Applications of Color in Design for Color-Deficient Users

By Alex Chaparro & Maria Chaparro

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olor represents a powerful tool for conveying information and leverages both the sensitivity of the human visual system to color (Chaparro, Stromeyer, Huang, Kronauer, & Eskew, 1993) and the rich and complex set of learned associations. Nevertheless, using color to encode information poses a number of challenges, including that (a) it lacks an ordered perceptual sequence, limiting its applicability when coding ordered data (Ware, 2013); (b) pseudocolor coding schemes, such as the rainbow-colored maps used to depict weather, terrain, and other information, can obscure data and lead to misinterpretation (Borland & Taylor, 2007; Rogowitz & Treinish, 1998); and (c) approximately 8% of men and 0.5% of women are color vision deficient (abbreviated CVD hereafter). CVD users do not experience the full array of hues seen by people with normal color vision and consequently face difficulty when colors they cannot discriminate between are used to encode information. This latter issue is the focus of this article.

PREVALENCE AND MISCONCEPTIONS OF COLOR DEFICIENCY

Color vision deficiency presents an accessibility issue, given the ubiquitous use of color in the design of tools and environments. The Americans With Disabilities Act (ADA) acknowledges that the needs of CVD users are not widely reflected in these tools and environments. The ADA states, “Products must provide at least one mode that allows access to all functionality without relying on users’ perception of color.” Additionally, “Color must not be used as the only visual means of conveying information, indicating an action, prompting a response, or distinguishing a visual element” (United States Access Board, 2010). Designs that accommodate CVD users enable them to perform as proficiently as other users. Despite federal regulations addressing universal accessibility (Lazar & Hochheiser, 2013), these challenges persist.

Surveys and anecdotal reports of CVD users document the daily challenges they confront when interacting with environments and technology that most people take for granted. Reports of difficulty include discriminating between color-coded electronic cables and highlighted text on displays, such as those used in airports designating gate and flight information (Dutton, 2014). For example, CVD users of a Google smartphone application that provides information on traffic congestion complained they could not distinguish between the red and green hues used to code traffic speed (“Google Maps Help,” 2014). A software update addressed this issue by employing a darker red to represent heavy traffic, which enabled CVD users to discriminate speed using a redundant brightness cue (Schwartz, 2006).

Recently, CVD American football aficionados cited difficulty following the flow of a game because they could not perceptually segregate players from the two teams who wore monochromatic red and green uniforms (Karmelek, 2016). Finally, an administrative specialist working with one of the authors (AC) was receiving training on a new software application that used a red or green color banner to indicate whether the information entered on the page was processed correctly. However, the assistant, who was CVD, could not discriminate between the red- and green-colored banners. These examples illustrate the importance of color vision in
modern society, in which colored displays and print material have become the norm. This advancement has the potential of becoming a barrier to the CVD rather than an aid.

The failure of tools or environments to support this user population may reflect common misconceptions about color deficiency. Designers and human factors specialists may assume accommodations are unnecessary because CVD users are restricted from employment in certain socially critical domains, such as medicine, aviation, or the military; that color deficiency is rare and consequently few users are inconvenienced; or that designing for CVD users is impractical. We aim to provide evidence that each of these assumptions is incorrect.

Color vision deficiency does not preclude individuals from employment in socially critical occupations such as medicine (Spalding, 1997, 1999) and aviation. In many cases, screening for color deficiency may not be required; and if it is required, individuals may apply for a waiver to perform the task (Cardosi & Hannon, 1999), as is the case for CVD air traffic controllers (“Guide for Aviation Medical Examiners,” 2016). A 2006 review of Federal Aviation Administration (FAA) records showed that 152 CVD air traffic controllers were employed by the FAA (Xing & Schroeder, 2006). Similarly, there are practicing CVD medical professionals (Spalding, 1997, 1999). CVD doctors report difficulty seeing redness associated with cyanosis or jaundice, or stains commonly used in histology or bacteriology (Cole 2007; Spalding, 1997, 1999). Their difficulties likely also extend to color-coded information on medical charts, images on electronic displays, color-coded cables, and leads on instrumentation.

