

## A COLOR-CODE DESIGN TOOL

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The FAA is developing a standard set of colors for use in air traffic control (ATC) displays. The set will be defined in terms of CIE  $Y_u'v'$  values, corresponding sRGB values, and color names. A significant complication is that the ATC controller population includes people who have color-vision deficiencies (CVDs). We have written a software tool to assist the FAA in selecting and testing a suitable set of colors. It accepts a set of  $Y_u'v'$  values as input and: (1) Draws graphics and calculates color-related figures of merit to predict whether the set will be acceptable for color-normal and CVD users; (2) Flags colors and pairings that violate criteria; and (3) Allows the designer to adjust the colors and see the results immediately. The tool should be useful for designing other color sets, also.

The Federal Aviation Administration (FAA) is conducting experiments to develop a standard set of colors for use in air traffic control (ATC) displays in terminal approach, en route, and oceanic ATC systems. The colors must be discriminable, recognizable, and legible for ATC controllers, including those with color-vision deficiencies (CVDs). The FAA intends to incorporate these colors in the ATC displays within new and modified ATC systems.

We have written a Microsoft Excel-based<sup>1</sup> tool (named *Palette Designer*) to assist with selecting a suitable set of display colors. *Palette Designer* (PD) allows users to input a candidate set of colors, expressed as CIE luminances and chromaticity coordinates. It then draws graphics and calculates figures of merit, derived from human factors research on color perception and embodied in human factors standards regarding the use of color on electronic displays.

### **Palette Designer's Main Table**

Figure 1 shows PD's main table. The first four columns allow the user to input a color name, CIE 1976  $u'v'$  chromaticity coordinates, and luminance for as many as 25 colors. (Excel's *Hide Rows* function has been used in the figures for the 11-color set shown herein for illustration.) Luminance is expressed as a percentage relative to the display's peak white luminance, i.e., the luminance produced when the red (R), green (G), and blue (B) tuple {255, 255, 255} is loaded to drive the computer's graphics card.

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<sup>1</sup> *Palette Designer* uses features unique to Excel 2010 for Windows presently. We are eliminating them so it can be used with Excel 2011 for OSX also. It was developed using federal funds, so it is available to the public with unlimited distribution. We are developing a website to distribute it freely. Meanwhile, please contact [davepost@woh.rr.com](mailto:davepost@woh.rr.com) to obtain copies.

Color name	u'	v'	%Y	sR	sG	sB	Pred R	Pred G	Pred B
White	0.1978	0.4683	100.00	255	255	255	251	237	243
Mustard	0.2092	0.5350	57.60	213	203	90	234	198	100
Rose	0.2500	0.4100	40.64	232	138	224	242	147	223
Dark Green	0.1460	0.5560	42.00	96	196	34	136	193	38
Gray	0.1978	0.4683	22.50	130	130	130	162	139	145
Blue	0.1570	0.3675	35.10	67	164	255	102	170	242
Orange	0.3276	0.5308	31.66	244	115	42	246	120	57
Red	0.4100	0.4800	20.90	245	22	95	246	26	111
Green	0.1350	0.5300	73.00	71	253	134	114	235	149
Yellow	0.1770	0.5470	85.00	203	255	79	228	236	89
Magenta	0.2750	0.3100	24.00	218	45	254	234	65	242
Background	0.1978	0.4683	0.01	0	0	0	0	0	0
Ambient from screen	0.1978	0.4683	0.38						
Stimulus size (arcmin)	20.0								

Figure 1. Palette Designer’s main table. User input goes in the green cells.

Toward the bottom of the main table, the user inputs the background color’s luminance and chromaticity coordinates. For the case shown, that color is black, i.e., the color produced for  $RGB = \{0, 0, 0\}$ , which produces measurably non-zero output typically because most contemporary displays (i.e., LCDs) emit light even for  $\{0, 0, 0\}$ . If the viewing environment includes illumination reflecting off the display screen (as in the example shown here), the user inputs the resulting luminance and chromaticity coordinates produced on the screen. Finally, the user inputs the size of the alphanumeric, symbology, or other stimuli that will be color coded.

