CHAPTER

Our Color Vision is Limited

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Human color perception has both strengths and limitations, many of which are relevant to user-interface design—for example:

- Our vision is optimized to detect contrasts (edges), not absolute brightness.
- Our ability to distinguish colors depends on how colors are presented.
- Some people have color blindness.
- The user's display and viewing conditions affect color perception.

To understand these qualities of human color vision, let's start with a brief description of how the human visual system processes color information from the environment.

HOW COLOR VISION WORKS

If you took introductory psychology or neurophysiology in college, you probably learned that the retina at the back of the human eye—the surface onto which the eye focuses images—has two types of light-receptor cells: rods and cones. You probably also learned that the rods detect light levels but not colors, while the cones detect colors. Finally, you probably learned that there are three types of cones—sensitive to red, green, and blue light—suggesting that our color vision is similar to video cameras and computer displays, which detect or project a wide variety of colors through combinations of red, green, and blue pixels.

What you learned in college is only partly right. People with normal vision do in fact have rods and three types of cones[1] in their retinas. The rods are sensitive to overall brightness while the three types of cones are sensitive to different frequencies of light. But that is where the truth departs from what most people learned in college, until recently.

[1] People with color blindness may have fewer than three cone types, and some women have four (Eagleman, 2012; Macdonald, 2016).

Designing with the Mind in Mind. https://doi.org/10.1016/B978-0-12-818202-4.00004-0

First, those of us who live in industrialized societies hardly use our rods at all. They function only at low levels of light. They are for getting around in poorly lighted environments—the environments our ancestors lived in until the 19th century. Today, we use our rods only when we are having dinner by candlelight, feeling our way around our dark house at night, camping outside after dark, etc. (see Chapter 5). In bright daylight and modern artificially lighted environments—where we spend most of our time—our rods provide little useful information. Most of the time, our vision is based entirely on input from our cones (Ware, 2008).

So how do our cones work? Are the three types of cones sensitive to red, green, and blue light, respectively? In fact, each type of cone is sensitive to a wider range of light frequencies than you might expect, and the sensitivity ranges of the three types overlap considerably. In addition, the overall sensitivity of the three types of cones differs greatly (see Fig. 4.1A):

- ***Low frequency***. These cones are sensitive to light over almost the entire range of visible light but are most sensitive to the middle (yellow) and low (red) frequencies.
- ***Medium frequency***. These cones respond to light ranging from the high-frequency blues through the lower middle-frequency yellows and oranges. Overall, they are less sensitive than the low-frequency cones.
- ***High frequency***. These cones are most sensitive to light at the upper end of the visible light spectrum—violets and blues—but also respond weakly to middle frequencies, such as green. These cones are much less sensitive overall than the other two types of cones and also less numerous. One result is that our eyes are much less sensitive to blues and violets than to other colors.

Compare a graph of the light sensitivity of our retinal cone cells (Fig. 4.1A) to what the graph might look like if electrical engineers had designed our retinas as a mosaic of receptors sensitive to red, green, and blue, like a camera (Fig. 4.1B).

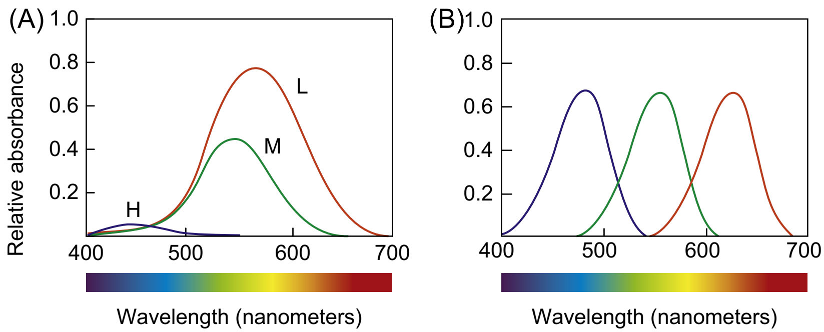

FIGURE 4.1

Sensitivity of the three types of retinal cones (A) versus artificial red, green, and blue receptors (B).

