

## Mapping: Methods & Tips

### Color Design for the Color Vision Impaired

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**Eight percent of men are affected by color vision impairment – they have difficulties distinguishing between colors and thus confuse certain colors that the majority of people see readily. Designers of maps and information graphics cannot disregard the needs of this relatively large group of media consumers. This article discusses the most common forms of color vision impairment, and introduces Color Oracle, a new software tool that assists the designer in verifying color schemes. Color Oracle filters maps and graphics in real-time and efficiently integrates with existing digital workflows. The paper also discusses color combinations and alternative visual variables for map symbology that those with color vision impairments can distinguish unambiguously. The presented techniques help the cartographer produce maps that are easy to read for those with color vision impairments and can still look good for those with normal color vision.**

#### Introduction

One in twelve men sees color differently than the rest of the population. Afflicted by a condition often inappropriately described as colorblindness, these men confuse certain colors that the majority of people are able to distinguish.<sup>1</sup> Their perception of hue, saturation and brightness varies. Color vision impairment is typically inherited due to a sex-linked recessive gene carried on the X chromosome and predominantly affects men. Eight percent of the male population may not appear as a large number, but when publishing in a mass market (e.g. for a major newspaper) the number of affected readers may reach tens of thousands. Maps with smaller circulation have fewer affected readers, but they may be critical members of the audience.

Designers, and especially cartographers, should ensure that their work is clear to the color impaired as well as to the viewer with full color vision. Such barrier-free, “universal” design is especially important when readers have very limited time to read maps and information graphics, as, for example, for the reading of evacuation plans in emergency situations. Universal design can even be required by law: In the United States, Section 508 of the Rehabilitation Act amendments to the Americans with Disabilities Act (ADA) requires disabled people receive equal or comparative access to information. Cartographers may also consider barrier-free design as part of their professional ethics, since color vision impairment is probably the most widespread physiologic impairment hampering map reading.

It is thus important for cartographers and designers of information graphics to know how the color vision impaired perceive color and what color combinations are confused. The first part of this article addresses this question by describing the most common forms of color vision impairment, and how they affect color perception. We then introduce Color Oracle, a new application for the digital simulation of color vision impairment. This software assists designers in verifying that color combinations are universally legible by filtering graphics on computer monitors in real-time. The final section provides practical tips for the selection of colors, and demonstrates how map legibility can be improved by the use of alternative visual variables and direct annotation.

#### Common types of color vision impairment

A wide range of color vision anomalies exist – some genetic and some the outcome of degenerative diseases, poisoning or physical injury. The commonly called “red-green blindness” is by far the most frequent form. It affects about 8% of all males, mainly causing difficulty when distinguishing colors emanating from the red-green portion of the visible spectrum.

Color vision is linked to the cones that respond to light entering the eye. People with full color vision perceive color with three types of cones, which are called L, M and S-cones. Each type registers light from a different portion of the spectrum. People who confuse red and green are affected by a complete lack or a dysfunction of the L and M-cones. A complete lack is called protanopia or deuteranopia. These forms of color impairment are relatively rare and can be

thought of as “pure” form of color deficiency. Dysfunctions of lesser degree are much more common. They are usually caused by a slight shift in sensitivity of one cone type towards another color hue in the light spectrum (protanomaly and deuteranomaly).

Table 1 lists the percentages of affected males by the four forms of red-green deficiency, and illustrates the perceived color spectra. The degree of impairment varies from one person to another between almost full color vision and “pure” protanopia and deuteranopia. Indeed, the measurable variation among individuals with “normal” vision is so large that the boundary between normal and color impaired vision is arbitrary. The spectra for protanomaly and deuteranomaly displayed in Table 1 (stared) are therefore very speculative and only provide a rough guess of how affected people could perceive color.

	Cones	Affected men	Estimated perceived color spectrum
Protanopia	L-cones absent	1%	
Protanomaly	L-cones abnormal	1%	
Deuteranopia	M-cones absent	1%	
Deuteranomaly	M-cones abnormal	5%	
Full color vision		92%	

Table 1. The four forms of red-green confusion. The protanopia and deuteranopia spectra are very similar, the protanomaly and deuteranomaly spectra are rough estimations (numbers are rounded, after Birch, 1993).

