values were very close to 100%, as can be seen from the characteristics of the two kinds of light mixed (see Hunt, 1987, chap. 5 and Appendix 7).

All children were tested individually in the color-naming task. The tiles were shown one at a time, in random sequence. The tiles were viewed binocularly from a distance of approximately 35 cm. The tester requested the child to respond with one color name, and no object names (such as *banana* or *tomato*) were allowed.

Table 2

Stimuli description: Color-Aid Identification, Chromatic Category, CIEu'v' Chromaticity Coordinates and Saturation, Dominant Wavelength ( $\lambda_D$ ), Standard (Control), Protanope, and Deuteranope Reflectances of the Tiles used in the Naming-Task

| Color-aid      | u'   | v'   | CIE Sat | $\lambda_D$ | R    | Rprot | Rdeut |
|----------------|------|------|---------|-------------|------|-------|-------|
| <b>Greens</b>  |      |      |         |             |      |       |       |
| 36 Ygc-HUE     | .138 | .512 | 1.08    | 516         | 22.6 | 25.93 | 20.92 |
| 45 G-HUE       | .123 | .466 | 1.13    | 494         | 13.6 | 16.47 | 12.15 |
| 115 G-EX       | .126 | .477 | 1.10    | 496         | 14.7 | 17.58 | 13.25 |
| 242 G-S2       | .150 | .475 | 0.78    | 496         | 8.9  | 10.13 | 8.26  |
| 48 G-T3        | .154 | .476 | 0.73    | 496         | 38.6 | 43.60 | 36.08 |
| 54 GC-T4       | .162 | .465 | 0.63    | 492         | 47.7 | 53.35 | 44.80 |
| 247 G-P3-1     | .176 | .473 | 0.44    | 495         | 16.0 | 17.27 | 15.35 |
| <b>Blues</b>   |      |      |         |             |      |       |       |
| 65 BC-HUE      | .119 | .330 | 2.17    | 580         | 9.4  | 12.78 | 7.65  |
| 276 B-S2       | .153 | .370 | 1.50    | 580         | 4.8  | 5.83  | 4.32  |
| 57 BG-T2       | .139 | .430 | 1.06    | 591         | 30.9 | 36.99 | 27.83 |
| <b>Purples</b> |      |      |         |             |      |       |       |
| 87 V-HUE       | .222 | .373 | 1.27    | 569         | 5.4  | 5.40  | 5.41  |
| 289 RVPI-1     | .225 | .423 | 0.64    | 566         | 12.9 | 12.59 | 13.05 |

Note.  $\lambda_D$  = Dominant wavelength; R = Standard reflectance; Rprot = Protanope reflectance; Rdeut = Deuteranope reflectance.

## Results

As in pilot studies, control subjects only committed a minimum number of erroneous denominations. Therefore, specific information about their responses will not be offered and the description of results will focus on the dichromat macular responses. Table 3 shows, for protanopes ( $n = 12$ ) and deuteranopes ( $n = 18$ ), the number of responses that every basic chromatic category received in response to every tile. Deuteranope responses are presented in brackets. According to Model 1, there are two types of expected responses. One (numbers on gray background) indicates a correct-category response; the other (underlined numbers) indicates an incorrect-category response to a specific tile, as predicted by Model 1. The results from Table 3 were analysed in four different ways.

First, for every tile, the number of correct responses was compared with that expected from the equiprobabilistic use of Model 1, which depends on the number of categories predicted. For example, Model 1 predicts green (correct response), yellow, orange, pink, and gray for tile number 36. Equiprobabilistic use of these categories should produce only 20% of correct responses or, in frequency terms, 2.4 correct responses (for analysis, we rounded off to the higher

value, 3). Using a  $\chi^2$  test, we found that the number of correct responses given by protanopes (11) was significantly higher than predicted by Model 1 for tile 36. In Table 3, asterisks indicate when correct response frequencies were higher than those predicted by Model 1 ( $p < .05$ , one tail).

Second, the number of correct responses in control and color-blind observers was compared. Table 4 shows that when all stimuli were grouped (A) and when the analysis was restricted to the three chromatic categories (B), both dichromat groups made significantly more errors than controls. Table 4 also shows that protanopes made more errors than deuteranopes (except for one case, all differences were significant).

Third, the number of correct responses was analyzed as a function of the saturation level for every type of stimuli (greens, blues, and purples) and of the kind of macular dichromat observer (protanopes and deuteranopes). Table 5 shows the errors made by both dichromatic groups for every chromatic category. Table 6 shows the results of applying a series of  $\chi^2$  tests to evaluate whether errors decreased significantly with the CIEu'v' saturation increment in every basic category. All the significant differences obtained correspond to a higher number of errors for less saturated stimuli.