Given the odd relationships among the sensitivities of our three types of retinal cone cells, one might wonder how the brain combines the signals from the cones to allow us to see a broad range of colors.

The answer is by *subtraction*. Neurons in the visual cortex at the back of our brain subtract the signals coming over the optic nerves from the medium- and low-frequency cones, producing a red–green *difference* signal channel. Other neurons in the visual cortex subtract the signals from the high- and low-frequency cones, yielding a yellow–blue *difference* signal channel. A third group of neurons in the visual cortex *adds* the signals coming from the low- and medium-frequency cones to produce an overall luminance (or black–white) signal channel.[2] These three channels are called *color-opponent channels*.

The brain then applies additional subtractive processes to all three color-opponent channels: signals coming from a given area of the retina are effectively subtracted from similar signals coming from nearby areas of the retina.

VISION IS OPTIMIZED FOR DETECTION OF EDGES, NOT BRIGHTNESS

All this subtraction makes our visual system much more sensitive to differences in color and brightness—that is, to contrasting colors and edges—than to absolute brightness levels.

To see this, look at the inner bar in Fig. 4.2. The inner bar looks darker on the right, but in fact is one solid shade of gray. To our contrast-sensitive visual system, it looks lighter on the left and darker on the right because the outer rectangle is darker on the left and lighter on the right.

The sensitivity of our visual system to contrast, edges, and rapid changes rather than to absolute brightness level is an advantage: it helped our distant ancestors recognize a leopard in the nearby bushes as the same dangerous animal whether they saw it in bright noon sunlight or in the early morning hours of a cloudy day. Similarly, being

FIGURE 4.2

The inner gray bar looks darker on the right but in fact is all one shade of gray.

[2] The overall brightness sum omits the signal from the high-frequency (blue-violet) cones. Those cones are so insensitive that their contributions to the total would be negligible, so omitting them makes little difference.

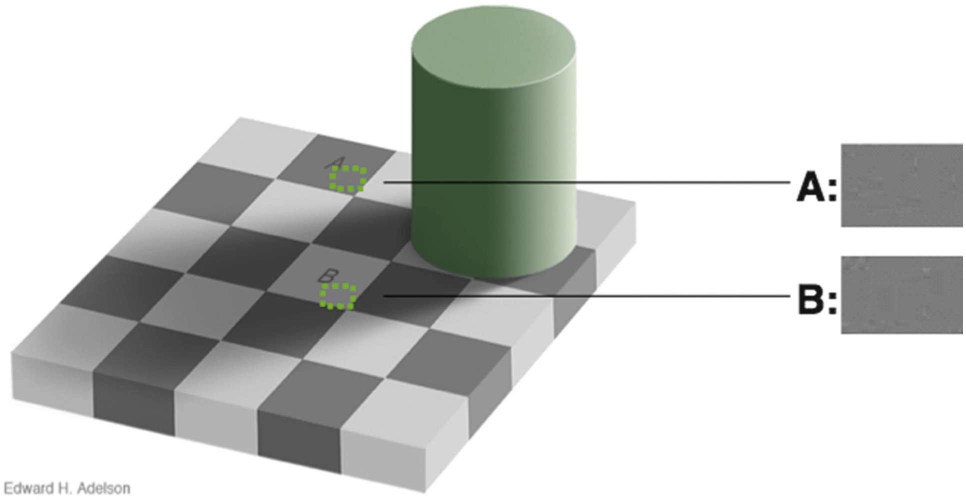

FIGURE 4.3

The squares marked A and B are the same gray. We see B as white because it is shaded from the cylinder's shadow.

sensitive to contrasting rather than absolute colors allows us to see a rose as the same red whether it is in the sun or shade.

Brain researcher Edward H. Adelson at the Massachusetts Institute of Technology developed an outstanding illustration of our visual system's insensitivity to absolute brightness and its sensitivity to contrast (see Fig. 4.3). As difficult as it may be to believe, square A on the checkerboard is exactly the same shade as square B. Square B only appears white because it is depicted as being in the cylinder's shadow.

