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Do dichromats see colours in this way? Assessing simulation tools without colorimetric measurements

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Abstract

Background: Simulcheck evaluates Colour Simulation Tools (CSTs, they transform colours to mimic those seen by colour vision deficients). Two CSTs (Variantor and Coblis) were used to know if the standard Simulcheck version (direct measurement based, DMB) can be substituted by another (RGB values based) not requiring sophisticated measurement instruments. **Method:** Ten normal trichromats performed the two psychophysical tasks included in the Simulcheck method. The Pseudoachromatic Stimuli Identification task provided the h_{uv} (hue angle) values of the pseudoachromatic stimuli: colours seen as red or green by normal trichromats but as grey by colour deficient people. The Minimum Achromatic Contrast task was used to compute the L_R (relative luminance) values of the pseudoachromatic stimuli. **Results and conclusions:** Simulcheck DMB version showed that Variantor was accurate to simulate protanopia but neither Variantor nor Coblis were accurate to simulate deuteranopia. Simulcheck RGB version provided accurate h_{uv} values, so this variable can be adequately estimated when lacking a colorimeter —an expensive and unusual apparatus—. Contrary, the inaccuracy of the L_R estimations provided by Simulcheck RGB version makes it advisable to compute this variable from the measurements performed with a photometer, a cheap and easy to find apparatus.

Keywords: Color vision, Simulation tools evaluation, Dichromacy, Colorimetry, Adobe RGB 1998, Psychophysics.

Resumen

¿Son estos los colores que ven los dicrómatas? Evaluando herramientas de simulación sin mediciones colorimétricas. **Antecedentes:** Simulcheck evalúa Herramientas de Simulación del Color (HSCs, transforman los colores para imitar lo que ven las personas con deficiencias en la visión cromática). Se utilizaron dos HSCs (Variantor y Coblis) para evaluar si la versión estándar de Simulcheck (basada en mediciones directas, BMD) puede sustituirse por otra que no requiere instrumentos de medición sofisticados (basada en valores RGB). **Método:** diez tricrómatas realizaron las tareas psicofísicas incluidas en el método Simulcheck. La de Identificación de Estímulos Pseudoacromáticos proporcionó el ángulo cromático (h_{uv}) de los estímulos que los observadores comunes ven rojos o verdes, pero grises las personas con deficiencias en la visión cromática. La de Mínimo Contraste Acromático proporcionó los valores L_R (luminancia relativa) de los estímulos pseudoacromáticos. **Resultados y conclusiones:** la versión BMD mostró que Variantor simuló adecuadamente la protanopia, pero que ni Variantor ni Coblis fueron adecuados para la deuteranopia. La Versión RGB del método Simulcheck proporcionó valores h_{uv} adecuados, consecuentemente se concluyó que esta variable puede estimarse adecuadamente sin un colorímetro –aparato caro e inusual—. Por el contrario, la inadecuación de las estimaciones de L_R proporcionadas por la versión RGB recomienda computar esta variable usando mediciones realizadas con un fotómetro, un aparato barato y fácil de encontrar.

Palabras clave: visión del color, evaluación de las herramientas de simulación, dicromatismo, colorimetría, adobe RGB 1998, psicofísica.

Dichromats have two instead of three cone types in the retina (Birch, 2001). Protanopes and deuteranopes (red-green dichromats) lack, respectively, long (L) or medium (M) wavelength-sensitive cones because of genetic factors (Neitz & Neitz, 2011). Dichromats see fewer colours than normal trichromats because they do not discriminate between stimuli only differing in the response of the cone type they lack (Lillo, Collado, Vitini, Ponte, & Sánchez, 1998).

Colour vision simulations available online (e.g. http://www.vischeck.com/examples/) or in some publications (Lillo & Moreira, 2013, Figures 4.5, 5.17, and 5.18) facilitate an intuitive understanding of some dichromats' everyday problems and why the visual search attentional control (Ponte & Sampedro, 1997) can be more difficult for them. Their main difficulty is that sometimes they see objects as being of the same colour while normal people see different colours related to different objects. For instance, the colours assigned to Madrid Metro lines 5 and 7 in maps and signs are seen of different colours by normal people (green and orange, respectively). The use of an accurate simulation tool (Brettel, Viénot, & Mollon, 1997; Lillo, Álvaro, & Moreira, 2014; Viénot, Brettel, & Mollon, 1999) will serve to determine whether a deuteranope sees these lines as similar colours (greenish yellows) and, therefore, can confuse them. Using the specialized

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nomenclature (e.g., Birch, 2001), the green and the orange of the lines 5 and 7 are pseudoisochromatic stimuli because they are the same colour (isochromatic) only for some people with colour vision deficiency (which is why the prefix "pseudo" is used).

