An experimental method for the assessment of color simulation tools

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The Simulcheck method for evaluating the accuracy of color simulation tools in relation to dichromats is described and used to test three color simulation tools: Variantor, Coblis, and Vischeck. A total of 10 dichromats (five protanopes, five deuteranopes) and 10 normal trichromats participated in the current study. Simulcheck includes two psychophysical tasks: the Pseudoachromatic Stimuli Identification task and the Minimum Achromatic Contrast task. The Pseudoachromatic Stimuli Identification task allows determination of the two chromatic angles ($h_{uv}$ values) that generate a minimum response in the yellow–blue opponent mechanism and, consequently, pseudoachromatic stimuli (greens or reds). The Minimum Achromatic Contrast task requires the selection of the gray background that produces minimum contrast (near zero change in the achromatic mechanism) for each pseudoachromatic stimulus selected in the previous task ($L_R$ values). Results showed important differences in the colorimetric transformations performed by the three evaluated simulation tools and their accuracy levels. Vischeck simulation accurately implemented the algorithm of Brettel, Viênot, and Mollon (1997). Only Vischeck appeared accurate (similarity in $h_{uv}$ and $L_R$ values between real and simulated dichromats) and, consequently, could render reliable color selections. It is concluded that Simulcheck is a consistent method because it provided an equivalent pattern of results for $h_{uv}$ and $L_R$ values irrespective of the stimulus set used to evaluate a simulation tool. Simulcheck was also considered valid because real dichromats provided expected $h_{uv}$ and $L_R$ values when performing the two psychophysical tasks included in this method.

Introduction

Most human beings are trichromats. They have three different retinal cones and need a minimum of three primaries to match any color. Some people (slightly above 2% of males; Sharpe, Stockman, Jägle, & Nathans, 1999) are, as are most mammals (Hemmi, James, & Taylor, 2002; Vorobyev, 2004), dichromats. They have only two cone types and require a minimum of two primary colors for matching any color. The clinical denominations of dichromatism (protanopia, deuteranopia, and tritanopia) specify the absent cone type (proto, deutera, and trita mean first, second, and third, respectively, in Greek). In the standard scientific nomenclature (Carroll, Neitz, & Neitz, 2002; Hunt & Pointer, 2011, chapter 1; Lewis & Zhaoping, 2006) such cones are frequently identified as “L,” “M,” and “S” because they are relatively more sensitive to long, medium, and short wavelengths, respectively.

Chromatic stimuli frequently improve visual memory performance for both normals and dichromats (Gegenfurtner, Wichmann, & Sharpe, 1998; Spence, Wong, Rusan, & Rastegar, 2006; Velisavljević & Elder, 2008). Color variations are frequently used to facilitate some visual tasks (Breslow, Trafton, & Ratwani, 2009; Yamani & McCarley, 2010). They include the localization (Remington, Johnston, Ruthruff, Gold, & Romera, 2000) and identification (Spence, Kulesa, & Rose, 1999) of some kind of information. Hue changes (color qualitative changes) are especially accurate for supporting identification tasks on complex visualizations (categorization, absolute numeric value judgments, etc.), whereas ordered lightness or saturation scales are superior for relative comparison tasks (differentiation between greater or lesser amounts of
something; Breslow et al., 2009). All the previously mentioned color uses (localization, identification, categorization, etc.) require seeing different colors in response to the stimuli used for representing different things.

Dichromats have more metamers than do normal trichromats (Lillo & Moreira, 2004); that is, they see the same color when responding to stimuli only differentiable thanks to the activity in the absent cone (L for protanopia, M for deuteranopia). According to clinical nomenclature (Birch, 2001; Fletcher & Voke, 1985), pseudoisochromatic stimuli are perceived as the same color by some people (i.e., protanopes or deuteranopes) but as different colors by normal people. Such stimuli are frequently used in classical color clinical diagnosis tests (Birch, 2001) and in the tests designed to be applied using new gadgets, such as different screen types (Pardo, Pérez, & Suero, 2001, 2004) and handheld game console displays (Suero, Pardo, & Pérez, 2010). Of course, new gadgets also can be used for performing everyday tasks requiring color differentiation or categorization, and the presence of pseudoisochromatic stimuli is a possible source of problems (Lillo & Moreira, 2013, chapter 5). For example, if red backgrounds are used to indicate some kind of emergency, their localization would be more difficult for people confusing such reds with other colors used.

According to the universal design framework (Vanderheiden, 2006), things and environments must be designed to allow easy use by normal and disabled people. In relation to color (Lillo & Moreira, 2013, chapter 5) the main goal of universal design is to promote similar, accurate uses by people with and without normal color perception. For example, when designing a political map its colors must be differentiable both for normals and dichromats. If we use an accurate color simulation tool, it will be easy to reach this goal.

Color simulation tools transform colors (original colors) to make them similar to the ones that people who are color blind presumably see (transformed colors). Most of the times, color transformation is done using some kind of software (Capilla, Díez-Ajenjo, Luque, & Malo, 2004; Luque, Fez, & Acevedo, 2014; Viénot, Brettel, & Mollon, 1999). Alternatively, optic filtering can be used (http://www.variantor.co.uk/page.php?sub=2&id=2). Colors differing in the original image but similar in the transformed one are considered pseudoisochromatic. Some simulation tools incorporate a “daltonization function” (Nakauchi & Onouchi, 2008) to avoid pseudoisochromatic colors selectively changing some colors in the original image. Along the same lines, the CIE (International Commission on Illumination) technical committee TC1-89 (http://www.cie.co.at/index.php/Technical+Committees) has been created to “study, evaluate, and recommend image enhancing techniques for color defective observers.”