Women are much less likely to be affected by red-green confusing vision than men with only 0.4% women impaired (Birch, 1993). Other rare forms of color vision impairment exist, which affect less than approximately 0.3% of all men and women. Tritanopia is a very rare lack of S-cones. The similarly rare monochromatic vision—true color blindness as the general public thinks of it—impedes any discrimination based on color (see Birch 1993 for more information about the different forms of color vision impairment).

The consequence of color vision impairment is that afflicted people are slower and considerably less successful in search tasks, when color is the primary attribute of the target object, or if color is used to organize visual displays (Cole, 2004). Seeking to address this problem, section 508 of the U.S. Rehabilitation Act states:

“Color coding shall not be used as the only means of conveying information, indicating an action, prompting a response, or distinguishing a visual element.” 1194.25(g).

While map reading by the color impaired has not been studied extensively, it was found that readers with impaired color vision make errors naming the boundary lines on multi-colored terrain maps (Kuyk et al., 1987). Another study confirmed that only a small percentage of color-impaired readers could name the colors of a weather radar display without error (Mertens and Milburn, 1996). A low level of illumination further impedes successful reading of color-coded information. Investigations have shown that under reduced illumination, subjects with impaired color vision make considerable more errors when identifying color (for more details see Cole, 2004).

A variety of assistive computer software can help the color impaired to more easily read color-coded information on screen. Examples include programs such as eyePilot (<http://colorhelper.com/>) or Visolve (<http://www.ryobi-sol.co.jp/visolve/en/>). These programs do not allow color impaired individuals to see the full range of colors. Instead, they increase the contrast between confusing colors. While this assistive technology can be extremely useful to the color-impaired, it must be considered as a last resort. For printed “hard copy” graphics, these digital tools are not convenient. Instead, maps and information graphics should be designed for universal legibility.

Specialized software helps the designer select universally legible color combinations, for example ColorBrewer, a popular online tool that suggests color schemes (Harrower and Brewer, 2003; [www.colorbrewer.org](http://www.colorbrewer.org)). Color Oracle and other simulators of color-impaired vision are complementary tools that help verifying the legibility of a design.

### Color Oracle

Color Oracle software allows the designer to see colors on screen as people with color vision impairments see them. It is permanently accessible via the Mac OS X menu bar or the Windows system tray. Color Oracle works by filtering whatever appears on the computer monitor, therefore its benefits are universally available to all applications. The Color Oracle user triggers a simulation by selecting the type of color impairment in a drop down menu (Figure 1). Color Oracle then takes a snapshot image of the pixel values currently shown on the monitor, and filters the pixels accordingly. The filtered image is displayed afterward in a borderless full-screen window floating above all other windows—the user sees the monitor colors switching to color impaired vision, without noticing the additional window. The window disappears when the user presses any key or clicks any mouse button. The designer can toggle between normal color vision and three varieties of simulated impaired vision to identify problematic color combinations. This approach

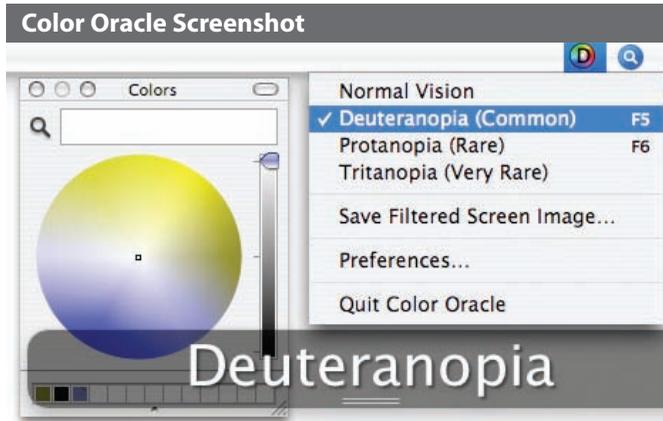


Figure 1. Screenshot of Color Oracle on Mac OS X simulating deuteranopia on a color picker wheel.

does not interfere with the user’s usual workflow and works with any graphics or mapping software.

Color Oracle simulates deuteranopia, protanopia, and tritanopia, which are the “pure” forms of color vision impairment. As explained in the previous section, these extreme forms, which are characterized by the complete functional absence of one type of cones, are not as common as the milder forms with partial or shifted sensitivity. These milder, intermediate forms are more difficult to simulate, since the dysfunctions vary to a high degree from person to person. It can however be assumed that if a color scheme is legible for someone with extreme color vision impairment, it will also be easily legible for those with a minor affliction.