DISCRIMINABILITY OF COLORS DEPENDS ON HOW THEY ARE PRESENTED

Even our ability to detect differences between colors is limited. Because of how our visual system works, three presentation factors affect our ability to distinguish colors from each other:

- ***Paleness***. The paler (less saturated) two colors are, the harder it is to tell them apart (see Fig. 4.4A).
- ***Color patch size***. The smaller or thinner objects are, the harder it is to distinguish their colors (see Fig. 4.4B). Text is often thin, so the exact color of text is often hard to determine.

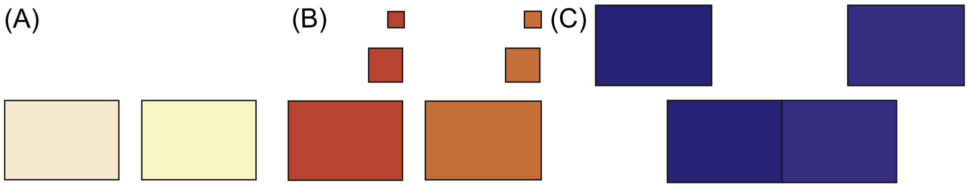

FIGURE 4.4

Factors affecting ability to distinguish colors: (A) paleness, (B) size, and (C) separation.

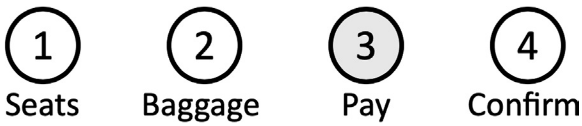

FIGURE 4.5

The current step is marked only with a pale color, making it hard for some users to see.

- ***Separation***. The more separated color patches are, the more difficult it is to distinguish their colors, especially if the separation is great enough to require eye motion between patches (see Fig. 4.4C).

Fig. 4.5 shows an example of color that is too pale to be seen by anyone on any device. It is a simulated airline website check-in step indicator. The current step is marked *only* with pale green in the circle. Maybe you can distinguish the green-filled circle from the white circles, but if you have a vision impairment or you are viewing this on a grayscale screen or a digital projector with a white-balance problem, maybe you cannot.

Small color patches are often seen in data charts and plots. Many business graphics packages produce legends on charts and plots but make the color patches in the legend very small (see Fig. 4.6). Color patches in chart legends should be large to help people distinguish the colors (see Fig. 4.7).

On websites, a common use of color is to distinguish unfollowed links from already followed ones. On some sites, the “followed” and “unfollowed” colors are too similar. The website of the Federal Reserve Bank of Minneapolis (see Fig. 4.8) has this problem. Furthermore, the two colors are shades of blue, the color range to which our eyes are least sensitive. Can you spot the two followed links?[3]

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[3] Already followed links in Fig. 4.8: Housing Units Authorized and House Price Index.

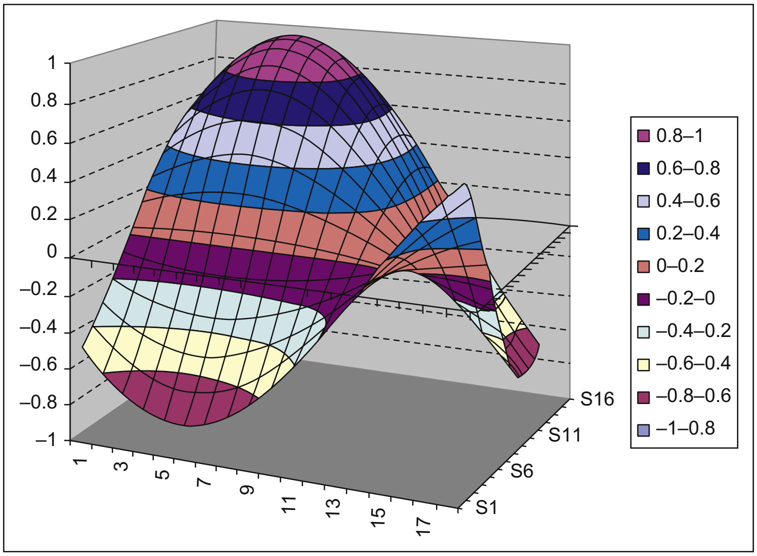

FIGURE 4.6

The tiny color patches in this chart legend are hard to distinguish.