Color simulation tools assume (implicit or explicitly) a “reduction view” theoretical framework (Broackes, 2010b; Byrne & Hilbert, 2010; Logvinenko, 2014) based on the following two premises: (1) Dichromats see only a subset of the colors experienced by normal trichromats and (2) there are pseudometameric (pseudoisochromatic) stimuli groups—that is, groups of stimuli that produce different colors ($C_{11}, C_{12}, \ldots, C_{1n}$) for people with normal color vision but only one color ($C'_1$) for dichromats (i.e., Vischeck is based on the algorithm of Brettel, Viénot, & Mollon, 1997). From the two previous premises, differences between color simulation tools can appear about (1) the stimuli included in each pseudoisochromatic group and (2) the color perceived when seeing any stimulus included in a specific pseudoisochromatic group. As will be shown, this last aspect is not relevant when making universal design.

When red–green dichromats (protanopes or deuteranopes) do a Rayleigh match (Birch, 2001, p. 53), the colors they perceive when seeing any mix of the green (545 nm) and the red (670 nm) lights can be matched by the yellow (589 nm, orangish-yellow) light adjusted to a specific intensity. This means that, for these dichromats, some pseudoisochromatic stimuli include lights that belong to very different color categories (red, orange, green, or yellow) for normal people. Consequently, such lights must not be used to symbolize different things (for example, different power levels in a mobile phone) regardless of the specific color seen by the dichromats. In conclusion, the key aspect when evaluating a color simulation tool is to know if it creates pseudoisochromatic stimuli groups equal to the ones existing in the simulated dichromat type. The notorious differences existing between the colors provided by different simulation tools (i.e., in lightness level) for the same type of dichromat make obvious that some tools do not work accurately.

Our main research goal was the design and evaluation of a method, Simulcheck, that aims to be useful for evaluating color simulation tools. Data collected in this research allow comparisons between real dichromats, simulation tools (Vischeck, Variantor, and Coblis), and a dichromat’s color appearance algorithm (Brettel et al., 1997; see Footnote 1). On one hand, as is usually the case, there was no information about the algorithm that supposedly was used by two simulation tools (Variantor and Coblis). Therefore, we took colorimetric measurements on the transformation performed by each tool. On the other hand, such information was available for Vischeck (based on Brettel et al., 1997; see Footnote 1), making it possible to test the algorithm’s implementation accuracy.
The real dichromats’ behavior in the two psychophysical tasks performed (see next paragraph) are analyzed. Later, the real dichromats’ data are compared with the behaviors predicted by the algorithm and with those of simulated dichromats in order to check the algorithm’s validity and the tool’s accuracy in simulating color vision. Finally, we compare the behaviors predicted by the algorithm with those provided by simulated dichromats.

Simulcheck includes two psychophysical tasks named Pseudoachromatic Stimuli Identification and Minimum Achromatic Contrast. Each task is related to a well-known fact of dichromatic color vision and with the performance of an opponent mechanism (the yellow–blue mechanism or the achromatic mechanism). Pseudoachromatic Stimuli Identification task. Color derives from the activity of red–green, yellow–blue, and achromatic mechanisms. It is commonly assumed that protanopes and deuteranopes have no functionality in

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**Figure 1.** Representation of the chromatic coordinates for the stimuli included in the two stimulus sets used in the Pseudoachromatic Stimuli Identification task. Maximum Chroma set: intersections between radii (40 different chromatic angles) and triangle perimeter; Constant Chroma set: intersections between radii and circle. The center of the circle corresponds to the achromatic point. The triangle vertices to the three screen primaries. Two confusion lines cross the achromatic point. Black line is for protanopes; gray line is for deuteranopes. Dotted segments are for pseudoachromatic greens; dashed segments are for pseudoachromatic reds.

**Figure 2.** Schematic version of the spatial configuration used in the Pseudoachromatic Stimuli Identification task. Twenty stimuli (a semiset) were simultaneously presented. Their chromatic angles ($h_{uv}$) changed from left to right.
the red–green mechanism and, consequently, see no differences between the grays and the stimuli producing a neutral response in their yellow–blue mechanism. Several works (Birch, 2001; Fletcher & Voke, 1985; Smith & Pokorny, 2003) have shown that each dichromat type has two dominant wavelengths ($\lambda_d$) and, consequently, two chromatic angles ($h_{uv}$) that identify pseudoachromatic angles. One (Smith & Pokorny, 2003) is located near $\lambda_d = 494$ nm ($h_{uv} = 183.95^\circ$) for protanopes and $\lambda_d = 499$ nm ($h_{uv} = 167.39^\circ$) for deuteranopes. We name stimuli with such $\lambda_d-h_{uv}$ values “pseudoachromatic greens” because they are categorized as greens (more specifically, bluish greens) by normal people. The other dominant wavelength associated with pseudoachromatic color (Smith & Pokorny, 2003) is located near $\lambda_d = -494$ nm ($h_{uv} = 3.95^\circ$) for protanopes and $\lambda_d = -499$ nm ($h_{uv} = 347.39^\circ$) for deuteranopes. We name stimuli with such $\lambda_d-h_{uv}$ values “pseudoachromatic reds” because they are categorized as reds (or reddish purples) by normal people.
The chromatic angles \( (h_{uv}) \) corresponding to the pseudoachromatic greens and reds are the first type of variable provided by Simulcheck to evaluate simulation tools’ accuracy. They allow specifying the stimuli that produce a minimum response in the yellow–blue mechanism of real and simulated dichromats.

**Minimum Achromatic Contrast.** Only the achromatic mechanism responds to the highest visible spatial frequencies (De Valois & De Valois, 1988, chapter 7; Kaiser & Boynton, 1996, chapter 9). It makes it possible to see small details and provides maximum visual acuity. The achromatic mechanism performance depends essentially on the response of L and M cones (Hunt & Pointer, 2011, chapter 1). For people with trichromatic color vision, its spectral sensitivity is very similar to the spectral luminous efficiency function for photopic vision (Hunt & Pointer, 2011, pp. 21–22), \( V(\lambda) \), and, consequently, to the weighting performed by the standard photometric measurement apparatuses (Kaiser & Boynton, 1996, appendixes 1 and 2). The achromatic mechanism spectral sensitivity is anomalous for people lacking L (protanopes) or M (deuteranopes) cones (Birch, 2001, figure 4.2). Such anomaly is bigger for the protanopes because L cones are more frequent and contribute more to the achromatic mechanism response (Carroll et al., 2002; Hunt & Pointer, 2011, chapter 1).