To simulate how a color will appear to a color impaired viewer, Color Oracle uses an algorithm based on confusion lines.<sup>2</sup> Simulations by Color Oracle are accurate, except for very saturated colors, which might slightly deviate from the values that are seen by persons with “pure” forms of color vision impairment. The software was developed by the authors of this article and is freely available from <http://colororacle.cartography.ch>.

### Color as seen by the color vision impaired

The blue-yellow color table in Figure 2 contains an estimation of all colors that a red-green confusing viewer can unambiguously distinguish compared with a normal vision viewer. Other colors can only be distinguished with difficulty or not at all, especially those along the vertical red-green ramp in Figure 2. The figure shows the b-plane of the CIE Lab color space, which is similar to the colors discernable by a red-green impaired reader. The Lab b-plane can be visualized in the color picker of Adobe Photoshop by selecting the “a” button to the right of Figure 2 and entering 0 in the associated field. The number of colors that red-green confusing readers can unambiguously distinguish is rather small.

### Confusing and Easily Distinguished Colors

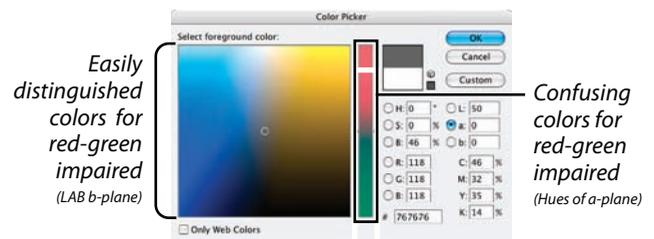


Figure 2. The Lab color mode in Photoshop can be used to explore red-green confusing vision.

Besides the well-known red-green combination, they also confuse other color pairs, as illustrated by Figure 3. Swatches grouped at the left show colors that readers with normal color vision can easily distinguish. The right side shows how red-green impaired readers confuse these colors. Dark green, brown, orange and dark red in the first row appear as almost indistinguishable olive-green tones to the red-green impaired. The second row contains less saturated blue, turquoise and purple, which are all seen as undistinguishable pale violet-blue. The saturated purple and various blue tones of the third row manifest as almost identical bluish tones. Cartographers should be wary of pairing these colors, especially for diverging quantitative color schemes.

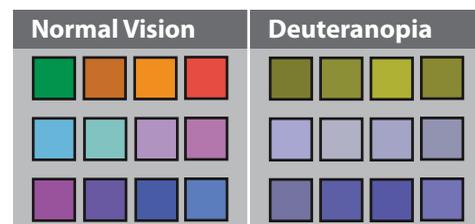


Figure 3. Colors as they appear to readers with normal vision and deuteranopia.

For example, the map in Figure 4 visualizes the approval and rejection of a ballot with a diverging red-green scheme (top left). Shades of red and green appear as undistinguishable shades of olive-green to a reader with deuteranopia (top right). Because the brightness varies between classes, the intensity of the voters’ opinion can be understood, but not the type of opinion (approval or rejection). The alternative purple-green color scheme is also legible by the red-green impaired reader (bottom row). The ColorBrewer online tool can help choose other, universally accessible color schemes.

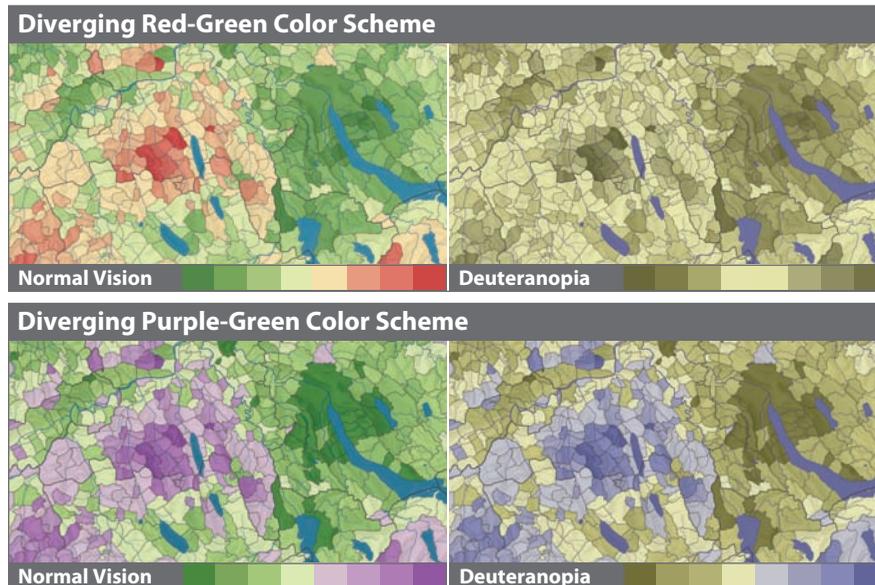


Figure 4. Color schemes on a choroplethic map of voting results. Readers with deuteranopia cannot interpret the red-green scheme of the top row. The purple-green scheme in the bottom row is legible by everyone. The diverging color ramps are depicted below the maps. (©Atlas of Switzerland 2, 2004).