Table 3  
*Response Matrix for Protanopes and Deuteranopes*

| Presented<br>Tile | Response    |             |             |             |        |             |             |             |             |             |          |
|-------------------|-------------|-------------|-------------|-------------|--------|-------------|-------------|-------------|-------------|-------------|----------|
|                   | Green       | Blue        | Purple      | Red         | Yellow | Orange      | Brown       | Pink        | Gray        | Black       | White    |
| 36 Ygc-HUE        | 11*(18*)    |             |             |             | 1      | <u>0(0)</u> | <u>0(0)</u> | <u>0(0)</u> | <u>0(0)</u> |             |          |
| 45 G-HUE          | 11*(18*)    | <u>0(0)</u> | <u>0(0)</u> |             |        |             | 1           | <u>0</u>    | <u>0(0)</u> |             |          |
| 115 G-EX          | 12*(17*)    | <u>0(0)</u> | <u>0(0)</u> |             |        | <u>0</u>    | <u>0</u>    | <u>0</u>    | <u>0(0)</u> | <u>1(1)</u> |          |
| 48 G-T3           | 11*(17*)    | <u>0(0)</u> |             |             | 1      | <u>0</u>    | <u>1(1)</u> | <u>0(0)</u> | <u>0(0)</u> |             |          |
| 242 G-S2          | 6(16*)      |             | <u>1(1)</u> |             |        |             | 3           | 1           |             | <u>2(1)</u> |          |
| 247 G-P3-1        | 9*(16*)     | <u>0(0)</u> | <u>0(0)</u> |             |        |             | <u>2(0)</u> | <u>0</u>    | <u>0(2)</u> | 1           |          |
| 54 GC-T4          | 6(13*)      |             |             |             | 1      |             | <u>1(1)</u> | <u>1(2)</u> | <u>1(2)</u> |             | <u>3</u> |
| 65 BC-HUE         |             | 11*(17*)    | <u>1(1)</u> | <u>0</u>    |        |             | <u>0</u>    |             |             |             |          |
| 276 B-S2          |             | 6(10*)      | <u>5(8)</u> |             |        |             |             | 1           |             |             |          |
| 57 BG-T2          | <u>3(5)</u> | 4(11*)      | <u>1(0)</u> |             |        |             |             | <u>1(0)</u> | <u>3(1)</u> | <u>1(1)</u> |          |
| 87 V-HUE          | <u>1(1)</u> | <u>5(7)</u> | 7*(10*)     | <u>0(1)</u> |        |             | <u>0(1)</u> | <u>2(2)</u> |             | <u>1(1)</u> |          |
| 289 RVP1-1        | <u>0(0)</u> | <u>5(1)</u> | 1(12*)      | <u>0</u>    |        |             | <u>0</u>    | <u>4</u>    | 1           | 1           |          |

*Note.* Numbers in gray rectangles represent the frequency of correct responses for the green (upper), blue (middle), and purple (lower) tiles. An asterisk indicates a frequency of correct responses statistically higher ( $p < .05$ ) than predicted by Model 1. Numbers in brackets correspond to deuteranope responses. Numbers with no brackets correspond to protanope responses. Underlined numbers indicate expected errors. Zero represents a category of expected errors that did not occur.

Table 4

Results of Statistical Comparisons between the Number of Correct Responses Obtained for the Various Observer Groups with the Different Stimuli Types

| Groups compared                  |  | $\chi^2$  |
|----------------------------------|--|-----------|
| A. All stimuli considered        |  |           |
| Protanopes vs. Deuteranopes      |  | 10.432**  |
| Protanopes vs. Control           |  | 107.045** |
| Deuteranopes vs. Control         |  | 51.960**  |
| B. Grouped by chromatic category |  |           |
| Green                            |  |           |
| Protanopes vs. Deuteranopes      |  | 10.432**  |
| Protanopes vs. Control           |  | 42.126**  |
| Deuteranopes vs. Control         |  | 15.011**  |
| Blue                             |  |           |
| Protanopes vs. Deuteranopes      |  | 1.386     |
| Protanopes vs. Control           |  | 24.128**  |
| Deuteranopes vs. Control         |  | 14.993**  |
| Purple                           |  |           |
| Protanopes vs. Deuteranopes      |  | 4.444*    |
| Protanopes vs. Control           |  | 48.040**  |
| Deuteranopes vs. Control         |  | 26.503**  |

Note. A = comparisons grouping the responses of all stimuli. B = grouping only the responses given to the tiles of the same chromatic category.