Colour simulation tools are useful to carry out universal designs (Vanderheiden & Jordan, 2012) suitable for people with and without deficiencies. In the particular case of colour, the hallmark is to create-select environments suitable for normal and for colour deficient people. For instance, if a political map uses different colours for different countries (e.g., Spain and Portugal), such colours should be differentiated by all users. To achieve this goal, some tools (e.g. Nakauchi & Onouchi, 2008) adopt a two-phase strategy. In the first phase, they detect pseudoisochromatic pairs. In the second phase, they replace one of the pair members with another colour easily differentiated from the remaining member. Obviously, the second phase only makes sense when the first phase functions properly.

A recent paper (Lillo et al., 2014) describes a method, called Simulcheck, to evaluate colour-simulation tools' accuracy. The method is based on pseudoachromatic stimuli identification, that is, those stimuli seen as chromatic (greenish or reddish) by common observers and as grey by dichromats. In that work, the Simulcheck method was used in optimal circumstances, that is, when sophisticated instruments were available to perform accurate photo-colorimetric measurements. Here, we will test whether Simulcheck can be used when lacking such measurement instruments, this being the most common situation outside of laboratories. Specifically, we will assess whether Simulcheck can be applied using the chromatic specifications of the Adobe RGB 1998 colour space (Adobe RGB).

Simulcheck requires computing two variables for each pseudoachromatic stimulus: h_{uv} (hue angle) and L_R (relative luminance). For a similar method, developed to assess colour vision in macaque monkeys, see Koida et al. (2013). Simulcheck uses the *Pseudoachromatic Stimuli Identification task* to know which h_{uv} (chromatic angle) values correspond to pseudoachromatic stimuli for real or simulated dichromats. Figure 1 is helpful to intuitively understand the concept of chromatic angle (see Hunt & Pointer, 2011, Chapter 3, for a more comprehensive description). The achromatic point from which a series of radii departs is located approximately in the centre of the diagram. One of the radii, the dashed line, corresponds to the h_{uv}= 0° and represents stimuli that can be seen as reddish. The next radius, h_{uv} = 45°, represents stimuli frequently seen as orangish. The next one, h_{uv} = 90°, represents those that tend to be seen as yellowish, etc. In synthesis, changing h_{uv} changes the colour hue.

The *Pseudoachromatic Stimuli Identification task* requires the selection of the less chromatic stimulus (grey, or near grey) from a set where the hue angle varies systematically. Lillo et al. (2014) found different selections for real protanopes and real deuteranopes. These values are similar to those found in other works (i.e., see Figure 6 in ref. Pridmore, 2014) and agree with the predictions made by the algorithm of Brettel et al. (1997, 3° and 183° for pseudoachromatic red and green in protanopia; 349° and 169° for pseudoachromatic red and green in deuteranopia). In the standard Simulcheck version (DMB, Direct Measurement Based), the h_{uv} values are estimated from the colorimetric measurements (Hunt & Pointer, 2011). Here, these values are also estimated transforming the RGB values of the pseudoachromatic stimuli selected from the Adobe RGB 1998 colour space (RGB version).

Simulcheck uses the *Minimum Achromatic Contrast task* to measure L_R (relative luminance). This task provides the achromatic background that makes it more difficult to read a text written with a pseudoachromatic colour (red or green). Such difficulty indicates that text and background produce a similar response in the achromatic mechanism (Lillo, Collado, Martín, & García, 1999; Lillo & Moreira, 2005). L_R value is computed by dividing the background luminance by the pseudoachromatic stimulus luminance. L_R values over one indicate that the dichromat (real or simulated) sees the stimulus lighter than do normal trichromats. The opposite is true for L_R values under one. Lillo et al. (2014, Table 2) found, as expected (see also ref. Brettel et al., 1997; see Figure 4 in ref. Pridmore, 2014) L_R values over one for real protanopes and the pseudoachromatic greens (they see such stimuli lighter than do common observers) but L_R values below one for real deuteranopes (they see the pseudoachromatic greens darker). The opposite pattern was found for the pseudoachromatic reds. Lillo et al. (2014) computed L_R in the standard way (from the *Y* measured values). Here, we will also estimate L_R, transforming the RGB values of the pseudoachromatic stimuli and the backgrounds selected to the Adobe RGB 1998 colour space.