The next three columns show the colors’ corresponding standard RGB (sRGB) values, which PD calculates according to IEC (1999). The last three columns show the RGB values that should reproduce the colors accurately on a secondary display for which a characterization file has been specified in another area of the spreadsheet (not shown). The file contains measurements of the luminances and chromaticity coordinates produced by the secondary display’s R, G, and B channels for RGB values ranging from 0 to 255. The calculated RGB values are obtained using the PLVC method described in Post and Calhoun (1989, 2000). If a secondary display is connected to the computer that is running PD and a characterization file is provided, a color-swath chart will be displayed there using the calculated RGB values so the user can see a colorimetrically accurate rendition of the current color set.

### Color-Swath Chart (Recognizability)

PD always displays the current color set in a swath chart on the main display screen using the calculated sRGB values, as shown in Figure 2. The colorimetric accuracy of the colors shown there depends on how well the main display conforms to the IEC (1999) sRGB standard. Ordinarily, the rendition will be at least approximately accurate. The swatches include character strings so the user can judge legibility, also. Those strings, including their font and size, are user-specified in another area of the spreadsheet (not shown).

### CIELUV Color-Difference Table (Search Time)

As shown in Figure 3, PD computes color differences between all pairings of the current color set, taking into account the user-specified ambient illumination and symbol size, using Equation 1, as presented by Carter (1989):

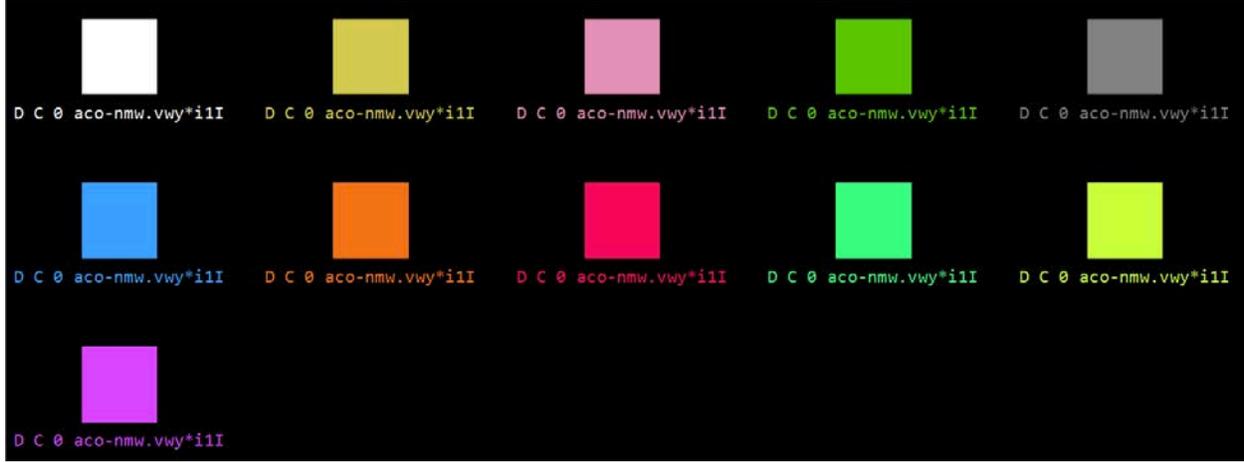


Figure 2. Color-swatch chart.