The screening requirements for color deficiency differ according to discipline, state, and country (Watson, 2014) and do not aid in the detection of color deficiency acquired later in life due to eye disease or injury. Common screening tools, such as the Ishihara pseudoisochromatic color plates, identify only whether an individual is CVD, not the severity of the condition (Cole, 2007) or its impact on job performance. CVD users themselves may not fully appreciate the severity of the condition or its effects (Kalmus, 1965). It is not uncommon for color deficiency to go undiagnosed; the individual may attribute his or her difficulty to a lack of knowledge or understanding (Pickford, 1972; Steward & Cole, 1989).

These facts confirm that individuals with color vision deficiency will be found in virtually every user population. Although there are few documented aviation incidents in which color vision deficiency was identified as a contributing factor (Ivan, Yates, Tredici, & Gooch, 1994; National Transportation Safety Board [NTSB], 2004), it would seem prudent for designers to consider it as an attribute of potential users.

### FREQUENCY OF COLOR DEFICIENCY

Table 1 illustrates the incidence of color deficiency in samples of people of European and non-European descent, revealing that it primarily affects men and is less common among Asian, Black, and Native American populations. Approximately 8% of, or one in every 12, men and 0.5% of women of European descent (see Table 2) are CVD. These numbers document the incidence of color vision deficiency, justifying the attention of human factors and product design experts.

| Group                        | Male | Female |
|------------------------------|------|--------|
| 1. European                  | 7.40 | 0.5    |
| 2. Asian                     | 4.17 | 0.58   |
| 3. African                   | 2.61 | 0.54   |
| 4. Australian                | 1.98 | 0.03   |
| 5. American Indian           | 1.94 | 0.63   |
| 6. South Pacific Islander    | 0.82 | —      |

Source. Sharpe, Stockman, Jägle, and Nathans (1999).

### RETINAL BASIS OF COLOR VISION

The human retina contains two classes of photoreceptors, rods and cones; the latter mediate color vision. There are three types of cones, each expressing a different type of photopigment with broad overlapping spectral sensitivity. Each of the three photopigments has a peak spectral sensitivity coinciding with the long-, medium- and short-wavelength portions of the visible spectrum; hence the recommended monikers of long-, middle- and short-wavelength cones rather than the misleading terms of red, green, and blue cones (Wolfe et al., 2006). A single cone’s response does not convey any information about hue (Rushton, 1972); hue perception requires a comparison of the response strength of two cones with different spectral sensitivity (i.e., long- and middle-wavelength cones) at a postreceptoral processing stage.

Table 2 lists the three classes of color deficiency:

(a) monochromacy, wherein the affected individual lacks two or all three of the cone photopigments;
(b) dichromacy, wherein the observer lacks one of the three cone photopigment types; and
(c) anomalous trichromacy, wherein one of the three cones expresses a photopigment with an altered spectral sensitivity.

Each of the forms of color deficiency alters color vision in different ways. The color experience of observers with normal color vision can be organized into a three-dimensional color space, such as that depicted in Figure 1, unlike the color space for dichromatic CVD observers, which is two-dimensional as a result of the loss of one of the orthogonal chromatic axes.

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Table 1. Incidence of Red-Green Color Deficiency in Different Racial Groups (in percentages)
It is estimated that observers with normal color vision can distinguish some 17,000 perceptual differences in hue in stimuli equated in luminance (Macadam, 1947) and about seven pure hues consisting of red, orange, yellow, green, cyan, blue, and violet. In addition to hue and brightness, the responses of the cones encode color saturation or purity of a color. A saturated red, such as crimson, is located near the perimeter of the color space, whereas a desaturated red, such as pink, is located near the central lightness or achromatic axis of the space. Saturated color lights or paints are desaturated by the addition of white light or paint, respectively.

The forms of color deficiency related to the short-wavelength cones (i.e., tritanopia and tritanomaly) are very rare and need not be considered in the design process. Addressing the needs of the other forms of color deficiency ensures that the vast majority of CVD users will be accommodated (Meyer & Greenberg, 1988).

Figure 2 is a computer simulation depicting how a color image might appear to observers with different forms of color vision. Observers with deuteranopia lack middle-wavelength cones, and observers with protanopia lack long-wavelength cones; those with both conditions are unable to discriminate between red and green but retain the ability to discriminate between blue and yellow hues. In the case of protanopia, the absence of the long-wavelength cones that have greater sensitivity to the long wavelengths (~650 nm to 700 nm) can cause red signal lights to appear dimmer and consequently less salient (Dain & King-Smith, 1981). Tritanopes, by contrast, lack the short-wavelength cones and retain the ability to discriminate between reds and greens but not between blues and yellows. The visual experiences of hue by rod and cone monochromats are colorless, consisting of shades of lightness varying between black and white, such as those seen in a black-and-white photograph.