Previously, we (Lillo, Collado, Martín, & García, 1999; Lillo & Moreira, 2005) developed the AMLA (AM = achromatic measurement, LA = luminosity adjustment) method to compute the transformed luminance \( (L_T) \) variable in people who are color blind.\(^4\) AMLA includes tasks similar to some others classically used for defining \( V(\lambda) \). The Minimum Achromatic Contrast task is the second Simulcheck task. It serves to determine the luminance that an achromatic background must have to make most difficult the reading of a colored text. It is assumed that the \( L_T \) value for such color is equal to the standard luminance \( (L) \) of the selected background. In the Simulcheck method, the Minimum Achromatic Contrast task is used to measure the \( L_T \) value for the pseudoachromatic greens and reds previously selected in the Pseudoachromatic Stimuli Identification task.

Comparing \( L_T \) with \( L \) provides relative luminance \( (L_R = L_T/L) \).\(^5\) \( L_R \) is the second variable used by Simulcheck to evaluate simulation tools’ accuracy—specifically, how much the responses of the achromatic mechanism differ between dichromats and normals. \( L_R \) values provide a very intuitive specification of such differences. Values over one correspond to stimuli that are perceived to be lighter by people who are color blind (real or simulated) than by normal people. The reverse is true when \( L_R \) is less than one.

We also evaluated Simulcheck’s consistency using two different stimulus sets in the Pseudoachromatic Stimuli Identification task. Although such sets had important colorimetric differences, we expected this fact did not substantially influence the pattern of results obtained for the \( h_{uv} \) and \( L_R \) values provided by Simulcheck.

Simulcheck was applied to real dichromats and to simulated dichromats using three color simulation tools. One of the tools was the Variantor goggles. Variantor goggles perform an optical transformation that works for any kind of visual stimulation and hence it is not restricted to screen colors. Variantor’s main limitation is that it does not provide different transformations for different types of dichromatism. The other two tools were free access tools: Vischeck (http://www.vischeck.com/vischeck/) and Coblis (http://www.color-blindness.com/coblis-color-blindness-simulator/). Both Vischeck and Coblis use software for transforming screen colors into other colors that are supposedly similar to the ones seen by protanopes or deuteranopes. For Vischeck the transformation is based in the algorithm developed by Brettel et al. (1997; see Footnote 1). There is no comparable information for Coblis and Variantor. We provide information about chromatic coordinates in order to specify the results produced by these software simulation tools. We used two stimulus sets (Maximum Chroma and Constant Chroma) for evaluating Simulcheck’s consistency.

## Methods

### Participants

A total of 10 normal trichromats (four men, six women; age range 22–30 years) and 10 dichromats (five protanopes, five deuteranopes; nine men, one woman; age range 21–34 years) took part in the experiment. Their color vision was tested with a set of psychophysical tests (Fletcher, 1980 [City University Color Vision Test]; Ishihara, 1996; Lanthony, 1985). In order to assign them to groups, participants with color vision deficiencies also performed a Rayleigh match in a Nagel anomaloscope (Tomey AF-1, Tomey, Nagoya, Japan). All participants collaborated voluntarily in the research and could stop their participation at any moment.

### Materials and stimuli

Stimuli were presented using a Sony Trinitron Multiscan 17 SEII screen (Sony, Tokyo, Japan) with a gamma correction equal to 2.15. Primaries luminance \( L \) values provided by Simulcheck.
(Y) and chromatic coordinates (u’, v’) were as follows: red (Y = 14.6; u’ = 0.404, v’ = 0.530), green (Y = 31.2; u’ = 0.119, v’ = 0.561), and blue (Y = 3.5; u’ = 0.170, v’ = 0.155). Equivalent values for the screen white were Y = 49.3; u’ = 0.204, v’ = 0.467. During part of the experiment normal trichromats used Variantor glasses (http://www.variantor.co.uk/page.php?sub=2&id=2; Cambridge Research Systems, Kent, UK). The measurements of primaries through the goggles provided the following results: red (Y = 86; u’ = 0.268, v’ = 0.524), green (Y = 6.65; u’ = 0.205, v’ = 0.546), and blue (Y = 0.35; u’ = 0.185, v’ = 0.161). Equivalent values for the screen white were Y = 7.95; u’ = 0.211, v’ = 0.447. All the measurements were performed using a Minolta CL-200 luxcolorimeter (Minolta, Tokyo, Japan) with the required accessories. The room where the screen was located had an illuminance level near 3 lux in the area near the screen.

Figure 1 gives the colorimetric characteristics of the stimuli included in the two stimulus sets of the Pseudoachromatic Stimuli Identification task. The 40 radii departing from the coordinates of white (u’ = 0.204, v’ = 0.467) correspond to chromatic angles (huv) changing in 9° steps (3°, 12°, 21°, . . ., 354°). Coordinates of stimulus sets were defined by the intersection of the radii and the triangle defined by the three screen primaries (Maximum Chroma set) or the radii and the circle (Constant Chroma set). The circle radius was defined by the less-saturated angle available in the monitor color gamut (huv = 183°, saturation, suv = 0.884). The stimuli included in this last set had similar C*uv (chroma) and L* (lightness) values (C*uv = 66.5, maximum value possible in all the chromatic angles; L* = 75). For the Maximum Chroma set, C*uv and L* changed for the different chromatic angles (C*uv was the maximum possible in each angle, and L* was the value that made possible such maximum C*uv).