$\Delta E^*_{uv-sc} w/ambient$	White	Mustard	Rose	Dark Green	Gray	Blue	Orange	Red	Green	Yellow
Mustard	13.94									
Rose	21.67	10.99								
Dark Green	21.69	12.05	17.54							
Gray	30.20	17.94	13.04	14.64						
Blue	24.19	16.35	15.12	11.81	11.14					
Orange	30.85	20.03	12.02	27.12	19.49	26.08				
Red	40.12	29.71	20.39	35.67	25.09	32.85	10.01			
Green	15.33	15.38	24.67	12.44	26.12	19.40	35.01	44.40		
Yellow	8.73	11.09	21.60	15.82	27.24	22.32	30.64	40.43	9.05	
Magenta	29.09	19.37	9.15	22.26	11.70	15.26	14.50	18.62	30.85	29.52

Figure 3. CIELUV color-difference table with values < criterion (28) highlighted.

$$\Delta E^*_{uv-sc} = \left( (K_L^* * \Delta L^*)^2 + (K_u^* * \Delta u^*)^2 + (K_v^* * \Delta v^*)^2 \right)^{0.5}, \quad (1)$$

where  $\Delta E^*_{uv-sc}$  is the size-corrected color difference, the coefficients  $K_L^*$ ,  $K_u^*$ , and  $K_v^*$  are computed as shown below, and  $\Delta L^*$ ,  $\Delta u^*$ , and  $\Delta v^*$  are computed in accordance with the conventions of the CIE 1976 ( $L^*u^*v^*$ ) color space (CIELUV) described in CIE (2004).

$$K_L^* = 1.0366 - e^{0.15263 - 0.05766A} \quad \text{for } 0 < A < 60, \quad (2)$$

$$K_u^* = 0.008991A - 0.0065 \quad \text{for } 0 < A \leq 32, \quad (3)$$

$$= 0.0257A - 0.5403 \quad \text{for } 32 < A < 60, \quad (4)$$

$$K_v^* = 0.005446A - 0.042 \quad \text{for } 0 < A \leq 32, \text{ and} \quad (5)$$

$$= 0.031A - 0.8594 \quad \text{for } 32 < A < 60, \quad (6)$$

where  $A$  is the visual angle subtended by the stimulus in arcmin. For  $A \geq 60$  arcmin,  $K_L^* = K_u^* = K_v^* = 1$ .

Carter (1989) estimated that a difference  $\geq 28$  is needed to yield asymptotic search times for color-coded stimuli; therefore, values  $< 28$  are highlighted in the table to alert the user. It can be seen that many pairs in Figure 3 fail the criterion, but this outcome predicts only that search times will be suboptimal – not that they will be unacceptable, necessarily. Nonetheless, the user

should try adjusting the nearest pairs to increase their Equation 1 color differences. Ideally, experimental testing should follow, to ensure that the search times are acceptable.

It is worth noting that the use of Equations 1-6 and a criterion of 28 is different and more complex than one sees in human factors color standards. A simpler equation and criterion of 20, also from Carter (1989), is seen typically. (Sometimes, the simpler equation and a criterion of 40, based on Carter and Carter, 1981, is seen instead.) We suspect the choice of the simpler equation that Carter (1989) showed to yield a substantially inferior  $R^2$  has been motivated by a bias toward ease of use, which underscores one of PD's advantages: It eliminates the need for users to perform or even understand more complex and accurate colorimetric calculations.

### CIELAB Color-Difference Table (Discriminability)

As shown in Figure 4, PD also computes color differences between all pairings of the current color set plus the background color, taking into account the user-specified ambient illumination, using the equation:

$$\Delta E^*_{ab} = ( (\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2 )^{0.5}, \quad (7)$$

where  $\Delta E^*_{ab}$  is the color difference and  $\Delta L^*$ ,  $\Delta a^*$ , and  $\Delta b^*$  are computed in accordance with the conventions of the CIE 1976 ( $L^*a^*b^*$ ) color space (CIELAB) described in CIE (2004).

PD's criterion value in this case is 9.9, which is the maximum that Brainard (2003, p. 203) obtained after computing 95% confidence intervals for the lengths of the major and minor axes of MacAdam's (1942) ellipses in CIELAB. The 9.9 criterion is taken here to be a conservative estimate of the minimum acceptable color difference among spatially adjacent colors that must be discriminable. All values in Figure 4 meet the criterion; hence, none are highlighted.