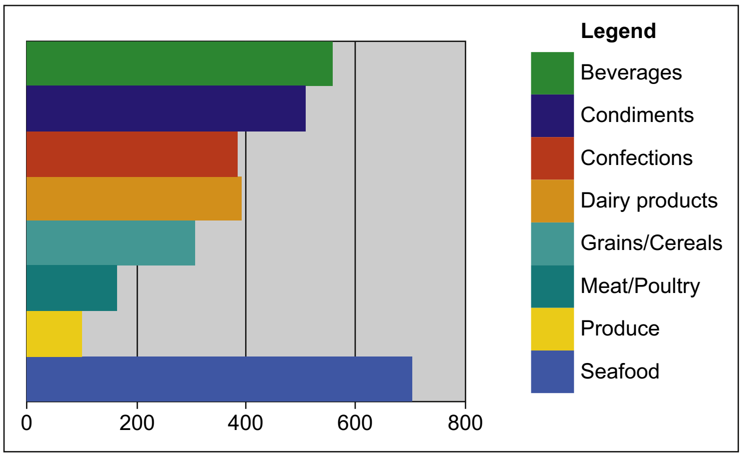

FIGURE 4.7

Large color patches make it easier to distinguish the colors.

- Housing Units Authorized, Percent Change October 2005 Year-to-Date Compared With a Year Earlier
- Electricity Consumption per Capita, 2001
- Drinking and Wastewater Needs per Capita, 2003 Dollars
- Manufactured Homes as a Percent of Total Homes, 2000
- Percent of Occupied Housing Units That Are Owner Occupied
- Percent Change in Private Employment Due to Growth/Decline in Establishments, 2000-2001
- Labor-Force Participation Rate, 2002
- Number of Bank Offices per 10,000 People, 2003
- Total Foreign-Born, 2000
- Retail Gasoline Prices, May 17, 2004
- Total Manufactured Exports per Capita, 2003
- House Price Index, Percent Change-Third Quarter 2002 to Third Quarter 2003
- State and Local Government Per Capita General Fund Expenditure, 1977-2000

FIGURE 4.8

The difference in color between visited and unvisited links is too subtle in MinneapolisFed.org's website.

COLOR BLINDNESS

A fourth factor of color presentation that affects design principles for interactive systems is whether the colors can be distinguished by people who have common types of color blindness. Except in severe cases, having color blindness doesn't mean a total inability to see colors. It just means that not all three of a normally sighted person's types of color-detecting cone receptor cells (see "How Color Vision Works," section above) function, making it difficult or impossible to distinguish certain *pairs* of colors. Approximately 8% of men and slightly under 0.5% of women have a color perception deficit: difficulty discriminating certain pairs of colors (Wolfmaier, 1999; Johnson and Finn, 2017). The most common type of color blindness is red–green; other types are rarer. Fig. 4.9 shows color pairs that people with red–green color blindness (deuteranopia) have trouble distinguishing.

The home finance application Moneydance provides a graphical breakdown of household expenses using color to indicate the various expense categories (see Fig. 4.10).

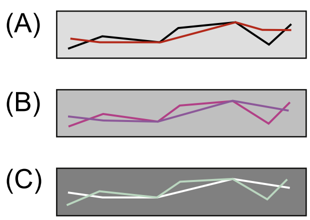

FIGURE 4.9

Red–green color-blind people cannot distinguish (A) dark-red from black, (B) blue from purple, and (C) light-green from white.