Previous work (op. cit.) used Simulcheck for evaluating several colour simulation tools. It was found that specific errors appeared for specific tools. For example, the Variantor goggles only provided one colour transformation. Such transformation produced h_{uv} and L_R values similar to those provided by real protanopes but not by real deuteranopes. Otherwise, the software tool named Coblis produced different colour transformations for both dichromacy types, but they were always inaccurate because of the systematic errors found both in h_{uv} (for example, about 140° instead of 183° for pseudoachromatic green and protanopia) and L_R (for example, L_R was over one for the pseudoachromatic reds both for protanopia and deuteranopia, although predicted L_R values for protanopia and pseudoachromatic reds were under one). Consequently, it

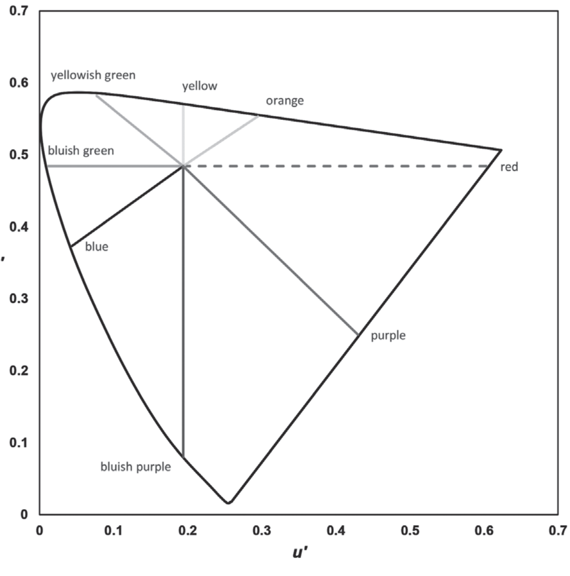

Figure 1. *Chromatic angle (h_{uv}) concept. The dots contained in each radius represent the colours of the same chromatic angle. Its value is the angle formed between the dashed line and the colour radius. The most common names for some values are indicated (0º red, 45º orange, 90º yellow, 135º yellowish green, 180º bluish green, 225º blue, 270º bluish purple, 315º purple)*

was possible to conclude that Variantor was only accurate for simulating protanopia, and Coblis was not accurate for simulating protanopia or deuteranopia.

Our current research used the same stimulus sets as in Lillo et al. (2014) but now applied to a new group of participants and including a novel way of analysing the data. As before, the stimuli in the Constant Chroma set had similar C^*_{uv} (chroma) and L^* (lightness) values, and the Maximum Chroma set used the maximum C^*_{uv} value available for each hue angle. As before, we also compared the empirical values obtained using Variantor and Coblis simulation tools with the expected values according to Brettel et al.'s (1997) algorithm. We expected that the stimulus set used would not affect the conclusions of the simulation tool's assessment. This study computed the Simulcheck variables (h_{uv} and L_R) in two different ways. The first one mimicked previous research (Lillo et al., 2014, Simulcheck DMB version) and required the availability of sophisticated photo-colorimetric instruments. The second way only required the RGB values of the stimuli used in the two Simulcheck tasks and the transformation of such values to the Adobe RGB 1998 colour space (Simulcheck RGB version). This latter version will be considered appropriate if it leads to the same conclusions as the first one.

Method

Participants

Ten trichromats (1 man, 9 women, age range 21-43) performed the two tasks included in the Simulcheck method. Participants' normal colour vision was confirmed by the results of a set of psychophysical tests (Fletcher, 1980; Ishihara, 1996; Lanthony, 1985). The research was conducted according to the principles of the Declaration of Helsinki, and all participants gave informed consent. This research was approved by the Universidad Complutense de Madrid - Hospital Clínico San Carlos review board.

Instruments

Stimuli were presented using a Sony Trinitron Multiscan 17 SEII screen (gamma = 2.15). The experimental room had an illuminance level near 5 lux in the screen surrounding area.

We performed standard photo-colorimetric measurements using a Minolta CL-200 luxo-colorimeter with the required accessories. The luminance (Y), relative luminance (Y/Y_n), chromatic coordinates (u' and v') and hue angle (h_{uv}) for the reference white (R = G = B = 255) and the 3 primaries were: Red ($Y = 14.6$ cd/m^2, $Y/Y_n = 0.296$, $u' = 0.404$, $v' = 0.530$, $h_{uv} = 17.48°$); green ($Y = 31.2$ cd/m^2, $Y/Y_n = 0.633$, $u' = 0.119$, $v' = 0.561$, $h_{uv} = 132.12°$); blue ($Y = 3.5$ cd/m^2, $Y/Y_n = 0.071$, $u' = 0.170$, $v' = 0.155$, $h_{uv} = 263.78°$); white ($Y = 49.3$ cd/m^2, $Y/Y_n = 1$, $u' = 0.204$, $v' = 0.467$). Table 1 shows the equivalent measurements obtained through the Variantor goggles (distributed by Cambridge Research Systems, http://www.variantor.co.uk/) or after each transformation performed by Coblis to simulate protanopia or deuteranopia.