Anomalous trichromats typically have less severe disturbances of color vision than dichromats and report more than two hues in the spectrum. However, assignments of colors to the spectrum can be shifted relative to those of observers with normal color vision and may require larger color differences to discriminate some hues. Individuals with extreme forms of anomalous trichromacy may show color discrimination performance on par with dichromats (Sharpe et al., 1999). One way to visualize color confusions made by dichromats is to plot the hues they confuse in the CIE (Commission Internationale d’Eclairage) color space (Wyszecki & Stiles, 1982). Each wavelength in the visible spectrum between 400 nm and 700 nm corresponds to a point defined by a set of
unique $x$- and $y$-coordinate values forming the perimeter of a "horseshoe." An illustration of this space is shown in Figure 3.

The hues of real objects or those used to represent data in a graph would fall within the perimeter of the horseshoe. The straight lines drawn through each of the CIE color spaces define hues that will appear identical to dichromatic users, assuming the colors are equated in brightness. The colors will appear different to users with normal color vision. It is important to note that the diagram shows that although protanopes and deuteranopes will confuse the often-cited red, green, and yellow hues, they will also confuse any set of colors that lie along a single line that spans the color space and intersects a unique point (not shown) outside the perimeter of the color space for each type of dichromatic vision.

Avoiding the use of red, green, and yellow does not ensure that dichromatic users will be able to discriminate the colors chosen to encode information. Rather, careful scrutiny of Figure 3 reveals that selection of hues lying on lines roughly orthogonal to the confusion lines will greatly reduce the potential for color confusions for most CVD users (Meyer & Greenberg, 1988). These colors will appear desaturated relative to colors lying closer to the perimeter of the space defined by monochromatic lights.

Monochromacy, or complete color blindness, is rare and is restricted to rod monochromats who possess a retina populated by only rod photoreceptors and cone monochromats who have a retina populated by one cone type. An account of the visual experiences of rod monochromats is provided in the book titled Island of the Colorblind by Oliver Sacks (1997). In rare cases, achromatopsia (i.e., the complete loss of color vision) may result from brain injury due to cortical trauma or cerebral infarction, which damages cortical areas associated with color processing (Yates, Diamantopoulos, & Daumann, 2001). The term color blindness is misleading, as individuals with the most common forms of color deficiency (e.g., dichromacy and anomalous trichromacy) are not truly color blind but experience either a subset of the hues experienced by color-normal observers or a shift in the appearance of hues.

Color deficiency can be acquired later in life as a result of exposure to toxic substances and co-occurring retinal or neural disorders, which increase in frequency with age (Yates et al., 2001). These changes are associated with blue-yellow color discrimination problems, which, unlike congenital forms, progressively worsen as the disease process advances. Two cases illustrate the potential consequences of such disease progression.

In 2012, a freight train crashed in Goodwell, Oklahoma, claiming the lives of three people (NTSB, 2013). The NTSB accident investigation revealed that the train engineer suffered from several eye conditions, including cataracts and
glaucoma, and had complained that he could not distinguish between the red and green signal lights. This mishap was foreshadowed by a 1996 train accident in New York City, where a train engineer failed to respond to a red signal light (NTSB, 1997). This train engineer also had visual problems caused by diabetic retinopathy, a condition that can affect the macular region of the eye, the part of the retina that supports best color vision and high acuity. (There is evidence that color-normal observers can misperceive the hue of signal lights under certain viewing conditions, such as the case of an Australian train engineer who misperceived a red warning light as appearing yellow; Wood, Atchison, & Chaparro, 2005.) These incidents illustrate the most severe and rare consequence of color deficiency and indicate areas in which design might mitigate against its recurrence.