Procedure

Participants performed 20 trials (10 for each stimulus set; five for pseudoachromatic green and five for red). Each trial included a Pseudoachromatic Stimuli Identification task (task 1) and, after it, a Minimum Achromatic Contrast task (task 2). Real dichromats performed the Pseudoachromatic Stimuli Identification task responding to the original stimuli included in both sets (Maximum Chroma and Constant Chroma; Figure 1), but normal trichromats responded, in different moments, to the stimuli transformed by each simulation tool (Variantor, Coblis, and Vischeck). One half of the normal observers performed all the trials with the optical tool (Variantor) before beginning with the software tools (Coblis and Vischeck; their trials were randomized); the other half did so in the opposite order. Figure 2 provides a schematic version of the spatial configuration used in the Pseudoachromatic Stimuli Identification task. A total of 20 stimuli (half set, a semiset) were simultaneously presented. They belonged to one of the two stimulus sets (Maximum Chroma or Constant Chroma). Chromatic angle (huv) value was increased from left to right by 9° steps (h1, h2, h3, . . ., h20). Each stimulus was a 1.3-cm-wide square that projected 1.5° by 1.5° when viewed from 50 cm. In half of the trials the leftmost stimulus huv was 84° ± 18° (pseudoachromatic green selection). In the other half it was 264° ± 18° (pseudoachromatic red selection). The ±18° random variation was used to avoid the presentation of the stimuli in exactly the same position across trials. The order of the pseudoachromatics (green and red) and the sets (Maximum Chroma and Constant Chroma) was randomized. In each of the 20 trials of the Pseudoachromatic Stimuli Identification task, participants were required to select the stimulus most similar to gray. If participants indicated that a hint of hue was still present, they were required to select the less-saturated stimulus.

Colors selected in the Pseudoachromatic Stimuli Identification task were used in the Minimum Achromatic Contrast task. They appeared in text (the word “ENSAYO” written two times) presented on 20 achromatic backgrounds (Figure 3). Each background measured 5.6 cm × 1 cm (6.4° × 1.2°). The full horizontal length for the semiset was 27.2 cm. The vertical length was 10 cm. The lightest background (L* = 100) was located at the upper left and the darkest background (L* = 2.04) was located in the lower right. L* changed in five L* steps between the more similar backgrounds. Both tasks’ stimuli configurations were presented on a gray background (L* = 90). In the Minimum Achromatic Contrast task, participants were required to select the background that made it most difficult to read the text.

Results

Colorimetric transformation and the implementation accuracy of the algorithm

In Figures 4 through 6, the blue and black symbols correspond to the Maximum Chroma and Constant Chroma stimulus sets, respectively. The solid lines correspond to the triangle and the circle used to define the Maximum Chroma and Constant Chroma sets without transformation. Figure 4 is for protanope simulations and Figure 5 is for deuteranope simulations. Figure 6 provides equivalent information for Variantor (no different transformation for protanopes and deuteranopes).
In order to test the accuracy of Vischeck in the implementation of Brettel et al.’s (1997) algorithm, a series of linear regression analyses of the chromatic coordinates of the transformed stimuli were performed. Table 1 provides the main results related to these analyses. The three leftmost columns specify the simulation tool, the stimulus set, and the location of transformed stimuli (over [Y, yellow] or below [B, blue] the achromatic point). The three next columns indicate the $R^2$ values (proportion of variance explained by the model), $F$-test statistic values, and degrees of freedom for each linear regression analysis. The rightmost columns indicate the dominant wavelengths matched by the best-fitting lines and the corresponding $huv$ values.

The Vischeck simulations for the Constant Chroma set were very close to straight lines (protanopia $R^2 = 0.980$; deuteranopia $R^2 = 0.982$). Best-fitting lines matched dominant wavelengths $\lambda_d \approx 575$ and 476 nm (yellow and blue, respectively; the same for protanopia and deuteranopia), which are almost identical to the ones that Brettel et al.’s (1997) algorithm assumes to be equally perceived by dichromats and normal trichromats ($\lambda_d = 575$ and 475 nm, respectively; $huv = 71.86^\circ$ and 252.19$^\circ$, respectively). The Vischeck lines corresponding to the Maximum Chroma set matched the following dominant wavelengths: protanope $\lambda_d \approx 575$ and 473 nm; deuteranope $\lambda_d \approx 575$ and 474 nm. The yellow dominant wavelength was the same irrespective of the stimulus set, but this was not true for the blue dominant wavelength. As can be observed in Figures 4A and 5A, monitor color gamut did not make it possible for the Maximum Chroma set to align along a unique straight line in both Vischeck simulations. Instead, two segments can be appreciated. The first segment radiates from the achromatic point to the triangle and matched dominant wavelength $\lambda_d \approx 475$ nm (protanope $R^2 = 0.988$, $F(1, 9) = 771.164$, $p < 0.001$; deuteranope $R^2 = 0.994$, $F(1, 13) = 2065.141$, $p < 0.001$). The second segment overlaps the line of the triangle defined by the green and blue primaries.

Only for comparison purposes, the same analyses were performed using the chromatic coordinates of the stimuli transformed by Coblis (we omit Variantor because its stimuli are close to an ellipse or a triangle but not to a straight line; Figure 6). Coblis’ simulation for protanopes was closer to a straight line (Figure 4B; minimum $R^2 = 0.726$) than its simulation for deuteranopes (Figure 5B; deuteranopia maximum $R^2 = 0.393$). Coblis’ protanopia simulation lines matched the same dominant wavelengths irrespective of the stimulus set (Maximum Chroma set $\lambda_d \approx 571$ and 466 nm; Constant Chroma set $\lambda_d \approx 571$ and 467 nm). Coblis’ deuteranopia simulation was not close to a straight line, but we show its results for contrast purposes. Such
simulation matched the following dominant wavelength: Maximum Chroma set $\lambda_d = 575$ and 470 nm; Constant Chroma set $\lambda_d = 577$ and 469 nm.

Real dichromats’ behavior

Results provided by real dichromats are now commented on. Next, we compared these results with (1) the predictions made by Brettel et al.’s (1997) algorithm and (2) the simulated dichromats.

Figures 7 (Pseudoachromatic Stimuli Identification) and 8 (Minimum Achromatic Contrast) show mean $h_{uv}$ and $L_R$ values both for real protanopes (left) and real deuteranopes (right). Each group of four bars shows the results for the two stimulus sets (Maximum Chroma and Constant Chroma) and the two pseudoachromatic selections (green and red). Bar colors and saturation are consistent with the type of pseudoachromatic selected (green and red) and the set (Maximum Chroma and Constant Chroma).