Two stimulus sets were used in the *Pseudoachromatic Stimuli Identification task*. Each set was composed of 40 stimuli whose h_{uv} changed in 9° steps (3°, 12°, 21°, …, 354°). Maximum Chroma set (MC, Figure 2a) chromatic coordinates were located at the intersection between the diagram radii and the triangle defined by the three screen primaries. The length of the shortest radius in Figure 2a determined the chromatic coordinates for all the Constant Chroma set stimuli (CC, Figure 2b). All these stimuli had similar C^*_{uv} and L^* values ($C^*_{uv} = 66.5$; $L^* = 75$).

Procedure

The *Pseudoachromatic Stimuli Identification task* (task 1) included 20 trials (10 for each stimulus set; 5 for the green semiset and 5 for the red one), for each colour transformation (Variantor, Coblis protanopia, Coblis deuteranopia). All trials with one tool were performed consecutively before beginning with another tool. Inter-transformation order was counterbalanced.

In every *Pseudoachromatic Stimuli Identification task* trial, 20 stimuli belonging to either MC or CC stimulus set were presented simultaneously. Hue angle value increased from left to right by 9° steps. Each stimulus was a 1.3 cm side square that projected 1.5° by 1.5° when looked from 50 cm. In order to avoid the presentation of the stimuli in the same position across trials, a +/- 18° random variation was used. One half of the trials presented a leftmost stimulus whose h_{uv} was 84° +/- 18° (pseudoachromatic green selection). In the other half it was 264° +/- 18° (pseudoachromatic red selection). The order of the green and red pseudoachromatics and the MC and CC stimulus sets was randomized. In each of the 20 trials of task 1, participants were required to select the stimulus most similar to grey. If they informed that there was no grey stimulus, they had to select the less saturated stimulus.

Figure 3 provides a schematic version of the spatial configuration in task 2 (*Minimum Achromatic Contrast*). It presents in text (the word "COLOUR") the colours selected in the previous task against 20 achromatic backgrounds changing in 5 L^* steps. Each background was 5.6 cm × 1 cm (6.4° × 1.2°). The full horizontal length of the semiset was 27.2 cm and the vertical length was 10 cm. In each of the 20 trials of task 2, participants were required to select the background that made it most difficult to read the text. Both tasks were presented on a grey background ($L^* = 90$).

Table 1

Luminance (Y), relative luminance factor (Y/Y_n), chromatic coordinates (u', v') and hue angles (h_{uv}) for the three primaries (red, green and blue) and the reference white after their transformation by Variantor or one of the transformations provided by Coblis (Coblis-P for protanopia transformation; Coblis-D for deuteranopia transformation)

	Simulation	**Y (cd/m^2)**	**Y/Y_n**	**u´**	**v´**	**h_{uv}**
Red	Variantor	0.95	0.119	0.268	0.524	53.49
	Coblis-P	13.07	0.265	0.214	0.551	83.04
	Coblis-D	19.45	0.394	0.199	0.553	93.59
Green	Variantor	6.65	0.836	0.205	0.546	93.47
	Coblis-P	7.88	0.160	0.208	0.523	85.99
	Coblis-D	4.39	0.089	0.230	0.475	17.66
Blue	Variantor	0.35	0.044	0.185	0.161	264.81
	Coblis-P	1.86	0.038	0.170	0.155	263.68
	Coblis-D	1.58	0.032	0.170	0.155	263.69
White	Variantor	7.95	1.000	0.211	0.447	–
	Coblis-P	49.30	1.000	0.204	0.467	–
	Coblis-D	49.30	1.000	0.204	0.467	–