### Designing maps to accommodate the color vision impaired

Greater clarity can be brought to maps by (1) choosing unambiguous color combinations, (2) using alternative visual variables, and (3) directly annotating features. These techniques will improve maps for those with full color vision and will establish a level of distinction for those with color-impaired vision. In this section, we concentrate on red-green confusion, since it is by far the most frequent form of color vision impairment.

Maps are made under optimal illumination, but they are often read in poorly illuminated rooms, hallways, or subway stations, making it hard to tell colors apart. A strong figure-ground contrast with a clear difference in brightness and saturation, as well as a reduced number of classes in color ramps help everyone to more easily read a map under normal and poorly lighted conditions.

### Distinguishing point classes

Dot maps often use hue as the only differentiating variable between different classes of points. This hue coding can be difficult to interpret for color-impaired readers. Figure 5 illustrates how point symbols can be redesigned to increase legibility. Varying the saturation increases contrast and differentiates the dots

only slightly for red-green impaired readers (“poor” column). While shifting hue from green to blue improves legibility (“better” column), the best solution is achieved with distinguishing geometric shapes in combination with varying hue and saturation. The last column shows that color could even be discarded and the map would still be legible with differing geometric shapes. Well-designed symbols are easy for the reader to decode without consulting a legend.

### Distinguishing line classes

To minimize confusion, color-coded lines on maps can be redesigned in a manner similar to color-coded dots (Figure 6). Changes to line width must be applied with care, however, since different stroke widths imply varying quantities (“poor” column). Directly annotating the lines with labels is a better solution that clarifies ambiguous colors and reduces the need to reference a legend. Figure 7 shows an example of a diagrammatic transportation map that uses labels for metro lines and stations. Readers can follow the line to its label at the route terminus to discern routes directly on the map, without relying on a color-coded legend.

**Point Features**

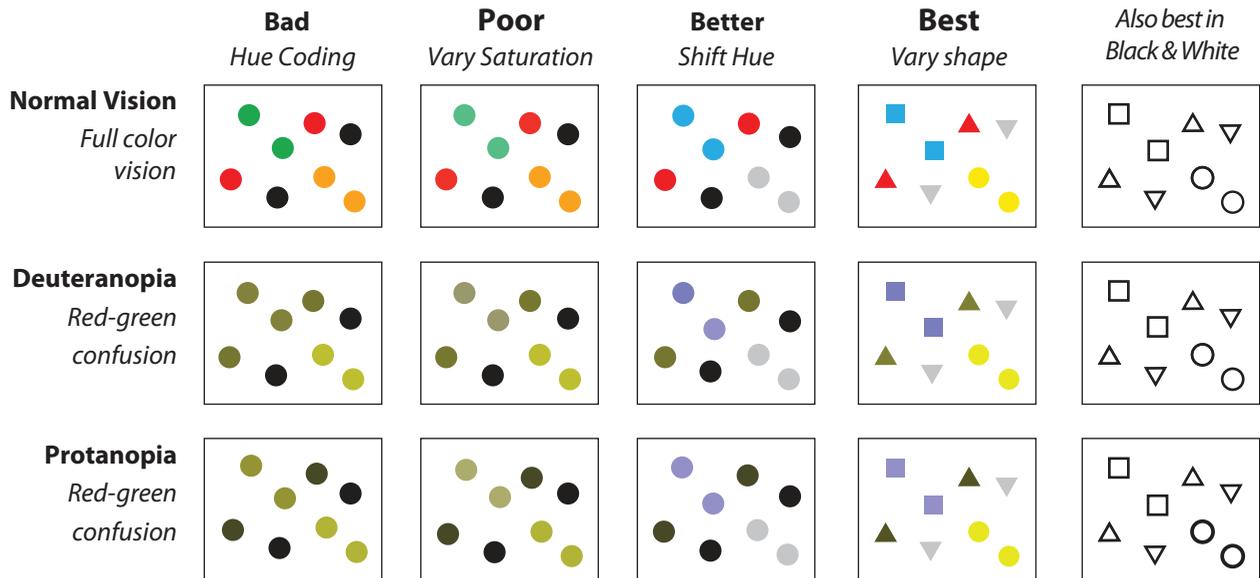


Figure 5. Point classes typical of a dot map distinguished by saturation, hue and shape.

