Digital Video Colourmaps for Checking the Legibility of Displays by Dichromats

Françoise Viénot,[1]* Hans Brettel,[2] John D. Mollon[3]

[1] Muséum National d'Histoire Naturelle, Laboratoire de Photobiologie, 43 rue Cuvier, 75005 Paris, France

[2] CNRS URA 820, Ecole Nationale Supérieure des Télécommunications, Département de Traitement du Signal et de l'Image, 46 rue Barrault, 75013 Paris, France

[3] Department of Experimental Psychology, Downing St, Cambridge CB2 3EB, UK

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Abstract: We propose replacement colourmaps that allow a designer to check the colours seen by protanopes and deuteranopes. Construction of the colourmaps is based on the LMS specification of the primaries of a standard video monitor and has been carried out for 256 colours, including 216 colours that are common to many graphics applications of MS Windows and Macintosh computing environments.

Key words: colour; dichromacy; computer; simulation; recognition; fundamentals; colour vision deficiencies

INTRODUCTION

Digital video technologies allow us to create and modify colour images. Most often, the choice of colour is supposed to enhance readability. However, for those who suffer from colour-blindness and who represent 8% of the male population, the choice of colours may not be optimal. Colour-blinds confuse colours that are discriminable for the normal. The most severely affected people are those who have a dichromatic form of colour vision deficiency. It is possible to compute colour confusions and to simulate dichromatic colour vision. Here, we propose colourmaps to replace the "system" ones, and to allow a designer with normal colour vision to simulate the colours seen by dichromats.

* Correspondence to: F. Viénot; e-mail: vienot@mnhn.fr

METHODS

The method is based on the LMS system, which specifies colours in terms of the relative excitations of the longwave sensitive (L), the middlewave sensitive (M), and the shortwave sensitive (S) cones. As dichromats lack one class of cone photopigment, they confuse colours that differ only in the excitation of the missing class of photopigment. In contrast to the case of the trichromatic observer, who requires colour specifications by three components, two components are sufficient to specify colour for the dichromat. One can construct a rule to reduce any set of confused colours to a single three-component colour specification.

Quantitative estimates of the colour perceptions typical of protanopic and deuteranopic observers have been given for the whole range of colours in the Munsell colour-order system.[1] Potentialities of computer graphics systems to synthesize a picture of the world as seen by dichromats have been outlined, and dichromatic versions of an image have been produced using (u', v') chromaticity transformation for every pixel.[2] A more general transformation for simulating colour-deficient vision, which circumvents the CIE *XYZ* system and comprises both the dichromatic and anomalous case, has been implemented in a colour editor for display design.[3,4]

Here, we construct colourmaps to replace a standard palette of 256 colours, including 216 colours that are common to many graphics applications of MS Windows and Macintosh computing environments, and show how a colour image would look for protanopes or for deuteranopes.

In our former publications,[5,6] we have given an illustration and described a detailed algorithm for simulating co-

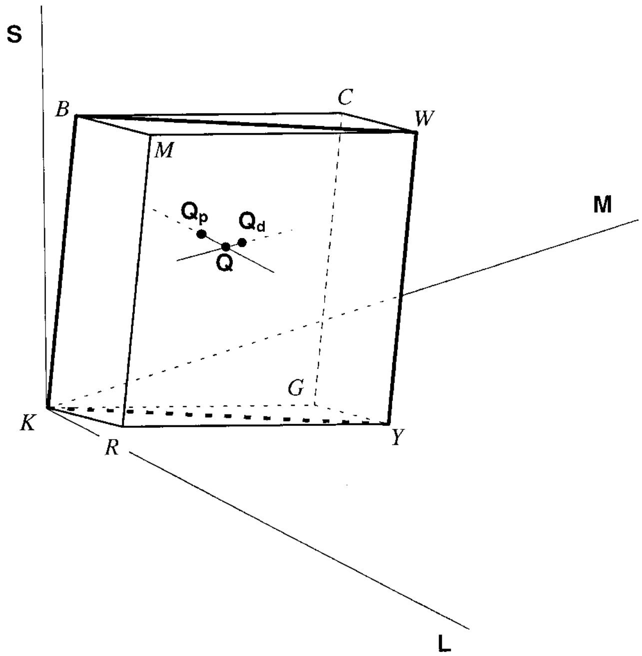

FIG. 1. Representation of stimuli in LMS space. All colours obtainable by combination of the primaries are included in the parallelpiped KBMRGCWY. K: Black. B: Blue primary. M: Magenta. R: Red primary. G: Green primary. C: Cyan. W: White. Y: Yellow. The replacement colours are located in the reduced plane KBWY. Q_pQ is a confusion line for protanope; all colours of Q_pQ line reduce to its intersection Q with the plane KBWY. Q_dQ is a confusion line for deuteranope; all colours of Q_dQ line reduce to its intersection Q with the plane KBWY.

lour appearance for dichromats. We proposed to reduce all stimuli belonging to a confusion line, i.e., to a line parallel to the axis of the missing photopigment in the LMS specification space, to a single colour and to represent the dichromat's colour space by two half-planes, each of which included the neutral axis and an anchor wavelength, which is the wavelength that appears similar to dichromats and normals. The advantage of specifying colours in the LMS colour space rather than the *XYZ* colour space is that the transformation takes into account the altered luminosity function of dichromats, especially for protanopes.