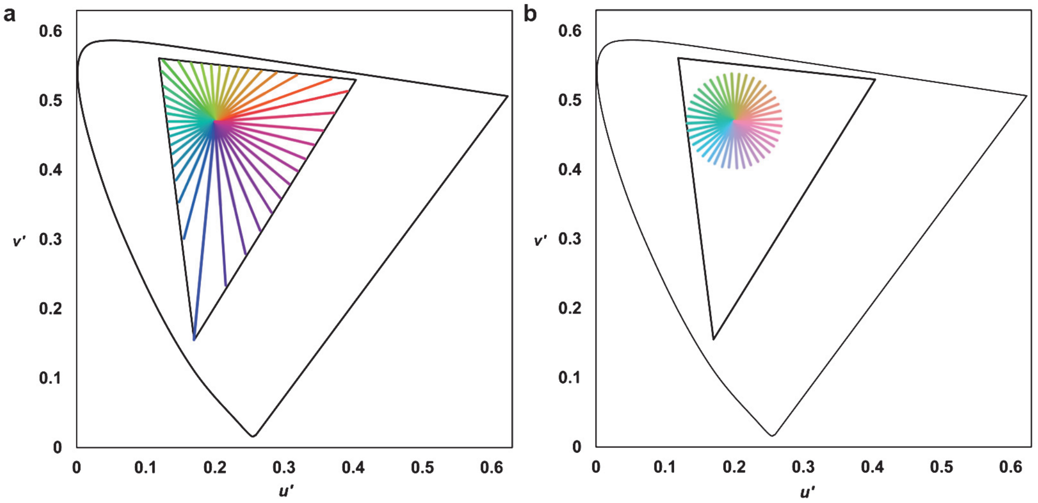

Figure 2. *Chromatic coordinates for the two stimulus sets used in the Pseudoachromatic Stimuli Identification task. Maximum Chroma (MC) set (a): Stimulus coordinates defined by the intersection between each radius (40 different hue angles) and the triangle drawn by the three primaries. Constant Chroma (CC) set (b): Stimulus coordinates defined by the last point represented for each radius*

Figure 3. *Schematic version of the spatial configuration used in the Minimum Achromatic Contrast task. Twenty achromatic backgrounds were presented simultaneously and changed from white (up and leftmost) to black (low and rightmost)*

Data analysis

Our research main goal was to compare the results of the evaluation of two different simulation tools in two different ways. One way used the results provided by standard colorimetric measurements (Simulcheck DMB version). The other one, Simulcheck RGB version, used the reference values defined in the Adobe RGB 1998 colour space (24-bit mode, see ref. Adobe RGB).

Figure 4 chromaticity diagram includes two triangles and two achromatic points. The black line triangle is the same appearing in Figures 2a and 2b. The coordinates for the screen primaries (black line triangle's vertices in Figure 4) and its reference white (black dot in Figure 4) were measured with a luxo-colorimeter (see Method). The grey line triangle in Figure 4 represents the primaries used in the Adobe RGB 1998 colour space: Red ($x = 0.648$, $y = 0.331$, $u' = 0.457$, $v' = 0.525$, $Y = 49.78$ cd/m^2); green ($x = 0.230$, $y = 0.702$, $u' = 0.084$, $v' = 0.576$, $Y = 100.11$ cd/m^2); blue ($x = 0.156$, $y = 0.066$, $u' = 0.179$, $v' = 0.171$, $Y = 10.12$ cd/m^2). Such primaries are normalized to the reference white used in the space (D50, $x = 0.346$, $y = 0.359$, $u' = 0.209$, $v' = 0.488$, grey dot in Figure 4) for a luminance equal to 160 cd/m^2 and gamma ≈ 2.2. Each triad of RGB values was used to perform the computations.

Results

DMB Simulcheck version

Confidence intervals (CIs) for the mean of the selected stimuli in task 1 (h_{uv}) and task 2 (L_R) were computed in order to determine whether the predicted values fell within these CIs. Computation was performed from standard colorimetric measurements (Simulcheck DMB version), or using the transformation of such values to the Adobe RGB 1998 colour space (RGB version). Figure 5 bar height shows the size of the differences between empirical h_{uv} or L_R mean and predicted values. For example, the leftmost

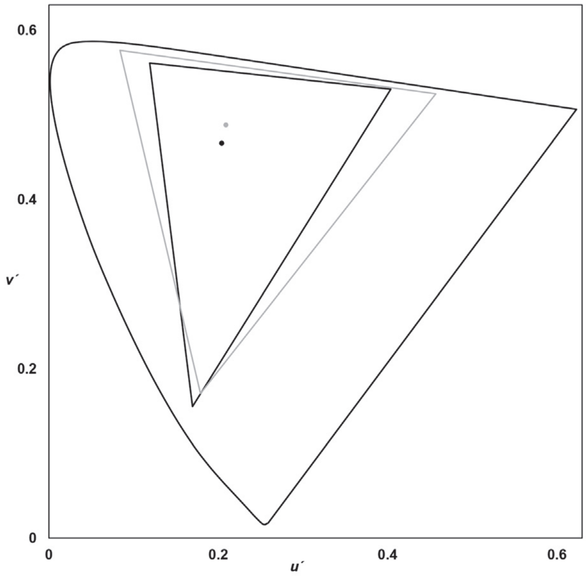

Figure 4. *Triangles defined by the chromatic coordinates of the actual screen's phosphors (black line) and the Adobe RGB 1998 colour space primaries (grey line). Dots indicate the reference white of the screen (black dot) and the Adobe RGB 1998 colour space (grey dot)*

bar in Figure 5a indicates that the h_{uv} difference (Δh_{uv}) for the combination of Variantor, MC and pseudoachromatic green was only 3.84°. The lack of asterisks indicates that such small difference was not significant ($p>0.05$), like most comparisons between Variantor empirical results and the predictions for protanopia (leftmost bars in Figures 5a and 5b, only one of eight comparisons was significant, $p<0.01$). Contrariwise, Figure 5 also shows that all the comparisons between Variantor and the expected values for deuteranopia (leftmost bars in Figures 5c and 5d) produced large and significant differences (Δh_{uv} between 12.33° and 17.39°, $p<0.01$; ΔL_R between -0.42 and 0.23, $p<0.001$).