\*  $p < .05$ . \*\*  $p < .01$ .

Table 5

Number of Errors for Protanopes and Deuteranopes as a Function of Stimuli Chromatic Category and Saturation Level

|              | Stimuli type    |                 |                 |                 |                |                  |                  |                  |
|--------------|-----------------|-----------------|-----------------|-----------------|----------------|------------------|------------------|------------------|
|              | Prototype Green | Saturated Green | Medium Green    | Low Green       | Saturated Blue | Low Blue         | Saturated Purple | Low Purple       |
| <b>Tiles</b> | <b>(36)</b>     | <b>(45+115)</b> | <b>(48+242)</b> | <b>(54+247)</b> | <b>(65)</b>    | <b>(57+276)</b>  | <b>(87)</b>      | <b>(289)</b>     |
| Protanopes   | 1/12<br>(8.3%)  | 1/24<br>(4.1%)  | 7/24<br>(21.1%) | 9/24<br>(37.5%) | 1/12<br>(8.3%) | 14/24<br>(58.3%) | 5/12<br>(41.7%)  | 11/12<br>(91.7%) |
| Deuteranopes | 0/18<br>(0%)    | 1/36<br>(2.7%)  | 3/36<br>(8.3%)  | 7/36<br>(19.4%) | 1/18<br>(5.5%) | 15/36<br>(41.7%) | 8/18<br>(44.4%)  | 6/18<br>(33.3%)  |

Note: Underlined numbers in bold type correspond to COLOR-AID identification tiles. In fractions, the denominator represents the maximum number of possible errors.

Table 6

Results of Comparing, in each Chromatic Category, the Frequency of Errors of the Stimuli Groups Described in Table 5

| Comparison                          | Protanopes<br>$\chi^2$ | Deuteranopes<br>$\chi^2$ |
|-------------------------------------|------------------------|--------------------------|
| Prototype green vs. Saturated green | 0.256                  | 0.509                    |
| Saturated green vs. Medium green    | 5.400*                 | 1.059                    |
| Saturated green vs. Low green       | 8.084**                | 5.063*                   |
| Medium green vs. Low green          | 0.375                  | 1.858                    |
| Saturated blue vs. Low blue         | 8.229**                | 7.505**                  |
| Saturated purple vs. Low purple     | 6.750**                | 0.468                    |

\*  $p < .05$ . \*\*  $p < .01$ .



Table 7

*Results of Statistical Comparisons between the Number of Expected and Unexpected Errors Obtained in the Three Groups of Color-Blind Observers: Total (Protanopes + Deuteranopes), Protanopes, and Deuteranopes*

|   | Groups compared                   | $\chi^2$ |
|---|-----------------------------------|----------|
| A. All stimuli considered                 | Total (protanopes + deuteranopes) | 24.206** |
|   | Protanopes                        | 9.949**  |
|   | Deuteranopes                      | 12.947** |
| B. Stimuli grouped by chromatic category. |                                   |          |
|   | Green                             |          |
|   | Total (protanopes + deuteranopes) | 5.526*   |
| Protanopes                                | 3.010*                            |          |
| Deuteranopes                              | 2.561                             |          |
| Blue                                      | Total (protanopes + deuteranopes) | 12.155** |
|   | Protanopes                        | 7.056**  |
|   | Deuteranopes                      | 5.236*   |
| Purple                                    | Total (protanopes + deuteranopes) | 7.500**  |
|   | Protanopes                        | 5.236*   |
|   | Deuteranopes                      | 2.489    |

\*  $p < .05$ . \*\*  $p < .01$ .

Given the reduced number of errors, incorrect responses to all files were grouped for the last analysis. Table 7 shows that the more frequent errors corresponded to those predicted by Model 1, specially when protanopes were considered. This same result was also found when only responses to each chromatic category were considered.

### Discussion

The results show that children diagnosed as dichromats perform more accurately than is predicted for a pure dichromat. This is especially true for high saturation stimuli. On the other hand, whereas low saturation stimuli increased naming errors for both clinical groups, this increase was significantly higher for protanopes. These results also confirm that macular dichromats tend to correctly name saturated greens.