Here we maintain this scheme of reduction, but we introduce three compromises in order to achieve the practical goal of replacement colourmaps that can be implemented on any graphics monitor.

First, instead of requiring individual calibration of the video display, we assume that the video display primaries and nominal white are representative of recent standards for Cathode Ray Tube (CRT) monitors[7,8] and that its video-transfer function is a power function with an exponent of 2.2 ("gamma").

Second, the video display standard is specified in terms of CIE 1931 (x, y) chromaticity coordinates, but the best sets of fundamentals are not derived from the CIE 1931 colorimetric observer. The Smith and Pokorny[9] set of fundamentals is derived from the Judd–Vos modified colorimetric observer,[10,11] i.e., an observer slightly different from the CIE 1931 one, with no possible linear transformation between them. Because the video display standard does not recommend a spectral power distribution for primaries but only chromaticities, we convert from (x, y) chromaticity coordinates to modified (x', y') coordinates using the formula of Vos[11] this formula strictly applies for spectral stimuli, and our second compromise consists in extending it to the primaries and the nominal white.

Third, in order to use as many colours as possible of the video display gamut, we choose replacement colours on a diagonal plane of the RGB colour space of the display device (Fig. 1).

RESULTS

Starting with a standard palette of 216 colours, which are commonly used with MS Windows and Macintosh computing environments, and which we have extended to 256

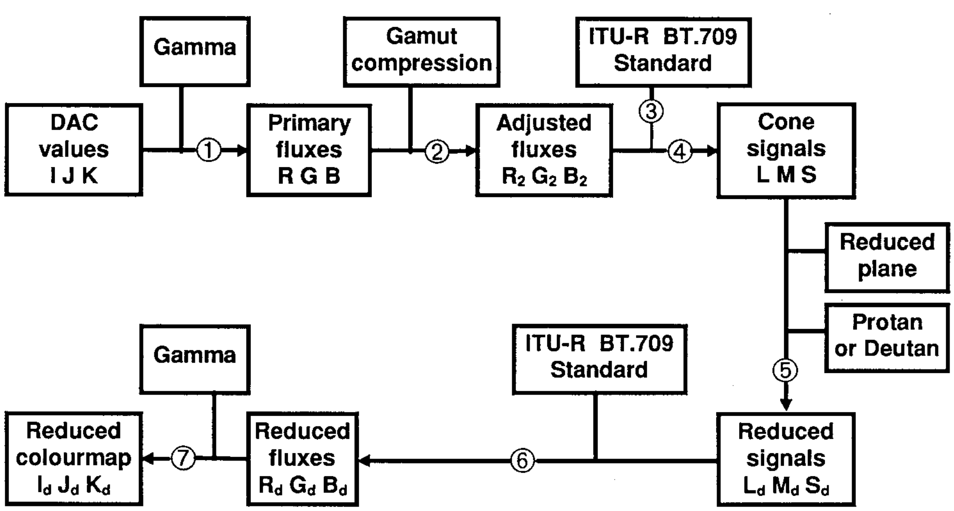

FIG. 2. Computational procedure giving the replacement colourmaps to simulate dichromatic vision (subscript *d*). Each operation is numbered according to the successive steps described in the Methods section.

TABLE I. Chromaticity (x, y) of primaries and reference white of the ITU-R BT.709 standard and of the NTSC. Modified chromaticity (x', y') converted from (x, y) using Vos (1978) transformation.

	ITU-R BT.709 standard		NTSC standard			
	x	y	x	y		
Red primary	0.64	0.33	0.67	0.33		
Green primary	0.30	0.60	0.21	0.71		
Blue primary	0.15	0.06	0.14	0.08		
Reference white	D65		CIE C		D93 white	
	0.3127	0.3290	0.310	0.316	0.2831	0.2971

	ITU-R BT.709 standard	
	x'	y'
Red primary	0.6384	0.3326
Green primary	0.3018	0.6008
Blue primary	0.1530	0.0682
Reference white	D65	
	0.3157	0.3345

colours, we have constructed two replacement colourmaps that illustrate protanopic and deuteranopic vision, respectively.

The transformation scheme to compute the replacement colourmaps includes several steps (Fig. 2).

1. Given (I, J, K) as the 8-bit DAC values for each of the (R, G, B) video channels, we compute the relative photometric quantities R, G, B:

$$R = (I/255)\hat{}2.2 \quad (1)$$

$$G = (J/255)\hat{}2.2 \quad (1)$$

$$B = (K/255)\hat{}2.2. \quad (1)$$

2. In order to produce reduced colours that are included in the colour gamut of the monitor, we slightly reduce the colour domain of the initial palette. This is achieved by appropriate scaling of the relative photometric quantities.