Figure 5 shows that none of the Coblis simulations was accurate. Both for protanopia (rightmost bars in Figures 5a and 5b) and deuteranopia (rightmost bars in Figures 5c and 5d), Δh_{uv} values were large (between -45.79° and -34.72° for protanopia; between -41.35° and -33.08° for deuteranopia) and significant ($p<0.001$). Something similar occurred for ΔL_R: Again, the differences were large (between -0.73 and 0.22 for protanopia; between -0.64 and 0.17 for deuteranopia) and significant ($p<0.001$).

Figure 5 also highlights a singular fact related to L_R deuteranopia simulations (Figure 5d): ΔL_R values had different sign depending on the pseudoachromatic stimuli and simulation tool considered. For Variantor, they were positive for the greens (0.19 for MC and 0.23 for CC) and negative for the reds (-0.42 for MC and -0.17 for CC). The opposite pattern was true for Coblis (-0.64 and -0.32, respectively, for the MC and CC pseudoachromatic greens; 0.17 and 0.15, respectively, for the MC and CC pseudoachromatic reds).

RGB Simulcheck version

As in Figure 5, the leftmost bars in Figure 6a show that the Δh_{uv} values were small and the comparisons between Variantor 95% CIs and the predicted values for protanopia were not significant ($p>0.05$). A different pattern appeared for ΔL_R in Variantor protanopia (leftmost bars in Figure 6b): Three out of four differences were significant ($p<0.01$, ΔL_R between -0.13 and 0.20). Regarding the comparisons between empirical Variantor 95% CIs and deuteranopia predicted values (leftmost bars in Figures 6c and 6d), there were significant and big differences both in Δh_{uv} ($p<0.01$, between 8.20° and 11.71°) and ΔL_R ($p<0.001$, between -0.34 and 0.16).

Figure 6 shows that none of the Coblis simulations was accurate both for protanopia (rightmost bars in Figures 6a and 6b) and deuteranopia (rightmost bars in Figures 6c and 6d). There were significant ($p<0.001$ for protanopia; $p<0.01$ for deuteranopia) and large differences both for Δh_{uv} (between -31.92° and -23.82° for protanopia; between -32.95° and -20.27° for deuteranopia) and ΔL_R (between -0.50 and 0.32 for protanopia; between -0.32 and 0.02 for deuteranopia).

Figure 6d reveals that the ΔL_R values regarding Variantor and Coblis for deuteranopia were inverse for pseudoachromatic greens (positive for Variantor and negative for Coblis) but not for reds. Specifically, ΔL_R values for pseudoachromatic reds were negative for Variantor MC (-0.34) and CC (-0.11), while they were also negative for Coblis MC set (-0.05) but positive for CC set (0.02).