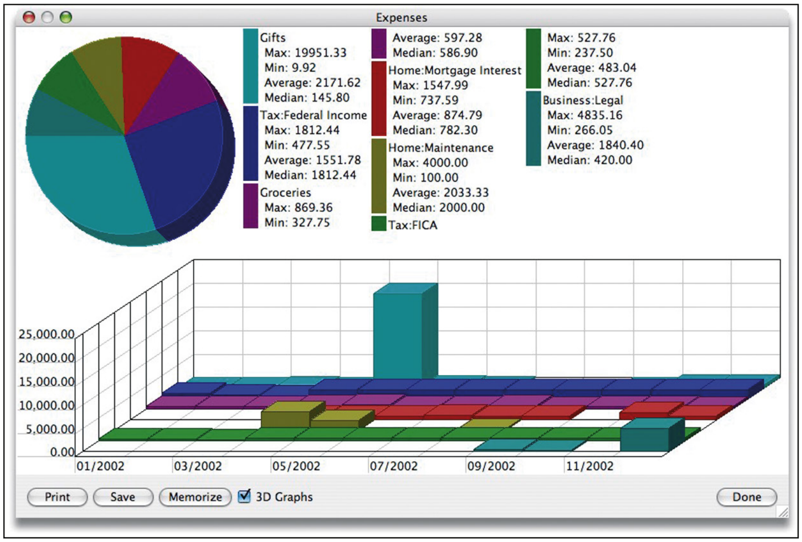

FIGURE 4.10

Moneydance's graph uses colors some users can't distinguish.

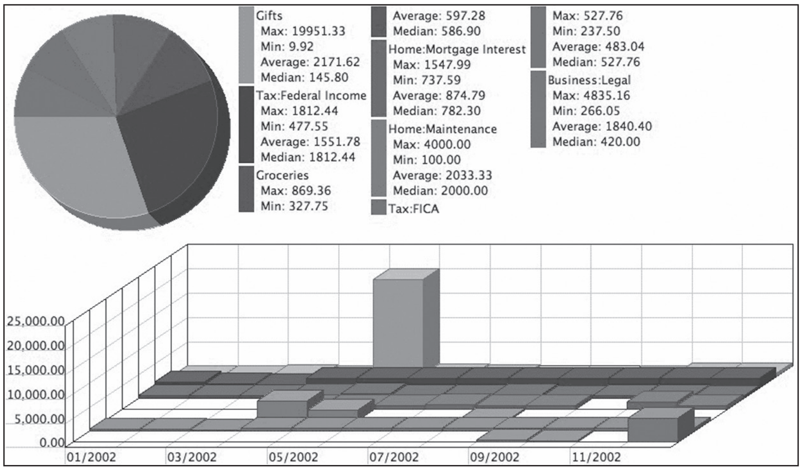

FIGURE 4.11

Moneydance's graph rendered in grayscale.

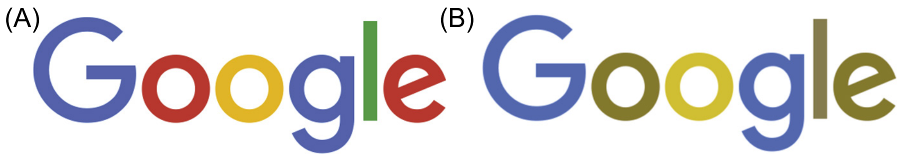

FIGURE 4.12

Google logo: (A) normal and (B) with deuteranopia (red–green color blindness) filter.

Unfortunately, many of the colors are hues that color-blind people cannot tell apart. For example, people with red–green color blindness cannot distinguish the blue from the purple or the green from the khaki. If you are not color-blind, you can get an idea of which colors in an image will be hard to distinguish by converting the image to grayscale (see Fig. 4.11), but as described in the "Guidelines for Using Color" section later in this chapter, it is best to run the image through a color-blindness filter or simulator (see Fig. 4.12).