For protanopes:

$$R_2 = 0.992052\ R + 0.003974 \quad (2)$$

$$G_2 = 0.992052\ G + 0.003974 \quad (2)$$

$$B_2 = 0.992052\ B + 0.003974. \quad (2)$$

For deuteranopes:

$$R_2 = 0.957237\ R + 0.0213814 \quad (2)$$

$$G_2 = 0.957237\ G + 0.0213814 \quad (2)$$

$$B_2 = 0.957237\ B + 0.0213814. \quad (2)$$

3. The LMS specification of each colour is obtained from the CIE 1931 (x, y) specifications of the CRT display by the following procedure. We first apply the Judd–Vos colorimetric modification[10,11]

$$x'_\lambda = \frac{1.0271x_\lambda - 0.00008y_\lambda - 0.00009}{0.03845x_\lambda + 0.01496y_\lambda + 1} \quad (3)$$

$$y'_\lambda = \frac{0.00376x_\lambda + 1.0072y_\lambda + 0.00764}{0.03845x_\lambda + 0.01496y_\lambda + 1} \quad (3)$$

to the chromaticity (x, y) of the red, green, and blue primaries and nominal white of the International Telecommunication Union ITU-R BT.709 standard[7] (Table I) and obtain slightly modified chromaticity coordinates (x', y').

Then we compute the corresponding modified (X_2, Y_2, Z_2) tristimulus values for the primaries and get the matrix[12]

$$\begin{pmatrix} X_2 \\ Y_2 \\ Z_2 \end{pmatrix} = \begin{pmatrix} RGB\_\text{to}\_XYZ \end{pmatrix} \begin{pmatrix} R_2 \\ G_2 \\ B_2 \end{pmatrix}$$

$$= \begin{pmatrix} 40.9568 & 35.5041 & 17.9167 \\ 21.3389 & 70.6743 & 7.98680 \\ 1.86297 & 11.4620 & 91.2367 \end{pmatrix} \begin{pmatrix} R_2 \\ G_2 \\ B_2 \end{pmatrix}.$$

From Smith and Pokorny,[9] we get

$$\begin{pmatrix} L \\ M \\ S \end{pmatrix} = \begin{pmatrix} XYZ\_\text{to}\_LMX \end{pmatrix} \begin{pmatrix} X_2 \\ Y_2 \\ Z_2 \end{pmatrix}$$

$$= \begin{pmatrix} 0.15514 & 0.54312 & -0.03286 \\ -0.15514 & 0.45684 & 0.03286 \\ 0 & 0 & 0.01608 \end{pmatrix} \begin{pmatrix} X_2 \\ Y_2 \\ Z_2 \end{pmatrix}.$$

The RGB to LMS matrix is the product of two matrices:

$$\begin{pmatrix} L \\ M \\ S \end{pmatrix} = \left(XYZ\_\text{to}\_LMS \right) \left(RGB\_\text{to}\_XYZ \right) \begin{pmatrix} R_2 \\ G_2 \\ B_2 \end{pmatrix}$$

$$\begin{pmatrix} L \\ M \\ S \end{pmatrix} = \left(RGB\_\text{to}\_LMS \right) \begin{pmatrix} R_2 \\ G_2 \\ B_2 \end{pmatrix}$$

$$= \begin{pmatrix} 17.8824 & 43.5161 & 4.11935 \\ 3.45565 & 27.1554 & 3.86714 \\ 0.0299566 & 0.184309 & 1.46709 \end{pmatrix} \times \begin{pmatrix} R_2 \\ G_2 \\ B_2 \end{pmatrix}. \quad (4)$$

4. The reduced colour domain is the plane including the origin, the white point, and the blue primary. Solving the plane equation for the origin (0, 0, 0), the blue primary stimulus (L_B, M_B, S_B) and the white stimulus (L_W, M_W, S_W) gives the equation of the reduced plane

$$\alpha L + \beta M + \gamma S = 0$$

with

$$\alpha = M_W S_B - M_B S_W$$

TABLE II. DAC values of replacement colourmaps, which allow a designer to check the readability of colour images by protanopes and deuteranopes. As the plane of reduced stimuli is a diagonal plane of the RGB colour space of the video display, DAC values for red and green primaries are equal.

Standard DAC values			Protan replacement values		Deutan replacement values	
I	J	K	I_p, J_p	K_p	I_d, J_d	K_d
255	255	255	255	255	253	253
204	255	255	249	254	239	253
153	255	255	246	254	229	254
102	255	255	243	254	222	255
51	255	255	242	254	218	255
0	255	255	241	254	217	255
255	204	255	210	255	219	252
204	204	255	204	255	203	253
153	204	255	199	254	191	253
102	204	255	196	254	181	254
51	204	255	194	254	176	254
0	204	255	193	254	175	254
255	153	255	168	255	190	251
204	153	255	160	255	171	252
153	153	255	153	255	155	253
102	153	255	149	254	143	253
51	153	255	146	254	136	253
0	153	255	145	254	134	253
255	102	255	131	255	167	250
204	102	255	120	255	144	251
153	102	255	110	255	123	252
102	102	255	103	255	107	253
51	102	255	99	254	97	253
0	102	255	98	254	94	253
255	51	255	105	255	152	250
204	51	255	89	255	126	251
153	51	255	74	255	102	252
102	51	255	62	255	80	252
51	51	255	54	255	65	253
0	51	255	51	255	60	253
255	0	255	96	255	148	250
204	0	255	77	255	121	251
153	0	255	59	255	94	252
102	0	255	42	255	70	252
51	0	255	27	255	51	252
0	0	255	21	255	44	253