As can be observed in Figures 7 and 8, even though $h_{uv}$ and $L_R$ values showed some differences depending on stimulus set, such differences were of reduced magnitude ($h_{uv}$) and did not appear on a qualitative level ($h_{uv}$ and $L_R$). Specifically, protanope $h_{uv}$ values were near 180° for the green pseudoachromatic and near 360° for the red pseudoachromatic (Figure 7, left), and deuteranope $h_{uv}$ values always represented a clockwise change (fewer degrees) in relation to protanopes (Figure 7, left bars higher). Protanope $L_R$ values were always lower for pseudoachromatic reds but the opposite was true for the pseudoachromatic greens.

Figure 6. Chromatic coordinates provided by the Variantor transformation. Solid lines include the chromatic coordinates of both original stimulus sets (triangle = Maximum Chroma; circle = Constant Chroma). Small symbols (triangles = Maximum Chroma; circles = Constant Chroma) show the chromatic coordinates after Variantor transformation.

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<th>$R^2$</th>
<th>$F$</th>
<th>df</th>
<th>$\lambda_d$</th>
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</tbody>
</table>

Table 1. Linear regression analyses values ($R^2$, $F$, and df), dominant wavelengths ($\lambda_d$), and chromatic angles ($h_{uv}$) matched by each simulation tool. Dichromat type: $P =$ protanope, $D =$ deuteranope. Stimulus set: $MC =$ Maximum Chroma, $CC =$ Constant Chroma; $Y =$ yellow, $B =$ blue. **$p < 0.01$; ***$p < 0.001$. 

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Several statistical analyses were performed to study the above patterns. There were no significant differences (Wilcoxon signed-rank test, null hypothesis: $h_{uv}$ Maximum Chroma $= h_{uv}$ Constant Chroma, $p > 0.05$) in $h_{uv}$ values of real dichromats depending on the stimulus set (exception made for red in deuteranopes, $p = 0.043$). On the other hand, there were significant differences (Mann-Whitney U test, null hypothesis: $h_{uv}$ or $L_R$ real protanope $= h_{uv}$ or $L_R$ real deuteranope, $p < 0.05$) in seven of the eight possible comparisons (two types of pseudoachromatics [red and green] $\times$ two stimulus sets $\times$ two variables [$h_{uv}$ and $L_R$]). The results can be summarized as follows. All deuteranope $h_{uv}$ values were different in the clockwise direction in relation to protanope $h_{uv}$ values ($p < 0.05$). Only for the green Maximum Chroma condition the difference was not significant ($z = -1.362, p = 0.111, N = 10$). Protanope $L_R$ values were significantly greater than the deuteranope $L_R$ values for the green pseudoachromatics ($p < 0.05$), but the opposite was true for the red pseudoachromatics ($p < 0.05$).

Brettel et al.’s (1997) algorithm versus real dichromats: Algorithm validity

From the rationale of the algorithm of Brettel et al. (1997), we derived the following predictions related to the performance of real and simulated dichromats in the experimental tasks.

Pseudoachromatic Stimuli Identification task. The $h_{uv}$ predicted values were obtained from the pseudoachro-
We computed confidence intervals (CI) for the mean of selected stimuli by real dichromats (outside brackets) and predicted values (between brackets) for each set (Maximum Chroma and Constant Chroma). **p < 0.01.

Real versus simulated dichromats: Tool accuracy

Figures 9 and 10 show mean differences between simulated and real dichromats ($D = S - R$). In order to facilitate comparisons, leftmost bars are for Vischeck, middle bars are for Variantor, and rightmost bars are for Coblis. Each group of four bars shows the results for a tool with the two stimulus sets (Maximum Chroma and Constant Chroma) and the two pseudoachromatic selections (green and red). Bar colors are consistent with the type of pseudoachromatic selected. In Figures 9 and 10, the upper parts (Figures 9A and 10A) are for protanopes and the lower parts (Figures 9B and 10B) are for deuteranopes. In Figures 9 and 10, the asterisks indicate the results of a series of Mann-Whitney U tests (null hypothesis: $h_{uv}$ or $L_R$ real dichromat = $h_{uv}$ or $L_R$ simulated dichromat; *p < 0.05, **p < 0.01).
As for real dichromats, although $h_{uv}$ and $L_R$ values showed some differences in each simulation tool depending on stimulus set, such differences did not appear on a qualitative level (see Footnote 6), so it is possible to summarize our results as follows. First, there were not big differences between Vischeck-simulated dichromats and real dichromats. Mann-Whitney U tests showed only one significant difference (Figure 9B) for $h_{uv}$ values (deuteranope simulation red Constant Chroma condition). For $L_R$ there were significant differences for both protanope Constant Chroma conditions (Figure 10A), while for deuteranope also appeared significant differences for two of the four possible comparisons (both greens; Figure 10B). Second, conversely, all the differences between Coblis-simulated dichromats and real dichromats were very big and significant (**$p < 0.01$; Figures 9 and 10). Finally, Variantor produced results halfway between both previous tools. Comparison with real protanopes showed small differences and frequently were not significant (Figures 9A and 10A), whereas for deuteranopes all differences were significant (Figures 9B and 10B) and bigger.