**Line Features**

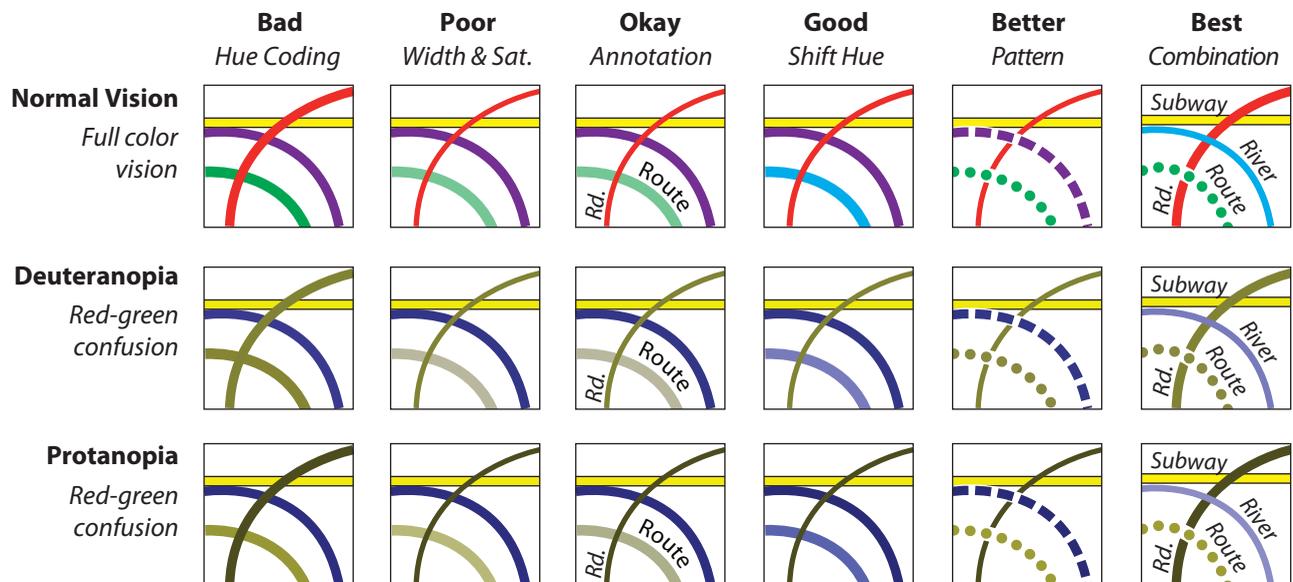


Figure 6. Line classes distinguished by width and saturation, annotation, hue and line pattern.

Altering color hue is another way to improve legibility ("better" column in Figure 6). A combination of modified hue and saturation with varying line patterns and annotations is our preferred solution, because it is legible to everyone ("best" column). While line patterns (dash, dot, etc.) can imply unwanted qualitative or quantitative meaning or create undesir-

able visual noise, for complex maps with more than a handful of line classes, texture can become essential.

**Distinguishing area classes**

Qualitative mapping can combine problem color hues as long as they are differentiated by saturation and



Figure 7. Annotation of metro lines and stations in the transportation diagram of Madrid.

value (dark red, bright green). The use of overlay hatching can sometimes avoid the use of problematic color combinations in choropleth maps.

For continuous tone raster data where colors merge into one another, scientists often apply spectral rainbow color ramps, which typically include red, orange, yellow, green, blue and purple. Brewer (1997) found

that many readers prefer such spectral color schemes, and that they are also easy to read and interpret. This finding challenges the opinion of many cartographers, who advise against the use of spectral schemes for ordered data. To accommodate red-green impaired readers, Brewer makes the following suggestions: (1) Vary lightness on the red-orange-yellow end of the rainbow. (2) Omit yellow-green to avoid confusion with orange. (3) For bipolar data, omit green and use a scheme with red, orange, yellow, light blue and dark blue; and align the yellow-blue transition with the pivot point of the diverging data range.