Standard DAC values			Protan replacement values		Deutan replacement values	
I	J	K	I_p, J_p	K_p	I_d, J_d	K_d
255	255	153	255	153	253	155
204	255	153	249	153	239	156
153	255	153	246	153	229	158
102	255	153	243	153	222	158
51	255	153	242	152	218	159
0	255	153	241	152	217	159
255	204	153	210	154	219	153
204	204	153	204	153	203	155
153	204	153	199	153	191	156
102	204	153	196	153	181	157
51	204	153	194	153	176	157
0	204	153	193	153	175	157
255	153	153	168	154	190	152
204	153	153	160	154	171	153
153	153	153	153	153	155	155
102	153	153	149	153	143	155
51	153	153	146	153	136	156
0	153	153	145	153	134	156
255	102	153	131	154	167	151
204	102	153	120	154	144	152
153	102	153	110	153	123	154
102	102	153	103	153	107	155
51	102	153	99	153	97	155
0	102	153	98	153	94	155
255	51	153	105	154	152	150
204	51	153	89	154	126	152
153	51	153	74	154	102	153
102	51	153	62	153	80	154
51	51	153	54	153	65	155
0	51	153	51	153	60	155
255	0	153	96	154	148	150
204	0	153	77	154	121	152
153	0	153	59	154	94	153
102	0	153	42	153	70	154
51	0	153	27	153	51	154
0	0	153	21	153	44	155

Standard DAC values			Protan replacement values		Deutan replacement values	
I	J	K	I_p, J_p	K_p	I_d, J_d	K_d
255	255	51	255	54	253	65
204	255	51	249	53	239	70
153	255	51	246	52	229	73
102	255	51	243	51	222	75
51	255	51	242	51	218	76
0	255	51	241	51	217	76
255	204	51	210	55	219	60
204	204	51	204	54	203	65
153	204	51	199	53	191	68
102	204	51	196	52	181	71
51	204	51	194	52	176	72
0	204	51	193	52	175	72
255	153	51	168	56	190	55
204	153	51	160	55	171	61
153	153	51	153	54	155	65
102	153	51	149	53	143	67
51	153	51	146	53	136	68
0	153	51	145	53	134	69
255	102	51	131	56	167	52
204	102	51	120	55	144	58
153	102	51	110	54	123	62
102	102	51	103	54	107	65
51	102	51	99	54	97	66
0	102	51	98	53	94	67
255	51	51	105	57	152	51
204	51	51	89	56	126	57
153	51	51	74	55	102	61
102	51	51	62	54	80	63
51	51	51	54	54	65	65
0	51	51	51	54	60	65
255	0	51	96	57	148	50
204	0	51	77	56	121	56
153	0	51	59	55	94	60
102	0	51	42	54	70	63
51	0	51	27	54	51	64
0	0	51	21	54	44	65

Standard DAC values			Protan replacement values		Deutan replacement values	
I	J	K	I_p, J_p	K_p	I_d, J_d	K_d
238	0	0	89	27	139	18
221	0	0	83	27	130	24
187	0	0	71	25	112	32
170	0	0	65	24	103	35
136	0	0	53	23	86	39
119	0	0	48	22	78	40
85	0	0	37	21	63	43
68	0	0	32	21	57	43
34	0	0	24	21	47	44
17	0	0	21	21	45	44
0	238	0	225	8	203	59
0	221	0	209	11	189	57
0	187	0	177	15	161	53
0	170	0	161	16	147	52
0	136	0	129	18	120	49
0	119	0	114	19	107	48
0	85	0	82	20	82	46
0	68	0	67	20	70	45
0	34	0	37	21	51	45
0	17	0	25	21	46	44
0	0	238	21	238	44	236
0	0	221	21	221	44	220
0	0	187	21	187	44	187
0	0	170	21	170	44	171
0	0	136	21	136	44	139
0	0	119	21	120	44	123
0	0	85	21	86	44	92
0	0	68	21	70	44	78
0	0	34	21	39	44	54
0	0	17	21	26	44	47
238	238	238	238	238	236	236
221	221	221	221	221	220	220
187	187	187	187	187	187	187
170	170	170	170	170	171	171
136	136	136	136	136	139	139
119	119	119	120	120	123	123

TABLE II. (*Continued*)