EXTERNAL FACTORS THAT INFLUENCE OUR ABILITY TO DISTINGUISH COLORS

The environment in which digital technology is used can also affect people's ability to distinguish colors—for example:

- ***Variations in color displays***. Computer displays vary in how they display colors depending on their technologies, driver software, or color settings. Digital projectors and auxiliary screens sometimes display colors differently than on the computer sending the image. Even monitors of the same model with the same settings may display colors slightly differently. Something that looks yellow on one display may look beige on another. Colors that are clearly different on one may look the same on another.
- ***Grayscale displays***. Although most displays these days are color, some devices, especially small handheld e-readers, have black-and-white or grayscale displays (see Fig. 4.13). A grayscale display can make different colors look the same.
- ***Daytime/nighttime adjustments and dark mode***. Most modern smartphones, tablets, and computers can adjust their color balance, either on demand or based on the time of day. Some color adjustments are subtle, such as when devices decrease the amount of blue in the display to avoid interfering with a user's ability to sleep after an evening of device use. Other color adjustments are dramatic, such as switching to "dark mode," which displays light content on dark backgrounds (ironically, like most computer terminals did many decades ago). All of these affect the colors users see in a user interface.

FIGURE 4.13

E-reader with grayscale screen.

- ***Display angle***. Some computer displays, particularly LCDs, work much better when viewed straight-on than at an angle. When LCDs are viewed at an angle, colors—and color differences—often are altered.
- ***Ambient illumination***. Strong light on a display washes out colors before it washes out light and dark areas, reducing color displays to grayscale, as anyone who has tried to use a bank ATM in direct sunlight knows. In offices, glare and venetian blind shadows can mask color differences. Smartphones and tablets are used everywhere, in all possible lighting conditions.

These external factors are usually out of the software designer's control. Designers should therefore keep in mind that they don't have full control of users' color viewing experiences. Colors that seem highly distinguishable in the development facility, on the development team's computer displays and under normal office lighting conditions, may not be as distinguishable in some environments where the software is used.

GUIDELINES FOR USING COLOR

In interactive software systems that rely on color to convey information, follow these five guidelines to assure that the users of the software receive the information:

- ***Use distinctive colors***. Recall that our visual system combines the signals from retinal cone cells to produce three color-opponent channels: red–green, yellow–blue, and black–white (luminance). The colors that people can distinguish most easily are those that cause a strong signal (positive or negative) on one of the three color-perception channels and neutral signals on the other two channels. Not surprisingly, those colors are red, green, yellow, blue, black, and white (see Fig. 4.14). All other colors cause signals on more than one color channel, so our visual system cannot distinguish them from other colors as quickly and easily as it can distinguish those six colors (Ware, 2008).
- ***Separate strong opponent colors***. Placing opponent colors right next to or on top of each other causes a disturbing shimmering sensation, so it should be avoided (see Fig. 4.15).
- ***Distinguish colors by saturation and brightness, as well as hue***. To make your software's use of colors perceptible to all sighted users, avoid subtle color differences. Make sure the contrast between colors is high (but see guideline 5). One way to test whether colors are different enough is to view them in grayscale. If you cannot distinguish the colors when they are rendered in grays, they are not different enough.
- ***Avoid color pairs that color-blind people cannot distinguish***. Such pairs include dark red versus black, dark red versus dark green, blue versus purple, light green versus white. Don't use dark reds, blues, or violets against any dark colors. Instead, use dark reds, blues, and violets against light yellows and greens.

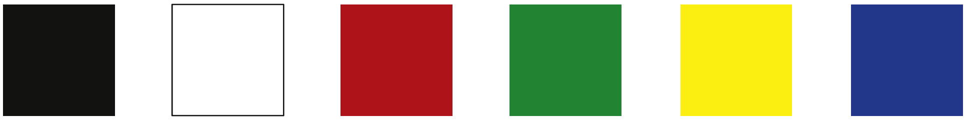

FIGURE 4.14

The most distinctive colors: black, white, red, green, yellow, and blue. Each color causes a strong signal on only one color-opponent channel.

FIGURE 4.15

Opponent colors, placed on or directly next to each other, clash.

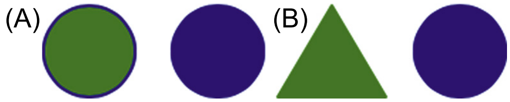

FIGURE 4.16

Don't use color alone to convey meaning (A). Use it redundantly with other cues—e.g., shape (B).