$\Delta E^*_{ab}$ w/ambient	White	Mustard	Rose	Dark Green	Gray	Blue	Orange	Red	Green	Yellow	Magenta
Mustard	60.12										
Rose	46.71	78.40									
Dark Green	88.72	45.60	114.13								
Gray	45.14	62.45	38.96	85.39							
Blue	62.84	110.39	57.23	129.39	54.04						
Orange	83.15	58.76	67.12	100.35	75.06	120.37					
Red	93.06	98.95	53.39	140.17	80.43	106.73	51.20				
Green	82.90	60.70	117.72	30.56	88.72	121.87	118.73	153.14			
Yellow	84.53	37.21	113.16	28.91	92.91	136.49	92.19	135.70	42.62		
Magenta	105.93	147.66	69.27	181.49	98.16	75.45	124.83	82.79	182.06	182.09	
Background	96.49	95.81	75.61	107.64	51.35	81.88	95.57	94.50	118.16	123.60	113.08

Figure 4. CIELAB color-difference table.

### Contrast-Ratio Table (Legibility)

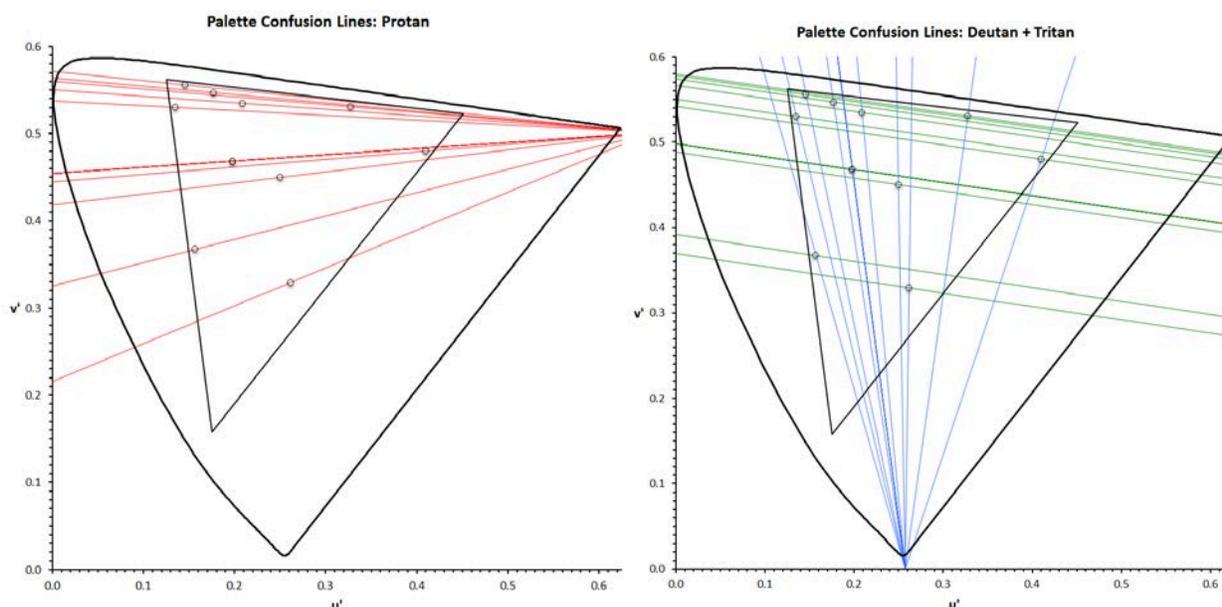
As shown in Figure 5, PD computes the luminance-contrast ratio for each color against the background color, taking into account the user-specified ambient illumination. The criterion for this case is 3:1, which is the minimum needed to ensure symbol legibility against the background according to many sources, such as ANSI-HFES-100 (2007) and MIL-HDBK-87213A (2005). All values in Figure 5 meet the criterion; hence, none are highlighted.