Standard DAC values			Protan replacement values		Deutan replacement values		Standard DAC values			Protan replacement values		Deutan replacement values		Standard DAC values			Protan replacement values		Deutan replacement values		Standard DAC values			Protan replacement values		Deutan replacement values	
I	J	K	I_p, J_p	K_p	I_d, J_d	K_d	I	J	K	I_p, J_p	K_p	I_d, J_d	K_d	I	J	K	I_p, J_p	K_p	I_d, J_d	K_d	I	J	K	I_p, J_p	K_p	I_d, J_d	K_d
255	255	204	255	204	253	203	255	255	102	255	103	253	107	255	255	0	255	21	253	44	85	85	85	86	86	92	92
204	255	204	249	204	239	205	204	255	102	249	102	239	110	204	255	0	249	17	239	52	68	68	68	70	70	78	78
153	255	204	246	203	229	205	153	255	102	246	102	229	112	153	255	0	246	12	229	56	34	34	34	39	39	54	54
102	255	204	243	203	222	206	102	255	102	243	102	222	113	102	255	0	243	8	222	59	17	17	17	26	26	47	47
51	255	204	242	203	218	206	51	255	102	242	102	218	114	51	255	0	242	4	218	60							
0	255	204	241	203	217	206	0	255	102	241	102	217	114	0	255	0	241	0	217	61							
255	204	204	210	204	219	202	255	204	102	210	104	219	105	255	204	0	210	24	219	36							
204	204	204	204	204	203	203	204	204	102	204	103	203	107	204	204	0	204	21	203	44							
153	204	204	199	204	191	204	153	204	102	199	103	191	109	153	204	0	199	18	191	50							
102	204	204	196	204	181	205	102	204	102	196	102	181	111	102	204	0	196	15	181	53							
51	204	204	194	204	176	205	51	204	102	194	102	176	111	51	204	0	194	14	176	55							
0	204	204	193	203	175	205	0	204	102	193	102	175	111	0	204	0	193	13	175	55							
255	153	204	168	204	190	201	255	153	102	168	104	190	102	255	153	0	168	26	190	27							
204	153	204	160	204	171	202	204	153	102	160	103	171	105	204	153	0	160	23	171	38							
153	153	204	153	204	155	203	153	153	102	153	103	155	107	153	153	0	153	21	155	44							
102	153	204	149	204	143	204	102	153	102	149	103	143	109	102	153	0	149	19	143	48							
51	153	204	146	204	136	204	51	153	102	146	103	136	109	51	153	0	146	18	136	50							
0	153	204	145	204	134	204	0	153	102	145	103	134	110	0	153	0	145	17	134	50							
255	102	204	131	204	167	200	255	102	102	131	104	167	101	255	102	0	131	27	167	18							
204	102	204	120	204	144	202	204	102	102	120	104	144	104	204	102	0	120	25	144	33							
153	102	204	110	204	123	203	153	102	102	110	103	123	106	153	102	0	110	22	123	40							
102	102	204	103	204	107	203	102	102	102	103	103	107	107	102	102	0	103	21	107	44							
51	102	204	99	204	97	204	51	102	102	99	103	97	108	51	102	0	99	20	97	46							
0	102	204	98	204	94	204	0	102	102	98	103	94	108	0	102	0	98	19	94	47							
255	51	204	105	204	152	200	255	51	102	105	104	152	100	255	51	0	105	28	152	9							
204	51	204	89	204	126	201	204	51	102	89	104	126	103	204	51	0	89	25	126	30							
153	51	204	74	204	102	202	153	51	102	74	103	102	105	153	51	0	74	23	102	38							
102	51	204	62	204	80	203	102	51	102	62	103	80	107	102	51	0	62	22	80	42							
51	51	204	54	204	65	203	51	51	102	54	103	65	107	51	51	0	54	21	65	44							
0	51	204	51	204	60	203	0	51	102	51	103	60	107	0	51	0	51	20	60	45							
255	0	204	96	204	148	200	255	0	102	96	104	148	100	255	0	0	96	28	148	0							
204	0	204	77	204	121	201	204	0	102	77	104	121	103	204	0	0	77	26	121	29							
153	0	204	59	204	94	202	153	0	102	59	103	94	105	153	0	0	59	23	94	37							
102	0	204	42	204	70	203	102	0	102	42	103	70	106	102	0	0	42	22	70	42							
51	0	204	27	204	51	203	51	0	102	27	103	51	107	51	0	0	27	21	51	44							
0	0	204	21	204	44	203	0	0	102	21	103	44	107	0	0	0	21	21	44	44							

$$\beta = S_W L_B - S_B L_W$$

$$\gamma = L_W M_B - L_B M_W.$$

The reduction of the normal colour domain to the dichromatic colour domain maintains the fundamental values corresponding to the existing photopigments, S and M for the protanope, and S and L for the deuteranope.