As noted earlier, one consequence of color deficiency is reduced saliency of long-wavelength lights. Research shows that CVD observers respond more slowly to red-colored lights (Atchison, Pedersen, Dain, & Wood, 2003; Pokorny, Smith, Verriest, & Pinckers, 1979) and make more errors in identifying them (Atchison et al., 2003). Atchison et al. (2003) reported that deuteranopes and protanopes were 53% and 35% slower, respectively, in identifying a red light than were observers with normal color vision. Interestingly, data on accidents for CVD drivers are equivocal and the subject of debate (Cole, 2004; Steward & Cole, 1989). The difficulties encountered by CVD individuals highlight the ways color can be used to support behavior. Table 3 lists the four types of perceptual judgments that color supports (Cole, 2004), and examples of each are provided. Comparative uses of color involve an observer evaluating whether two colors match or not. In connotative judgments, color is assigned a specific meaning, such as danger or magnitude. In denotative applications, color is used to segregate or attract attention. Finally, color may be used to enhance aesthetics, induce an emotional response, or establish a mood. In some applications, color may serve dual purposes, as in the case of maps, in which color is employed to reduce visual clutter (a denotative application) and convey information about different roadway types (a connotative application).

REdundant coding

The informal cues relied on by the CVD offer hints of strategies that can be purposefully employed to accommodate their needs. As noted earlier, CVD drivers report using redundant cues, such as brightness and position, to identify whether the red, amber, or green traffic signal is illuminated (Steward & Cole, 1989). Anecdotal comments from CVD drivers indicate that this is not always an effective strategy, as the signal lights may be

**Daily Experiences of the Color Deficient**

Protanopes and deuteranopes cite more problems with a variety of obstacles in their professional and everyday lives than do anomalous trichromats (Steward & Cole, 1989). They report difficulty with everyday tasks, including the following:

- Color-coded illustrations in printed materials, including books, academic journals, magazines, and weather and road maps (Cole & Lian, 2006; Dutton, 2014; Wong, 2011).
- Interpreting color coding used to denote targets, urgency (O’Brien, Cole, Maddocks, & Forbes, 2002), or value (Spalding, 1999).
- Problems with colored lights, including brake lights, dashboard warning lights, signal lights at intersections (Cole, 2004; Steward & Cole, 1989), and LEDs used on equipment indicating status (Dutton, 2014).
installed horizontally to allow for greater vertical clearance, or the relative brightness of the signal lights may vary according to manufacturer, age, and/or environmental conditions.

In the case of stop and yield road signs, the text, shape, and color of the sign offer redundant cues, ensuring the transmission of information even under degraded environmental conditions when one or more of the visual codes may not be perceptible (Wickens & Hollands, 2000). Similarly, in data presentations and visualization (graphs, maps, etc.), line thickness, shape, brightness differences, color saturation, and line pattern (dashed versus solid) represent types of redundant coding that enable a reader to correctly interpret a graph despite the color codes that might be employed (Jenny & Kelso, 2007; Murphy, 2015). Thus it is not always necessary to avoid the use of red, yellow, and green hues, provided redundant codes are available.

This strategy does have limitations, and not all redundant cues are equally effective in attracting a user’s attention. For instance, text, shape, and size (Xing, 2006) are not as effective as the color red in attracting a user’s attention. Flashing or an increase in brightness may be more readily salient (Xing & Schroeder, 2006) and effective in attracting attention. To maximize the effectiveness of redundant cues requires consideration of the task and in the context in which the signal will appear.

### SOFTWARE TOOLS FOR SELECTING EFFECTIVE COLOR SCHEMES

Most human factors practitioners lack the specialized training and technical tools of color vision scientists. Nevertheless, a number of useful and often free tools are now available that developers can use to evaluate candidate color schemes to ensure their suitability for CVD and normally sighted user populations. Popular software packages, including Photoshop and Illustrator, support a proofing function called Color Universal Design (Adobe Illustrator, 2014), which simulates how a candidate image might appear to people with different types of color vision deficiency.

There are a number of online tools that Web and interface design teams can use to evaluate color schemes to ensure they are discriminable by both normally sighted and CVD observers. This need was recognized by the journal Nature (How to Submit, 2016), which encouraged authors to make figures accessible to all readers by proof-checking graphical illustrations online. Color Oracle (Jenny, 2016) is one such simulation tool, as is Vischeck (About Vischeck, 2016), which offers similar functionality, allowing users to simulate how an image or a Web page may appear to CVD users.