The high similarity for each tool between the two pseudoachromatic greens and reds (Maximum Chroma and Constant Chroma ones) shows that the change of stimulus set produced only minor variations in the results of $h_{uv}$ (Figure 9). Such impression agrees with the results provided by a series of Wilcoxon analyses where no significant differences (null hypothesis: $h_{uv}$ Maximum Chroma = $h_{uv}$ Constant Chroma; $p < 0.05$)
Brettel et al.’s (1997) algorithm versus simulated dichromats’ behavior

As previously done for real dichromats (Table 2), we computed CIs for the mean of the selected stimuli by Vischeck-simulated dichromats (normal trichromats using Vischeck) in task 1 \( (h_{uv}) \) and task 2 \( (L_R) \) to check if the predicted values derived from Brettel et al.’s (1997) algorithm fell within that range (one-sample \( t \)-test, null hypothesis: \( h_{uv} \) or \( L_R \) predicted = \( h_{uv} \) or \( L_R \) real or simulated dichromat; \(*p < 0.05, **p < 0.01, ***p < 0.01 \). This kind of analysis can be especially useful because it allows potential users of Simulcheck to test if the pattern of results is compatible with a supposed underlying algorithm, even when no real dichromats are available. Only for comparison purposes, the same analyses were performed for the stimulus selections of normal trichromats using Coblis and Variantor. Figures 11 (Pseudoachromatic Stimuli Identification) and 12 (Minimum Achromatic Contrast) show the differences between the mean of empirical data and predicted values \( (D = S - R) \). In order to facilitate comparisons, the first bars are for real dichromats, the second bars are for Vischeck, the third bars are for Variantor, and the fourth bars are for Coblis. Each group of four bars shows the results for a real or simulated dichromat with the two stimulus sets (Maximum Chroma and Constant Chroma) and the two pseudoachromatic selections (green and red). Bar colors are consistent with the type of pseudoachromatic selected. In Figures 11 and 12, the upper parts (Figures 11A and 12A) are for protanopes and the lower parts.
(Figures 11B and 12B) are for deuteranopes. Error bars represent 95% CIs for the empirical values of real and simulated dichromats, so significant differences arise when zero is not included inside error bars.

Although several comparisons (11 of 16) between Vischeck-simulated dichromats and predictions derived by Brettel et al. (1997) were significant, the magnitude of such differences was minor (Figures 11 and 12). Conversely, the predictions of the algorithm were always out of the CIs for Coblis-simulated dichromats. All the differences were very big and strongly significant (***, p < 0.001; Figures 11 and 12). On the other hand, Variantor produced results halfway between both previous tools. Variantor simulation CIs better fit Brettel et al.’s (1997) predictions for protanopia (four of eight differences were small and significant; Figures 11A and 12A), whereas all the differences were big and significant for deuteranopia (Figures 11B and 12B).

**Discussion**

New tools aimed at making colors similar to the ones seen by people with color vision deficiencies are becoming increasingly common. A recent paper (Luque et al., 2014) shows that similar transformations are possible even with video streams. Several websites (i.e., http://play.google.com/store/apps) provide free appli-
cations ready for working in mobile phones, tablets, and other electronic gadgets. Of course, this availability carries with it the prospect of detecting and eliminating pseudoisochromatic stimuli with the aim of promoting the use of accurate colors for people with and without normal color vision (“universal design”; Vanderheiden, 2006). On the other hand, as the application of the Simulcheck method in this paper has shown, there are good reasons to be cautious about the accuracy of some simulation tools.

Simulcheck is a versatile method that allows the evaluation of simulation tools in different ways. Each one requires comparing two of the following data: (1) predictions derived from the algorithm theoretically used by the tool, (2) the behaviors really provided by responding to the stimuli transformed by the tool (simulated dichromats), and (3) the behaviors of real dichromats. Because in our research the color transformation algorithm was known only for Vischeck, only for this tool was fair the comparison of the algorithm-based predictions and the results provided by real dichromats (algorithm validity; see Table 2 and bars labeled “real” in Figures 11 and 12), or the ones produced when using the tool (bars labeled “Vischeck” in Figures 11 and 12). Obviously, for the three evaluated tools (Vischeck, Variantor, and Coblis) the comparison between real and simulated dichromats (tool accuracy evaluation; Figures 9 and 10) was appropriate.

Simulcheck is a consistent method because it leads to similar conclusions even when using colorimetrically different sets (Maximum Chroma or Constant Chroma sets). For example, when considering the results summarized in Figures 9 and 10 (tool accuracy evaluation), both the Maximum Chroma and Constant Chroma bars lead to conclude the following: (1) Coblis

![Graph showing differences in L_R between the mean of dichromats' data (real or simulated) and predicted values for protanopes (A) and deuteranopes (B). See Figure 11 caption for a detailed description. *p < 0.05; **p < 0.01; ***p < 0.001.]
simulations were inaccurate for both dichromats types, (2) Variantor-simulated dichromats were very similar to real protanopes (small and frequently no significant differences) but not to real deuteranopes, and (3) only Vischeck simulations were accurate for both protanopes and deuteranopes. Nevertheless, we recommend the use of the Constant Chroma set for potential users of Simulcheck because it is not so dependent on the color gamut of the monitor used to implement the method.

The high validity of the Vischeck algorithm was indicated by the high agreement found between the predictions derived from Brettel et al. (1997) and the empirical $h_{uv}$ and $L_R$ values provided by real dichromats (see Table 2 and the bars labeled “real” in Figures 11 and 12). The only exception was for $L_R$ (Table 2; empirical 95% CI [0.72, 0.88]; predicted, 0.94) in the red pseudoachromatic Constant Chroma condition. Even in this case the value type ($<1$) was accurately predicted.

Apart from Simulcheck’s results, there was high colorimetric similarity between the performed color transformation (Figures 4A and 5A; Table 1) and the predictions derived from Brettel et al. (1997). As expected, the transformed color coordinates were near to $\lambda_d = 575$ and 475 nm, indicating high implementation accuracy. Returning to Simulcheck, qualitative analysis (see Footnote 6) based on $h_{uv}$ and $L_R$ values can be used not only to synthesize the results provided by the evaluation of a color transformation tool but also to define a series of requisites that must be fulfilled by any algorithm or simulation tool that can be considered accurate; (1) It must provide different color transformations for each dichromat type (something not done by Variantor; see Figure 6), and (2) the specific $h_{uv}$ and $L_R$ values for the pseudoachromatic reds and greens must show specific relations. The $h_{uv}$ values are more in the clockwise direction for deuteranopes (see Figure 7 and Table 2, upper part), and $L_R$ values for the pseudoachromatic reds are smaller when simulating protanopes (the opposite for the greens; reverse pattern when simulating deuteranopes; see Figure 8 and Table 2, lower part).