The replacement tristimulus value corresponding to the missing photopigment is, for the protanope,

$$L_p = -(\beta M + \gamma S)/\alpha;$$

and, for the deuteranope,

$$M_d = -(\alpha L + \gamma S)/\beta.$$

This results in the following linear transformations for reducing the normal colour domain to the dichromat colour domain, for protanopes:

$$\begin{pmatrix} L_p \\ M_p \\ S_p \end{pmatrix} = \begin{pmatrix} 0 & 2.02344 & -2.52581 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} L \\ M \\ S \end{pmatrix} \quad (5)$$

and for deuteranopes:

$$\begin{pmatrix} L_d \\ M_d \\ S_d \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0.494207 & 0 & 1.24827 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} L \\ M \\ S \end{pmatrix}. \quad (5)$$

5. Transformation of $L_d M_d S_d$ or $L_p M_p S_p$ to RGB is obtained using the inverse matrix of matrix (4) in step 3):

$$\begin{pmatrix} R_d \\ G_d \\ B_d \end{pmatrix} = (\ RGB\_to\_LMS\ )^{-1} \begin{pmatrix} L_d \\ M_d \\ S_d \end{pmatrix}$$

$$\begin{pmatrix} R_d \\ G_d \\ B_d \end{pmatrix} = \begin{pmatrix} 0.080944 & -0.130504 & 0.116721 \\ -0.0102485 & 0.0540194 & -0.113615 \\ -0.000365294 & -0.00412163 & 0.693513 \end{pmatrix} \times \begin{pmatrix} L_d \\ M_d \\ S_d \end{pmatrix}. \quad (6)$$

6. DAC-values of the replacement colourmaps are obtained using the inverse of the relationship described in step (1):

$$I_d = 255\ R_d\wedge(1/2.2) \quad (7)$$

$$J_d = 255\ G_d\wedge(1/2.2) \quad (7)$$

$$K_d = 255\ B_d\wedge(1/2.2). \quad (7)$$

Table II shows the DAC values of the resulting replacement colourmaps.

Because the plane of reduced stimuli is a diagonal plane of the RGB colour space of the video display, DAC values for red and green primaries are equal.

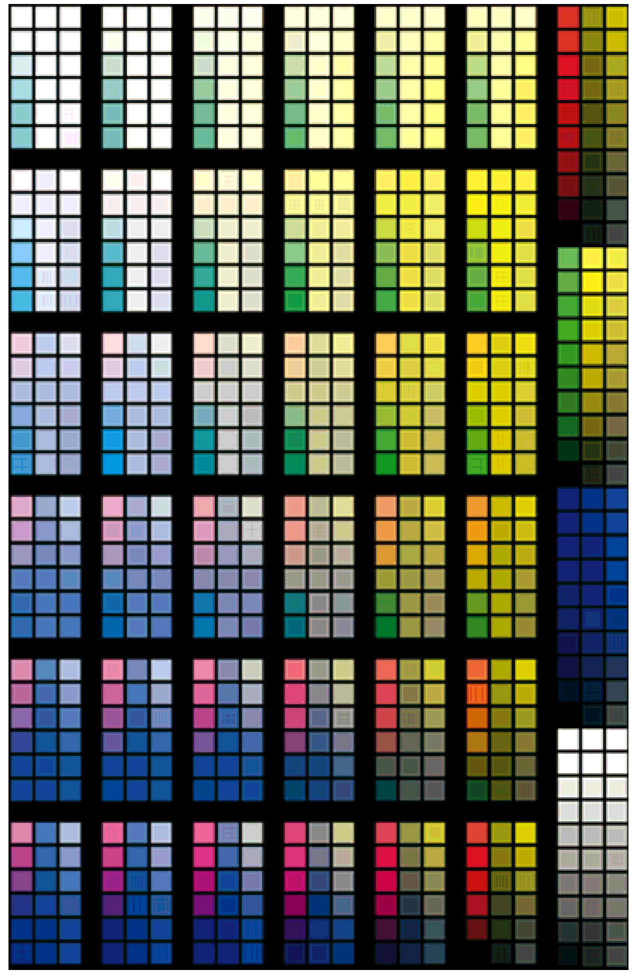

FIG. 3. Colour illustration of the 256 colour palettes specified in Table II. Within each block, the first column illustrates the original colour of the normal colourmap, the second and third columns illustrate its appearance in the protan and deutan transformation. The vertical sequence of samples is as in Table II.

Figure 3 illustrates side-by-side every sample of the 256 colour palette of Table II in its normal, protan, and deutan version, in the same order as in the table. It can be seen that samples of the colourful left column are replaced by yellow or blue shades, in various lightnesses or saturations. It can be seen also that the protan and the deutan transformation yield colours of different lightnesses.

Figure 4 shows an example where the normal, protan, and deutan versions of an RATP-RER transportation map of Paris (France) are presented in colour. The Réseau Express Régional (RER) of Régie Autonome des Transports Parisiens (RATP, Paris, France) is the underground and train network, which operates between Paris and its outskirts. All colours of the transportation map that have been originally used by the designer are part of Table II. The protan and deutan versions result from replacing the normal colourmap by the protan or by the deutan colourmap. Although our algorithm was not available by the time the map was designed, the various transportation

FIG. 4. Normal, protan, and deutan versions of the transportation map of the RATP-RER (Paris, France). The original image has been produced using a high-resolution version of the map provided by RATP (by courtesy of RATP). Every colour has been adjusted in order to comply with the Web version accessible at: http://www.ratp.fr/Transpor/Reseaux/planrer.htm. All colours are part of Table II. The protan and deutan versions result from the replacement of the normal colourmap by the protan or by the deutan colourmap. The original red transportation line is transformed in a darker shade in the protan version than in the deutan version. Left: normal version. Upper-right: protan version. Lower-right: deutan version.

lines are still identifiable. Now that it is available, guidance on the choice of colours can be obtained simply by substituting the colourmaps.