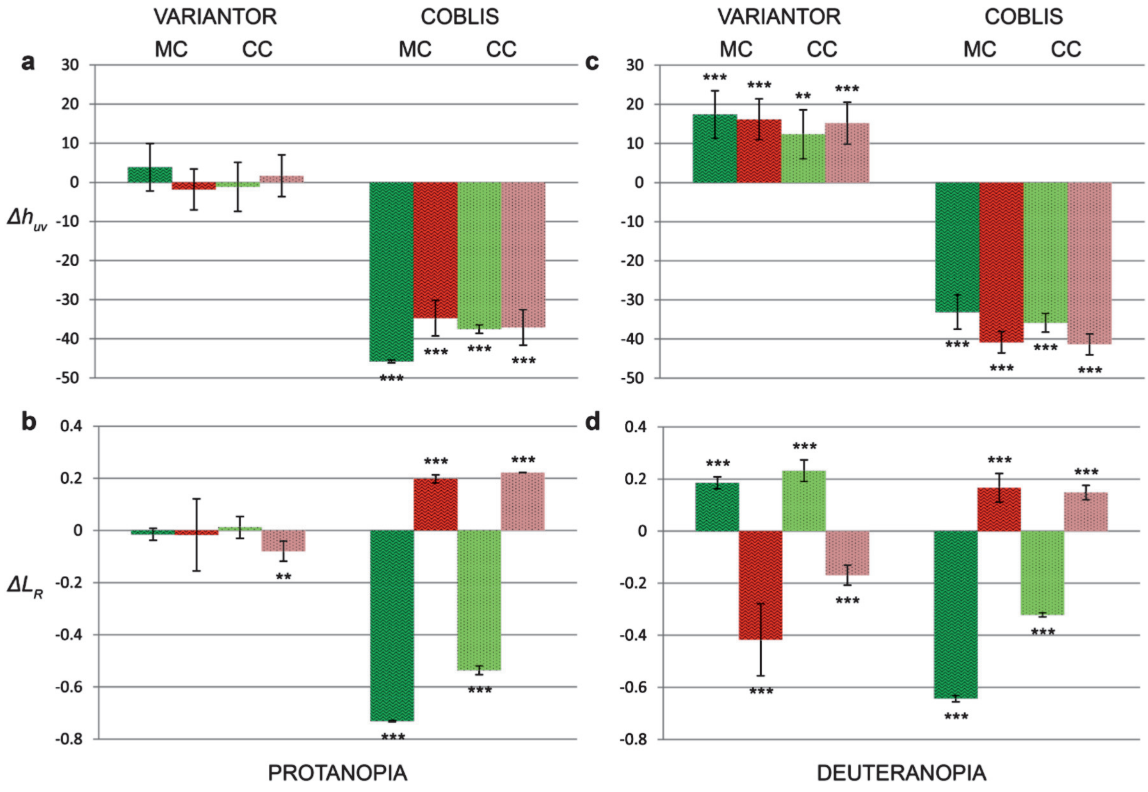

Figure 5. *Differences in h_{uv} (Δh_{uv}, a and c) and L_R (ΔL_R, b and d) between the mean of the empirical data and the predicted values for protanopia (a and b) and deuteranopia (c and d) using colorimetric measurements. Each group of four bars represents the results of the simulated dichromats for the two stimulus sets (MC = Maximum Chroma; CC = Constant Chroma) for the two pseudoachromatic selections (green and red). Its colours are consistent with the set and type of pseudoachromatic selections. Error bars show 95% CIs of empirical values. ** $p<0.01$; *** $p<0.001$*