The most parsimonious interpretation of our results is similar to that proposed by Montag (1994) and assumes that diagnosed dichromats only behave like true dichromats in response to small-sized stimuli that project exclusively onto the macula. However, when stimuli also project onto the periphery, these same observers become anomalous trichromats and show partial functionality of their red-green mechanism, presumably because of the information provided for the cone type that is absent in macula but that could be present in peripheral retina. The increase of errors produced by reduced saturation and the fact that most of them were predictable from Model 2 are consistent with this explanation.

An alternative explanation would postulate that the anomalous dichromatism observed in macular dichromats would depend, partially or totally, on the information provided by the rods in the retina. This explanation could only be fully discarded if a study were carried out in which the response of these photoreceptors was saturated by the stimulation intensity, thus annulling their informative ability. Although the illuminances employed in this study (250-400 lux) almost achieve this effect (see, for example, Hood & Finkelstein, 1986, Table 5.1), higher values should have been used in order to reject definitely any explanation of the results based on rod activity. Nevertheless, with regard to alternative explanations, those derived from the recent discovery of detectable differences within the same type of cone (Neitz & Neitz, 1998) should not be discarded. That is, contrary to prior assumptions by the scientific community, there are small differences in the spectral sensitivities of the same type of cones (for example, protocones or deutercones). At least theoretically, this variability may contribute to compensating for the loss of a cone type that characterizes macular dichromats.

As mentioned previously, our group's work is highly related to that of Montag (1994; Montag & Boynton, 1989). In both cases, a naming task of chromatic samples was used, and, more important, better-than-expected results were obtained in observers with only two types of cones in their retina. Nevertheless, Montag and our research group used the data in significantly different ways. In Montag's work, following the tradition of Boynton and Olson (1987), the names provided by the color-blind were used to calculate

the position of the centroids of each of the 11 basic categories and, based on the comparison with common observers' categories, the authors were able to make deductions about the perceptive causes of the errors (a weakness in the response capacity of the red-green mechanism). However, no effort was made to make specific predictions about the identity of the naming errors (whose basic category, in fact, is used incorrectly for a specific sample). In an attempt to predict these naming errors, we undertook the present study, thus developing what has been called Model 2.

The main implication of our results is that, like Montag (1994; Montag & Boynton, 1989), they challenge an eminent idea that has pervaded many related fields of visual perception: that the visual response produced by medium- or large-sized stimuli is similar to that produced by small stimuli projected onto the macular retina. This idea underlies contemporary photometry, for example, although it is currently receiving much criticism in this area (Fotios & Levermore, 1997; Lynes, 1996). This idea is also essential to what we have called Model 1, which postulated that small-field dichromats will still be dichromats even with large-sized stimuli (i.e., most everyday stimuli). According to the results from the last thirty years (e.g., Montag, 1994; Nagy, 1980; Scheibner & Boynton, 1968; Smith & Pokorny, 1977), the high rate of correct denominations by macular dichromats that we observed would never have been predicted under the assumption of a pure dichromatic retina.

If there is so much evidence against it, what fate awaits Model 1? It will probably still be considered an appropriate model in specific contexts because it accurately accounts for functional vision with small-sized stimuli. For example, it has been successfully used to predict which backgrounds would make reading color-letter messages more difficult (Lillo, Collado, Martín, & García, 1999). In this task, as in most reading tasks, the essential aspect was the way in which small contours are distinguished from their background. For this task, no help can be expected from peripheral cones and, consequently, Model 1 is accurate. It is also accurate to predict naming errors in small-sized stimuli (Paramei, Bimler, & Cavonius, 1998). Moreover, this model has dominated scientific thought on visual perception for most of this century and due to this, it is described as being accurate in general books on perception (see, for example, Coren, Ward, & Enns, 1994), in publications that are directly related to standard evaluation of chromatic alteration (see, for example, Birch, 1993; Lillo, 1996), and in guidelines to help the color-blind (e.g., Rigden, 1999).

Model 2 incorporates the predictions made by Model 1, as far as the processing of small-sized stimuli is concerned, but assumes that, as more peripheral stimulation is involved, the more will peripheral cones, similar to the one missing from the macula, contribute to the visual response. From this framework, pseudoisochromaticity lines can be used to predict which categories are expectable as erroneous responses, but will only predict error frequency when small-

sized stimuli are used. Error reduction is predicted when large-sized and very saturated stimuli are projected onto the retina, as in our experiment. However, additional research is needed before a more quantitative relation between stimulus size and response accuracy can be established. In order to adapt the model to the characteristics of Spanish speakers as much as possible, basic research should be carried out to determine the exact basic Spanish category volumes. Thus, in our model, the volumes determined from Boynton and Olson's (1987) results can be substituted by other volumes, more specific to the Spanish population.

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