DISCUSSION

Although the colourmaps we propose have been constructed along the same lines as those used in the full "TrueColour" representation,[6] we should evaluate how far the simulation of dichromatic vision is affected by the simplification of the algorithm that we have adopted here.

Colorimetric Accuracy

When proper calibration of the user's video display is not available, the lack of conformity with the ITU standard may be a source of discrepancy. We have computed the errors of confused colours originating from poor calibration taking as a model the most common shifts of CRT parameters. In Table III, we indicate the errors in terms of DAC values for a few samples of the protan replacement palette:

if the primaries and reference white have the chromaticity recommended by the National Television Systems Committee[12] instead of those recommended by ITU (Table I),

TABLE III. Computed DAC values, $I_pJ_pK_p$ for the protan replacement colourmap, considering different CRT primaries, reference white, and transfer functions. First column: I J K refer to a few DAC values selected from the original colourmap. Following columns: $I_pJ_pK_p$ are obtained by performing steps 1–7 of the computation as indicated in the block diagram in Fig. 2. Last line gives the scaling factor used to compute the replacement DAC values in each case, which at the same time is the maximum achievable scaling factor enabling the reduction of the entire colour gamut within the real colour gamut of the monitor.

DAC values of the original colourmap			DAC values for the protan replacement map: ITU standard D65 white Gamma 2.2		NTSC standard CIE C white Gamma 2.2		ITU-R BT.709 primaries D93 white Gamma 2.2		ITU-R BT.709 primaries D65 white Gamma 1.8	
I	J	K	I_p, J_p	K_p	I'_p, J'_p	K'_p	I''_p, J''_p	K''_p	I'''_p, J'''_p	K'''_p
255	255	255	255	255	254	254	255	255	254	254
0	255	255	241	254	235	255	243	254	238	254
255	0	255	96	255	112	253	89	255	77	255
0	0	255	21	255	30	254	17	255	12	254
255	255	0	255	21	254	30	255	17	254	12
0	255	0	241	0	235	41	243	0	238	0
255	0	0	96	28	112	0	89	23	77	17
0	0	0	21	21	30	30	17	17	12	12
170	0	0	65	24	77	24	60	20	52	15
85	0	0	37	21	46	29	33	18	29	13
0	170	0	161	16	158	35	163	13	159	8
0	85	0	82	20	82	31	82	16	81	11
0	0	170	21	170	30	170	17	170	12	170
0	0	85	21	86	30	88	17	86	12	86
Scaling factor			0.992052		0.982004		0.994881		0.992052	

if D93 reference illuminant[13] is used as the nominal white instead of D65,

if the gamma value is 1.8 instead of 2.2.

This gives a figure of merit of the replacement colourmaps. It shows that significant discrepancies could arise from changing either the primaries or the video transfer function; the former should not occur, since all ITU members have agreed on a unique recommendation that is gaining acceptance for CRT based applications,[8] but the latter is easily encountered in practice. However, changing the nominal white would have minimal effect on the palette.

Simplification of the Reduction Scheme

We propose replacement colourmaps for simulating protanopic vision and deuteranopic vision, which are the most severe cases of colour deficiency. Anomalous trichromatic observers do not confuse all colours of a colour confusion line, so they would be able to discriminate the colours that are indiscriminable by a dichromatic observer of the same type.

In the absence of an officially recommended set of cone fundamentals, either those of Smith and Pokorny[9] or those of Stockman, MacLeod, and Johnson[14] are currently employed in research. We assume that both come close to the average normal observer.

Strictly, the Smith and Pokorny transformation applies to modified tristimulus values obtained from the spectral power distribution of the stimulus and the colour-matching functions modified by Judd and Vos.[11] Because the ITU video display standard does not specify the primaries in terms of spectral power distribution but in terms of CIE 1931 chromaticity coordinates, we have extended the application of the Vos formula to the chromaticity coordinates of the primaries and nominal white. In order to evaluate the error introduced by this procedure, we have compared the results with those obtained by a rigorous calculation for an actual video display.

First, we have measured the (x, y) chromaticity coordi-

TABLE IV. Comparison between measurements and calculations for an actual CRT video display (IIYAMA MF-8617A 1995). Columns 2–4: (x, y) chromaticity coordinates and (Y) luminance (normalized to 100) in the CIE 1931 colorimetric system. Column 5–7: (x', y') chromaticity coordinates and (Y_m) luminance obtained using the Judd–Vos modified colour-matching functions. Column 8–9: (x', y') chromaticity coordinates obtained applying the Vos formula to (x, y) CIE 1931 chromaticity coordinates.