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**Table 3. Four Types of General Perceptual Judgments That Color Supports**

| Type               | Examples                                                                 |
|--------------------|--------------------------------------------------------------------------|
| Comparative:       | Same–different judgments: Comparative judgments requiring relative or absolute evaluations of whether two colors are identical or not, as in the case of a homeowner who must evaluate whether two paint samples match. |
| Denotative:        | Visual search: Color serves as a visually salient cue that makes visual search more efficient by capturing attention (Wolfe & Horowitz, 2004). Segmentation: Shared color can organize the visual scene. Gestalt psychologists recognized color’s effectiveness as a grouping principle serving as a basis of segregation (Koffka, 1935; Wertheimer, 1923). This perceptual property is used in the design of the Ishihara color plates for identifying color deficiency. Reducing visual clutter: Color can reduce visual clutter by providing order in graphical illustrations, such as maps, in which color is used to represent different types of roadways that might otherwise appear as a knot of spaghetti. |
| Connotative:       | Identification: The distinctive coloring of an object can facilitate identification. Colored flight deck jerseys are used on aircraft carriers to identify an individual’s trade (e.g., red: ordnance men, crash and salvage crews, explosive ordnance disposal; yellow: aircraft handling officers; green: catapult and arresting gear crews; white: squadron plane inspectors, landing signal officer). Indicating status: Colored LEDs on a printer indicate its status; traffic signal lights allow drivers to determine whether they are clear to proceed. Indicating magnitude: The color-coded heat maps indicate temperature. Revealing material properties: In nature, color can reveal differences in the material properties of objects (Katz, 1935; Mollon, 1989). For instance, the color of a berry may indicate whether it is poisonous, and the color of a banana or orange indicates whether it is ripe. |
| Aesthetic:         | Supporting aesthetic judgments: Color can be used in design to prime cultural and psychological associations that may vary depending on context. In a related fashion, color is used to convey mood (blue for depression) or serves as a metaphor, such as “green with envy.” |

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*Schroeder, 2006* and effective in attracting attention. To maximize the effectiveness of redundant cues requires consideration of the task and context in which the signal will appear.
However, users beware: With the rare exception (i.e., Vischeck), most of the online sites do not specify the algorithm used to simulate color vision deficiency, and some of the Web sites are not fully functional (i.e., Vischeck). Finally, until recently there had been no published evaluations of the accuracy of these software simulation tools (Lillo, Álvaro, & Moreira, 2014). Lillo et al. (2014) compared Vischeck, Coblis (www.color-blindness.com/coblis-color-blindness-simulator/), and a set of glasses that simulate color vision deficiency (Variantor; www.variantor.co.uk). They found that only Vischeck provided an accurate simulation of the colors seen by protanopes and deuteranopes.

Colorbrewer (Brewer, 2016) is another online resource specifically developed to assist users in the selection of color schemes for maps. This sophisticated application guides users through the selection of alternative color schemes based on the different data types (i.e., sequential, categorical, diverging) that the user may have, while also identifying whether the chosen color scheme is appropriate for CVD users. Colorbrewer illustrates how a well-designed tool can eliminate much of the trial and error of designing for normally sighted and CVD users.

Additionally, maps convey an impressive amount of information using multiple forms of information expression. A combination of modified hue and saturation with varying textures, shapes, line weight, line patterns (dots, dashes), and annotations is legible to everyone (Jenny & Kelso, 2007). These strategies for coding information can be employed in domains where regulations may not afford the designer use of extensive color palettes (i.e., aviation, military) or where certain colors (e.g., green, red, and yellow) have predefined meanings and their use is tightly controlled.

SUMMARY

In conclusion, those with color vision deficiency continue to confront challenges in everyday tasks in which color is used to encode information. These challenges persist despite the availability of tools and strategies that enable design teams to evaluate alternative color schemes to ensure they are discriminable by CVD and normally sighted users. These strategies and tools are effective only to the degree to which CVD users are recognized as an important user population that should be considered in the design and evaluation of software and hardware wherein color is strategically employed to convey information. Generally, this has not been the case and may stem from the failure to recognize the frequency of color deficiency and that CVD users are members of virtually all user populations.

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feature | Applications of Color in Design for Color-Deficient Users

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Alex Chaparro is the Carl/Rozina Cassat Professor in Aging and Director of the Regional Institute on Aging at Wichita State University. He received his PhD from Texas Tech University and completed his postdoctoral studies at Harvard University before joining Wichita State University. His interests include basic and applied research concerning aging, visual perception, driving, and aviation. He is a member of the Human Factors and Ergonomics Society and the American Gerontological Society. He can be contacted at alex.chaparro@wichita.edu.

Maria Chaparro received her BS in professional writing and technology at the University of South Florida. She is a research assistant at the Applied Psychology Research Institute at Wichita State University.