Assessing a simulation tool using the $h_{uv}$ and $L_R$ variables has two important advantages. First, it explicitly differentiates between two aspects of color vision: the activity in the yellow–blue mechanism (a qualitative aspect, measured through $h_{uv}$) and the activity in the achromatic mechanism (a quantitative aspect, measured through $L_R$). It must be remembered that each of these aspects is usually associated with a different color use (Breslow et al., 2009). Second, this makes it easier to understand the consequences of a simulation error. Let’s use an example to illustrate this. The rightmost bars in Figure 9 indicate that, as we commented before, there were important differences between the values of the pseudoachromatic angles of Coblis simulations and real dichromats. Real protanopes and deuteranopes both selected $h_{uv}$ values near 180° (Figure 7), a bluish green emerald for normal observers. On the contrary, Coblis values were near 140° (–40° in Figure 9), a chromatic angle that for normal observers is related with pure (no bluish) greens. Consequently, if Coblis is used to decide, for example, which colors must not be side by side on a political map (to help image perceptual segmentation, see Francis, Bias, & Shive, 2010), important errors can appear. The probability of errors associated with Coblis use is increased when considering its inaccuracy in measuring $L_R$ (Figure 10). More specifically, although we found that relative to normals real protanopes see green pseudoachromatics as lighter ($L_R$ values near 1.17) but the red ones as darker ($L_R$ under 0.84), Coblis simulations provided exactly the opposite pattern. This is a very significant error considering that the reduced sensitivity of the protanopes to long wavelengths (see, e.g., Birch, 2001) has led some authors (see McIntyre, 2002, for a recent example) to refer to “red blindness” for naming protanopes.

There is great conceptual similarity between Simulcheck and the test designed to assess color vision in macaque monkeys (Koida et al., 2013). Both methods use two psychophysical tasks. The first task (Pseudoachromatic Stimuli Identification task in our nomenclature) allows the determination of pseudoachromatic angles ($h_{uv}$). Both for monkeys and humans, protanope $h_{uv}$ values were near 0° (pseudoachromatic reds) and 180° (pseudoachromatic greens). The second task (Minimum Achromatic Contrast task in Simulcheck) had a similar goal in both studies: the evaluation of the relative response of the achromatic mechanism. Again, similar results appeared in this case. Protanopes (the only type of dichromat among Koida’s monkeys) showed reduced sensitivity to long-wavelength stimuli (the only stimul type used in the second task with the monkeys).

Simulcheck is a method that can be described as versatile (can be used for evaluating tool accuracy and algorithm validity), consistent (provides qualitatively similar results using different stimulus sets), selective (evaluates, through $h_{uv}$ and $L_R$, two different color visions mechanisms), and useful (makes it easy to understand the inaccuracies of simulation tools). In our opinion, its main limitation is that it assumes permanent functional dichromatism in people diagnosed as protanope or deuteranope. This is inaccurate because it leads to an underestimation of the color vision capacities of these groups of people.

In a paper originally published in German titled “Dichromatische Fovea, Trichromatische Peripherie” (“Dichromatic Fovea, Trichromatic Periphery”; see a short description of the Nagel works, see Broackes [2010a] or Smith & Pokorny [1977]), Wilibald Nagel
(1905) showed that many diagnosed dichromats, like himself, behaved as expected for dichromats when responding to small stimuli (e.g., the ones used in the standard Nagel anomaloscope) but as expected for anomalous trichromats when responding to bigger stimuli. Although this discovery was ignored for a long time, several works (Boynton & Scheibner, 1967; Lillo, Moreira, Álvaro, & Davies, 2014; Moreira et al., 2014; Nagy, 1980; Scheibner & Boynton, 1968; Smith & Pokorny, 1977) have confirmed and extended Nagel’s discovery: Big stimuli (>3°) improve the capacity of clinical dichromats to discriminate stimuli (this changes from dichromacy to anomalous trichromacy). This improvement can be related to some kind of residual activity in the red–green mechanism.

As stated in the Introduction, valid and accurate simulation tools make isochromatic those stimuli that differ only in terms of the response in the cone type that a dichromat lacks. Such transformation is fully valid when, as happens in conventional underground maps, the size of visual elements is small. For example, the tool makes it possible to know which lines are seen by the dichromat as having similar color. However, this color transformation can be less accurate when, as happens for some political maps, there are relatively big visual elements (i.e., color background). In this case, some clinically diagnosed dichromats will become anomalous trichromats and the residual activity in their red–green mechanism will allow the differentiation between some stimuli that are pseudoisochromatic for a true dichromat.

Because of the influence of red–green residual activity, it is possible that the best simulation tool leads us to the erroneous conclusion that big stimuli are pseudoisochromatic. Adopting such a conservative criterion is not a serious problem when performing universal design because this error only leads to the avoidance of the simultaneous use of stimuli that are very similar for some people (clinical diagnosed dichromats). Consequently, such a conservative criterion avoids difficult differentiations and makes performance in some color-based tasks easier.

Simulcheck’s first task (Pseudoachromatic Stimuli Identification) allows us to know which chromatic angles are associated with minor responses in the dichromats’ yellow–blue mechanism. This choice makes the task relatively easy because $h_{uv}$ variation in the proximities of the pseudoachromatic stimuli produces qualitative changes (hue varies from blue to yellow or vice versa) that are easy to appreciate. These changes would not appear if the same kind of choice task were used to identify the $h_{uv}$ that produces maximum responses in the yellow–blue mechanism. This kind of information (maximum chroma identification) would complement the one actually provided by Simulcheck (good simulation tools must be accurate in both aspects) but would require the exclusive use of the Constant Chroma set (see Figure 1) to avoid unwanted variations in the chromatism perceived by dichromats. We are now considering how to change Simulcheck’s first task to get information about $h_{uv}$ values associated with the yellow–blue mechanism’s minimum and maximum responses.