Contrast ratio w/ambient	White	Mustard	Rose	Dark Green	Gray	Blue	Orange	Red	Green	Yellow	Magenta
Background	257.4:1	148.7:1	105.2:1	108.7:1	58.7:1	91.0:1	82.2:1	54.6:1	188.2:1	218.9:1	72.0:1

Figure 5. Luminance contrast-ratio table.

### Protan, Deutan, and Tritan Confusion-Line Charts for CVD Viewers

As shown in Figures 6 and 7, PD draws a confusion line for each color for protanopic (red-weak), deuteranopic (green-weak), and tritanopic (blue-weak) viewers, using the copunctal points from Wyszecki and Stiles (1982, p. 464). It also shows the sRGB chromaticity gamut so users can see the colors' spacing within that gamut. The figures show that the Yellow and Orange lines are nearly colinear for protans, and the Dark Green and Orange lines are nearly colinear for deutans. These observations indicate that luminance differences must be provided between those color pairs so CVD viewers will be able to discriminate and recognize them.



Figures 6 and 7. Protan, deutan, and tritan confusion lines for the color set, plotted on the CIE 1976  $u'v'$ -chromaticity diagram with the sRGB chromaticity gamut (inset triangle) included.

### Color-Adjustment Tools

PD allows users to adjust each color's luminance and chromaticity coordinates by making changes directly in the appropriate cells of its main table or by clicking a color name and then using the computer keyboard's arrow keys to change the color's luminance or move it on the CIE 1976  $u'v'$ -chromaticity diagram. Either way, the results are reflected immediately in all the figures and tables. This interactive mechanism simplifies exploring ways to improve the discriminability, recognizability, and legibility of the colors under consideration.

### General Utility

Palette Designer aids the design of color codes by automating the calculation of important figures of merit found in human factors design standards for color use on electronic

displays and producing helpful graphical representations. Although we created the tool to facilitate development of a color palette for air traffic control displays, we believe that it could be useful for any project that involves designing color codes for electronic displays.

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## References

- ANSI-HFES-100 (2007). *Human factors engineering of computer workstations*. Santa Monica, CA: Human Factors Society.
- Brainard, D. H. (2003). Color appearance and color difference specification. In S. K. Shevell (Ed.), *The science of color* (2nd ed.). Oxford: Elsevier.
- Carter, R. C. (1989). Calculate (don't guess) the effects of symbol size on usefulness of color. In *Proceedings of the Human Factors Society 33rd Annual Meeting* (pp. 1368-1372). Santa Monica, CA: Human Factors Society.
- Carter, R. C., & Carter, E. C. (1988). Color coding for rapid location of small symbols. *Color Research and Application*, 13, 226-234.
- CIE (2004) *Colorimetry* (3<sup>rd</sup> edition). Publication 15. Vienna, Austria: Commission Internationale de l'Éclairage.
- IEC (1999). *Multimedia systems and equipment - Colour measurement and management - Part 2-1: Colour management – Default RGB colour space – sRGB* (1999). Publication 61966-2-1:1999. Geneva, Switzerland: International Electrotechnical Commission.
- MacAdam, D. L. (1942). Visual sensitivities to color differences in daylight. *Journal of the Optical Society of America*, 32, 247-274.
- MIL-HDBK-87213A (2005). *Electronically/optically generated airborne displays*. Washington, DC: US Department of Defense.
- Post, D. L., & Calhoun, C. S. (1989). An evaluation of methods for producing desired colors on CRT monitors. *Color Research and Application*, 14, 172-186.
- Post, D. L., & Calhoun, C. S. (2000). Further evaluation of methods for producing desired colors on CRT monitors. *Color Research and Application*, 25, 90-104.
- Wyszecki, G., & Stiles, W. S. (1982). *Color science* (2nd ed.). New York: Wiley.