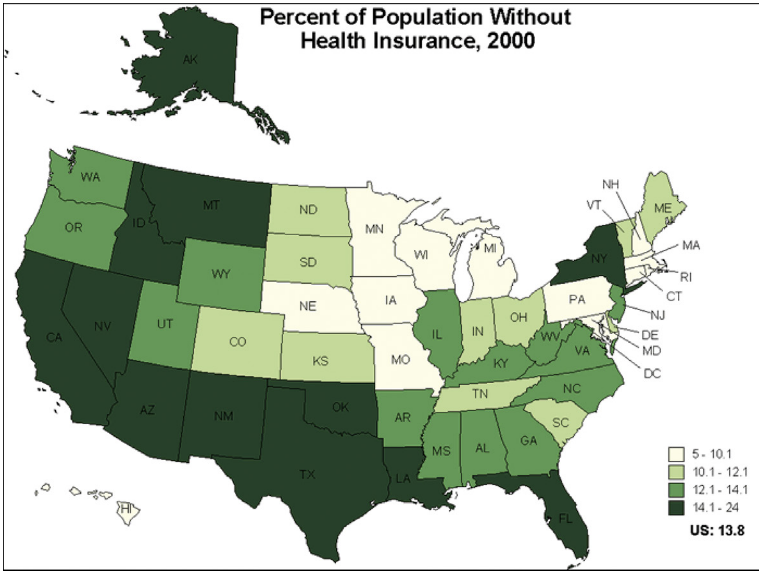

FIGURE 4.17

MinneapolisFed.org's graph uses shade differences visible to all sighted people on any display.

Use an online color-blindness simulator[4] to check web pages and images to see how people with various color-vision deficiencies would see them.

- ***Use color redundantly with other cues***. Don't rely on color alone. If you use color to mark something, mark it another way as well. For example, if green means one thing and blue means something else, don't show green and blue dots; show a green triangle versus a blue dot, so both shape *and* color indicate the difference (see Fig. 4.16).

[4] Search the Web for "color-blindness filter" or "color-blindness simulator."

FIGURE 4.18

(A) Poor design; (B) improved, more accessible design: the current step is highlighted redundantly using boldness and a more saturated color.

A graph from the Federal Reserve Bank follows guideline 3 above by using shades of green (see Fig. 4.17). This is a well-designed graph. Any sighted person could read it.

Now let's use guideline 5 (above) to fix the design problem discussed earlier (see Fig. 4.5), where the current step in a simulated airline check-in process was marked *only* with a pale green (see Fig. 4.18A). A simple way to correct it would be to mark the current step with a **bold** circle, a **bold** step number, a **bold** label below the circle, and increase the saturation of the green so it contrasts more strongly with the white backgrounds of the other circles (see Fig. 4.18B). To allow blind people using screen readers to know what step they are one, one can also set the ALT-text of the current step to "current step" to mark it. With these improvements, the current step is marked *redundantly*, as guideline 4 recommends.

IMPORTANT TAKEAWAYS

- People with normal color vision have three types of cone receptor cells in the retinas of their eyes. People with color blindness have only two functioning types—in rare cases one type—of cone receptor cells. A small percentage of women have four types.
- Human color vision works mainly by subtraction: ***red - green*** and ***blue - yellow***. This makes our visual system sensitive mainly to contrast, edges, and quick changes and relatively insensitive to overall brightness levels or absolute colors.
- Our ability to see differences between two patches of color depends on:
    - Paleness: The paler two color patches are, the harder it is to distinguish them.

    - Size: The larger the patches, the easier it is for us to distinguish the colors.
    - Separation: The closer together they are, the easier they are to distinguish.
- Several external factors influence our ability to distinguish colors:
    - Color displays may vary in color balance.
    - Some displays, such as those on many e-readers, are grayscale or black and white.
    - Many modern displays allow users to adjust color balance. Evening/night mode (which lowers blue levels) and dark-versus-light mode.
    - The angle at which some screens are viewed affects how colors appear.
    - Ambient light.
- Guidelines for using color:
    - Use distinctive colors.
    - Separate strong opponent colors.
    - Distinguish colors by saturation and brightness as well as hue.
    - Avoid color pairs that color-blind people cannot distinguish.
    - Use color redundantly with other cues.