Even when considering the effects of the residual activity of the red–green mechanism or possible improvements related to the availability of information about yellow–blue maximum responses, it can be concluded that Simulcheck is a useful method for selecting among an increasing number of simulation tools the ones that make it possible to perform color universal designs. Simulcheck requires the measurement of only two key colorimetric variables—$h_{uv}$ and $L_R$—for two pseudoachromatic grays and can be described as versatile, consistent, selective, and useful. Its application in the present study indicated that, among the evaluated tools, only Vischeck provided an accurate simulation of the colors for both protanopes and deuteranopes.

**Keywords:** red–green color blindness, dichromacy, psychophysics, forced choice, simulation tools evaluation, computer simulation, optical simulation

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**Footnotes**

1Brettel et al. (1997) used $\mathbf{Q}$ for an original stimulus and $\mathbf{Q}'$ for the one that normals and dichromats saw with the same color ($\mathbf{Q}' = \text{transformed stimulus}$). They used the LMS colorimetry (based on the response of $\text{L}$, $\text{M}$, $\text{S}$ cones) to decide which $\mathbf{Q}'$ ($\mathbf{Q}' = \mathbf{L}_O', \mathbf{M}_O', \mathbf{S}_O'$) correspond to every specific $\mathbf{Q}$ ($\mathbf{Q} = \mathbf{L}_O, \mathbf{M}_O, \mathbf{S}_O$). The specification is based on the following assumptions: (1)
Dichromats and trichromats have the same perceptions when seeing equienergetic stimuli, and (2) for dichromats, LMS space is reduced to two half-planes (those corresponding to 575 or 475 nm). In the LMS space, each confusion line is parallel to an axis: the L (M_Q = M_O and S_Q = S_O) for the protanopes and the M (L_Q = L_O and S_Q = S_O) for the deuteranopes. Q’s coordinates are determined by the intersection between (A) the confusion line and (B) the half-plane defined by the origin (O), the equienergetic stimulus E, and the corresponding monochromatic stimuli (575 or 475 nm).

2Two radii of Figure 1 specify the chromatic angle (h_m) of a stimulus. One (not shown) corresponds to the horizontal line extended from the achromatic point to the right of the diagram. The other is the radius including the stimuli. All the stimuli sharing a dominant wavelength (i.e., \( \lambda_d = 494 \text{ nm} \)) also share a chromatic angle (i.e., h_m = 183.95°).

3The intersection of dashed and dotted lines in Figure 1 defines achromatic point coordinates (the ones corresponding to the screen white). The black line originates in the protanope convergence point (not shown; \( u' = 0.656, v' = 0.5051 \)) and finishes in 494 nm. Stímulis represented by a point in the radius, extended between the achromatic point and the 494-nm position (black dotted segment), have such dominant wavelength (\( \lambda_d = 494 \text{ nm} \)). Stimuli represented by the complementary radius (black dashed segment) have a negative dominant wavelength (\( \lambda_d = -494 \text{ nm} \)). Negative values are used for radii ending in the purple line (the one extended between 400 and 700 nm in the diagram) because there are no monochromatic stimuli included in the purple line.

4Transformed luminance (L_T) was named “effective luminance (Y_E)” in previous AMLA (AM = achromatic measurement, LA = luminosity adjustment) descriptions. The main variable provided by the AMLA method was named “relative effective luminance (Y_E)” and derives from comparing target stimulus (Y_E) and reference white (Y_N) effective luminances (Y_E = Y_E/Y_N). This variable (Y_E) is very similar to the luminance factor (\( \beta \)) in standard photometry (i.e., Hunt & Pointer, 2011, appendix 1). AMLA assumes that standard and effective luminances have the same level (Y_E = Y) for achromatic stimuli but not (Y_E ≠ Y) for chromatic ones. Consequently, their Y_E level is determined using the following procedure: (1) Some psychophysical task is used to know which achromatic stimulus has the same Y_E as the target chromatic stimulus (LA = luminosity adjustment). (2) The achromatic stimuli standard luminance (Y) is measured (AM = achromatic measurement). It is assumed that the result is the target chromatic stimulus effective luminance (Y_E).

5Despite the similarity in their denominations, Y_E (relative effective luminance, included in previous AMLA descriptions; see Footnote 4) and L_R (relative luminance, included in Simulcheck) refers to two different kind of comparisons where stimulus effective luminance (Y_E) is used. Y_E results from comparing Y_E with the assumed maximum (luminance of the reference white). L_R results from comparing Y_E with normal observers’ effective luminance. To avoid conceptual confusion between both variables, in this paper (1) naming of variables related to luminance includes “L” (as is usual in photometry; i.e., Hunt & Pointer, 2011, appendix 1) and not Y (as is usual in colorimetry; i.e., Hunt & Pointer, 2011, chapter 2) and (2) instead of “effective luminance (Y_E),” the expression “transformed luminance (L_T)” is used.

6Figure 1 helps to differentiate quantitative and qualitative predictions. As can be seen, for example, the radius extending near 700 nm is intersected in different localizations by the circle (Constant Chroma set) and the triangle (Maximum Chroma set). Because the radius is the same (one corresponding to reddish colors), the same qualitative prediction was done for both sets. The L_R value was under one for protanopes because for this type of colors the effective luminance must be under the standard. On the other hand, because the intersections differ in their distance to the achromatic point, there were different quantitative predictions for both sets. The predicted L_R was smaller for the Maximum Chroma set.

7The algorithm of Brettel et al. (1997) uses LMS colorimetry to specify the colors that supposedly elicit the same perceptions in normal trichromats and dichromats (see Footnote 1). We used LMS colorimetry to predict L_R values and a standard chromaticity diagram to predict h_m values. This is a traditional and usual way to represent the confusion lines for dichromats (Hunt & Pointer, 2011; Kaiser & Boynton, 1996; Smith & Pokorny, 2003; Wyszecki & Stiles, 1982), so we have used it for simplicity and to directly link the predictions to the expected behavior of our subjects.

References