The precipitation map in the first row of Figure 8, for example, shows low quantities of rainfall in red, and intermediate values in green. Hence, low and intermediate values appear identical for readers with deuteranopia. The map in the second row uses an alternative spectral ramp that omits yellow-green, uses a darker red, and places the transition between yellow and blue at the mean of all values. To bring further clarity to the map, selected high and low values could be labeled when the map is printed. For a digital map, the user could query values by hovering the mouse over map locations.

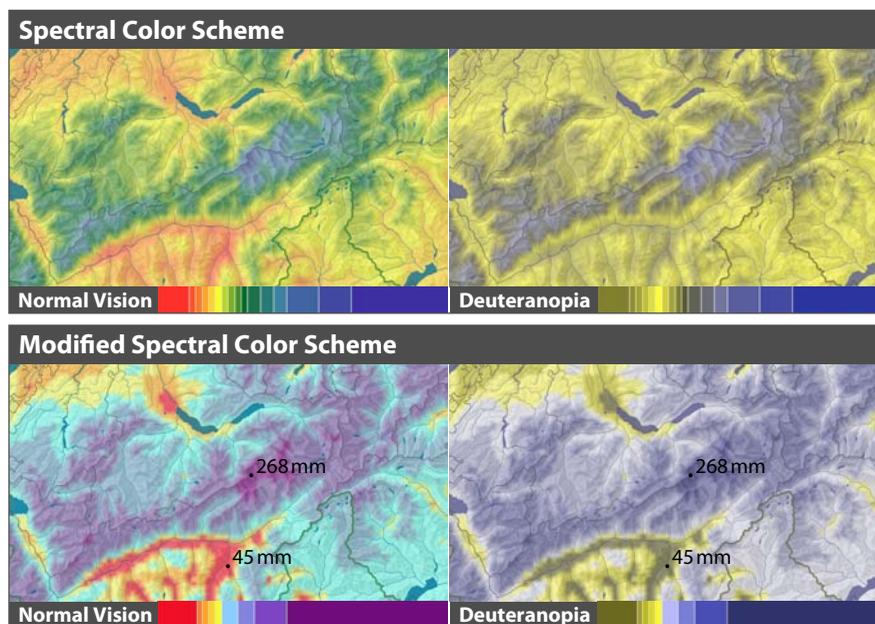


Figure 8. Spectral color schemes for precipitation maps with rainbow colors (top row) and with an improved spectral scheme (bottom row). Color ramps are depicted below the maps. (Mean monthly precipitation in January, ©Atlas of Switzerland 2, 2004).

## Conclusion

Color impaired vision affects a significant portion of the population and therefore must be taken into account by the cartographer. Color Oracle provides a convenient method to verify that colors on a map are legible to everyone. Indeed, we have discovered many problematic color combinations in our daily mapmaking work thanks to the help of Color Oracle. Adjusting color schemes is not always simple and forces the cartographer to reassess well-established conventions—for example, red-green color schemes for voting maps or rainbow color ramps for precipitation maps.

When adjusting a color scheme, the cartographer has to find a balance: On one side, the 8 percent of men who are color impaired have the right of equal access to information. On the other side, the 96 percent of the population with normal vision has the right for pleasant maps that are easy to read. It is the cartographer's responsibility to adjust colors where judged appropriate.

To avoid problematic color combinations, the cartographer should use colors with strong contrast and supplemental visual variables, such as shape, size, and pattern variations to allow all readers to discern and directly interpret a symbol without consulting a legend. Additional techniques include simplification of the map design and annotating the map directly where the reader might be confused.

Interactive digital maps can further support color impaired readers by providing tooltips or labels that are displayed on-demand. Digital environments should additionally allow the user to customize color schemes to suite their needs, and provide methods to query individual values.

Color Oracle provides a convenient tool for seeing maps the same way that color impaired readers do. It is now an integral part of our workflow and we hope you also find it valuable for designing maps that are universally accessible to all.

## Notes

1. Anomalous color vision is commonly called "color-blindness". This term, however, is not appropriate because it erroneously suggests that affected subjects cannot see colors. This article generally uses "color vision impairment", as suggested by Olson and Brewer (1997).

2. For more information about the algorithm, see Brettel et al. (1997) and Vienot et al. (1999). Meyer and Greenberg (1988) propose a related method. Fulton (2005) suggests that the confusion lines, which are the base for this algorithm, should be improved, especially for saturated colors.

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