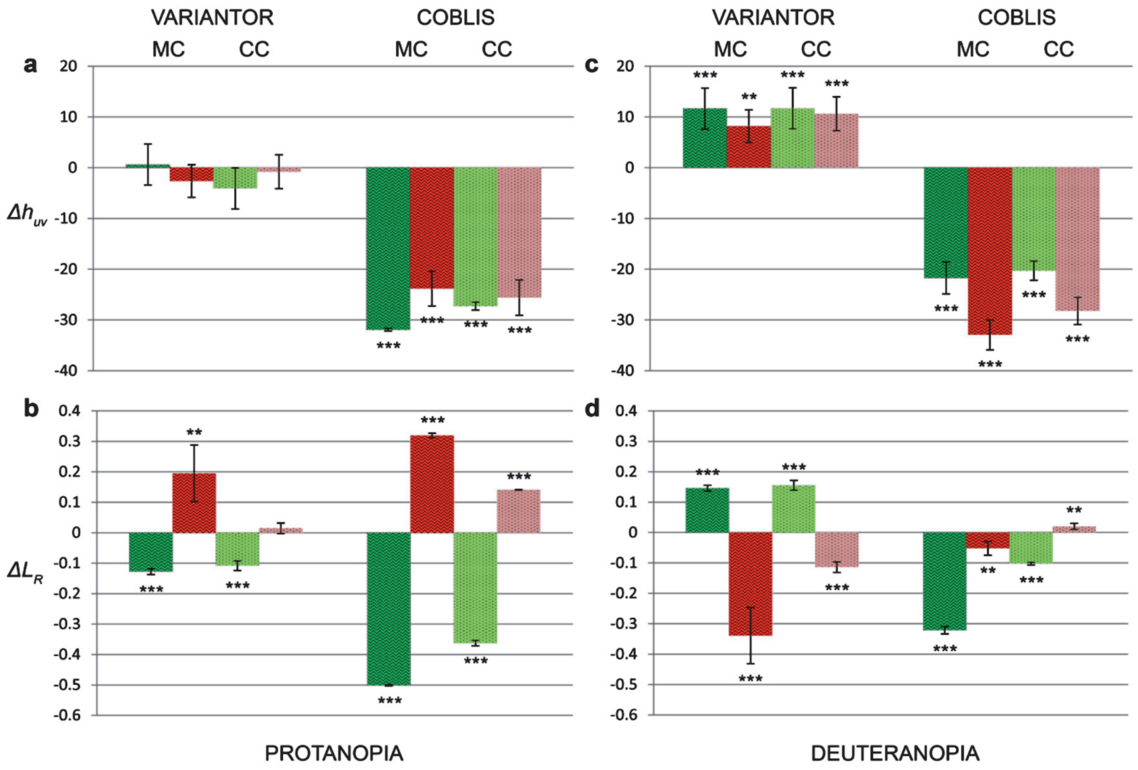

Figure 6. *Differences in* h_{uv} *(*Δh_{uv}*; a and c) and* L_R *(*ΔL_R*, b and d) between the mean of the empirical data and the predicted values for protanopia (a and b) and deuteranopia (c and d) using Adobe RGB 1998 computations. Each group of four bars represents the results of the simulated dichromats for the two stimulus sets (MC = Maximum Chroma; CC = Constant Chroma) for the two pseudoachromatic selections (green and red). Its colours are consistent with the set and type of pseudoachromatic selections. Error bars show 95% CIs of empirical values. ** p<0.01; *** p<0.001*

Discussion

DMB results (Figure 5) confirmed Lillo et al.'s (2014) main findings. We also found that Variantor accurately simulated protanope vision both when considering pseudoachromatic stimuli identification (h_{uv}, op. cit., Figure 11a) and when we measured these stimuli's relative luminance (L_R, op. cit., Figure 12a). No other CST-colour deficiency type combination provided such results. That is, Variantor did not accurately simulate deuteranope vision (op.cit, Figures 11b and 12b), and none of the Coblis simulations was accurate for their target dichromat type.

DMB and RGB versions provided equivalent results for the *Pseudoachromatic Stimuli Identification task* (compare Δh_{uv} values in Figures 5 and 6). Both versions produced small Δh_{uv} values for the combination Variantor-protanopia. On the other hand, similar sign (positive or negative) and magnitude errors emerged for the other CST- dichromat type combinations: Not very large and positive errors for Variantor-Deuteranopia; larger and negative errors for Coblis-protanopia and Coblis-deuteranopia.

RGB version accuracy in computing h_{uv} values has three important consequences: (1) It promotes Simulcheck method use because this version does not require the use of an expensive and difficult to find apparatus (a colorimeter). (2) It gives meaning to the L_R calculus. (3) It provides very relevant information for performing universal designs (Vanderheiden & Jordan, 2012): the h_{uv} of the stimuli that produce a neutral response in the yellow-blue mechanism (Birch, 2001; Fletcher & Voke, 1985; Smith & Pokorny, 2003). This mechanism mainly accounts for red-green dichromats' colour naming and it is also the most important mechanism to explain colour preference in such observers and in normal trichromats (Álvaro, Moreira, Lillo, & Franklin, 2015). This result is also very important considering a recent research (Bonnardel, Piolat, & Le Bigot, 2011) showing the impact of the colours used in web design both for the website appeal and for the cognitive processes of the users.

RGB version capacity for providing accurate h_{uv} values depends on the similarity of the colour gamuts produced by the primaries of the actual screen's phosphors and the Adobe RGB 1998 colour space (see Figure 4). As it can be seen in Suero, Pardo, and Pérez (2010, Figure 2), such gamuts are also similar to those provided by some CRT screens, TFT screens and game console displays (Nintendo DS and Sony PSP). Obviously, insofar as the upcoming screens increase their colour gamut, it will be necessary to replace the Adobe RGB 1998 colour space by other spaces to perform accurate h_{uv} estimations.

RGB version was not fully accurate in computing L_R values. There were some important differences with the results provided by the DMB version. For example, although leftmost bars in Figure 5d (DMB version) show reduced ΔL_R values for the combination Variantor-protanopia, it does not occur when L_R values were estimated by the RGB version (see leftmost bars in Figure 6b). Another important disagreement between the DMB and the RGB L_R values emerged for the combination Coblis-deuteranopia (Figures 5d and 6d). Disagreements in the L_R calculus arose because primary luminances varied from one Simulcheck version to another (luminance values compared with white: red, 31%, green, 63%, blue, 6%, in DMB version; red, 26%, green, 56%, blue, 18%, in RGB version). As L_R results from comparing two luminances, changes in the luminances lead to changes in L_R.

Though the RGB version is not accurate in computing L_R values, the practical relevance of this fact is reduced because: (1) L_R results from dividing the pseudoachromatic stimulus luminance by those corresponding to the background selected in the *Minimum Achromatic Contrast task*. (2) Such result can be accurately obtained using cheap and easy to find photometric apparatus (Lillo & Moreira, 2005).

Synthetizing, colour simulation tools can be very useful to promote colour universal design and the Simulcheck method can be very useful for knowing if such simulation tools work accurately. Until now, the method's main limitation was that it required a colorimeter for measuring the chromatic angle of the pseudoisochromatic stimuli. The RGB Simulcheck method eliminates this limitation.

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