	Measurements: x	y	Y	Results obtained using Vos cmfs: x'	y'	Y_m	$x'\ y'$ converted from $x\ y$: x'	y'
RED	0.6254	0.3370	24.4929	0.6242	0.3406	24.5046	0.6241	0.3396
GREEN	0.2818	0.6006	67.8719	0.2838	0.6052	67.8903	0.2837	0.6017
BLUE	0.1500	0.0646	7.6353	0.1545	0.0727	8.1588	0.1530	0.0727
WHITE	0.3127	0.3290	100	0.3175	0.3394	100.55	0.3157	0.3345

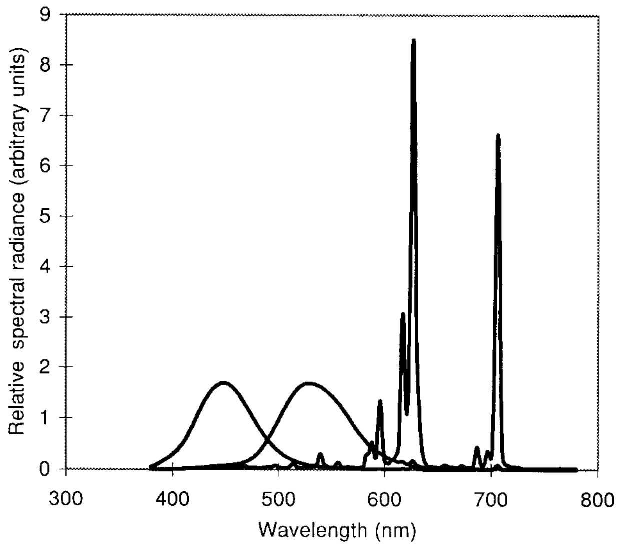

FIG. 5. Relative spectral power distribution of the primaries of a CRT video display (IIYAMA MF-8617A 1995) adjusted to give a metamer of D65 as the nominal white.

nates of four CRT video displays and selected the one (IIYAMA MF-8617A 1995) that best conformed to the ITU standard (Table IV). Then we have measured the spectral power distribution of its primaries every 5 nm using a calibrated telespectrophotometer (Minolta CS-1000), and we have computed the absolute spectral power distribution (Fig. 5) and the (Y) luminance of the primaries that gives a metamer of D65 as the nominal white (Table IV). Knowing the absolute spectral power distribution of the primaries, it is possible to calculate the (X', Y', Z') modified tristimulus values and the (x', y') modified chromaticity coordinates of the primaries and the white for the Judd–Vos modified colorimetric observer, using the modified colour-matching functions given by Vos.[11] We have also computed the result of applying the Vos modification[11] (step 3 of the procedure described in the methods section) to the CIE 1931 (x, y) chromaticity coordinates of the measured video display. It appears that the values differ only on the third digit. Then we have computed the full palette for this actual monitor using the procedure described in the Methods section, and the full palette for the same monitor starting the transformation with the (x', y') modified chromaticity coordinates directly obtained from the absolute spectral power distribution of the primaries and the white. For every element of the 256 colour palette, the difference in DAC-value is never larger than one (Table V). This leads us to conclude that, for our particular application, extending the Vos formula to the primaries and the white of a CRT video display is satisfactory.

We are aware that several sources of inter-observer variability[15] such as lens pigmentation, macular pigmentation, cone effective optical density, and spectral sensitivity of the visual photopigments are also ignored in this simplified scheme for illustrating the losses of dichromatic colour vision.

Finally, by adopting the diagonal plane on which to project the confused colours, we slightly distort the colour appearance of the simulated dichromatic image, compared to our previous simulation. In terms of dominant wavelengths, this corresponds to a shift from 475 to 464 nm for the blue anchor wavelength, and to a shift from 575 to 571 nm for the yellow anchor wavelength.

CONCLUSION

In conclusion, replacing a normal palette by a reduced palette allows the designer to check the readability of colour information by dichromatic observers in any displayed image. Although an accurate simulation of dichromatic vision would require a careful calibration of the video display, our colourmaps provide an immediate and efficient warning of possible losses of readability by

TABLE V. DAC values, $I_pJ_pK_p$, for the protan replacement colourmap computed for the actual CRT video display (IIYAMA MF-8617A 1995), obtained using the Judd–Vos modified colour-matching functions with the spectral distribution of the primaries, or obtained applying the Vos formula to (x, y) CIE 1931 chromaticity coordinates.

DAC values of the original colourmap			DAC values obtained using Vos cmfs		DAC values obtained applying Vos formula	
I	J	K	I_p, J_p	K_p	I'_p, J'_p	K'_p
255	255	255	254	254	254	254
0	255	255	238	254	238	254
255	0	255	105	255	106	255
0	0	255	23	254	23	254
255	255	0	254	23	254	23
0	255	0	238	0	238	0
255	0	0	105	32	106	32
0	0	0	23	23	23	23
170	0	0	72	27	72	27
85	0	0	40	24	41	24
0	170	0	159	18	159	18
0	85	0	81	22	81	22
0	0	170	23	170	23	170
0	0	85	23	87	23	87
	Scaling factor		0.989729		0.989725	

colour-deficients. This tool could be used to check the legibility of transport colour signals, control panels, and information displays.

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