

# Spectral Schemes: Controversial Color Use on Maps

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**ABSTRACT.** Cartographers have long discouraged the use of spectral, or rainbow, color schemes on thematic maps of quantitative geographic data, though such color use is common in GIS and scientific visualization. Recent research, however, has shown that spectral schemes are preferred and are interpreted accurately when used as multi-hue renditions of diverging schemes. Both spectral and diverging schemes can emphasize a critical point within a data range with light colors and emphasize both high and low extremes of the data with dark colors. Although spectral schemes include multiple saturated hues, they can be designed to accommodate map reading by people with red-green impaired color vision by skipping over the yellow-greens in the spectral sequence. Cartographers should encourage use of spectral color schemes for depicting diverging quantitative data, rather than insisting that these schemes should not be used.

**KEYWORDS:** cartography, map design, spectral color schemes, color vision

## Introduction

Spectral color schemes are common on rainbow weather maps in the daily news, in scientific visualizations, and in GIS-based mapping. Yet, cartographers continue to discourage their use for representing quantitative geographic data on thematic maps. Spectral schemes are preferred and interpreted accurately when used as multi-hue renditions of diverging schemes (Brewer et al. 1997), and careful variation in both hue and lightness within spectral schemes aids map reading. Like a diverging scheme, spectral schemes can be designed with light colors emphasizing a critical point within a data range and dark colors emphasizing both high and low extremes of the data. The multiple saturated hues of spectral schemes may confuse people with red-green color-vision impairments but, again, careful design permits spectral schemes to accommodate these map readers. Cartographers should encourage use of well designed spectral color schemes for thematic maps of diverging data, rather than generally discouraging use because of inappropriate applications of spectral schemes to sequential data.

This paper begins with a critique of the assumption that spectral schemes are illogical. Examples of diverging data and spectral color use

are presented from mapping in cartography, geography, and scientific journals. Results from two research projects in which spectral schemes led to good map reading performance by people with both normal and impaired color vision are described. Finally, the suggestion that spectral schemes do not accommodate people with impaired color vision is addressed with a recommended adjustment to the spectral sequence.

## Literature Review

Bertin's writings (1981; 1983) are influential in shaping our discipline's approach to data representation. His opinions about the use of color hue are cast in a strident tone: "I am indeed against color when it masks incompetence;... when people believe it capable of representing ordered data" (Bertin 1981, p. 222). The following sample of recent quotes about spectral schemes by cartographers and other authors echo and elaborate Bertin's opinions. Rarely do we find this degree of consensus or emotion expressed about a subjective challenge of symbolization. We have been recommending that spectral schemes should not be used to represent ordered data. These claims have established a conventional wisdom that spectral schemes are illogical and inappropriate for the representation of quantitative data. My own earlier writings on the issue are no exception, as can be seen in the following list of statements:

Do not use the saturated spectrum as a sequential scheme. [Brewer 1994a, p. 138]

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There appears to be general agreement among cartographers that the color dimension of value [lightness] be used to symbolize an ordered array of data magnitudes... Hue differences alone should not be used, but if they are, part-spectral schemes are preferred over the full-spectral ones. [Dent 1996, p. 306; cites Cuff 1973]

A common objection by cartographers to maps of quantities produced by noncartographers is that these maps often ignore the importance of the linear order schema and employ a set of eye-catching (but randomly ordered) hues. Sometimes the hues are ordered, but according to wavelength of hue. Wavelength ordering is not immediately recognized by our visual system, and therefore is unlikely to prompt the appropriate linear order schema on the part of the viewer. [MacEachren 1995, p. 188]

Hue differences usually fail at portraying differences in percentages, rates, median values, and other intensity measures because spectral hues have no logical ordering in the mind's eye... there is no simple, readily remembered and easily used sequence of hues that would obviate a map reader's needing to refer back and forth repeatedly between map and key... The use of spectral hues to portray intensity differences is a strong clue that the mapmaker either knows little about map design or cares little about the map user. ...most users will find [a] full spectral scale of primary hues confusing, complex, and comparatively difficult to decode. [Monmonier 1991, pp. 150 and 152]

The spectral progression on relief maps is a convention of long standing and thus is well known through regular appearance on school maps and atlas maps for the general public. Except for its familiarity, it is graphically illogical with little to recommend it...[Robinson et al. 1984, p. 186]

In a later edition of the text, an added advantage of spectral schemes is recognized but they are still dismissed, albeit with softened language:

Except for its familiarity and map-legend matching advantage, there is little reason

to use spectral progressions for quantitative data. Communicating the geographic pattern of magnitude variation generally is a more important objective, and a spectral hue progression does not inherently carry a magnitude message. [Robinson et al. 1995, p. 389]

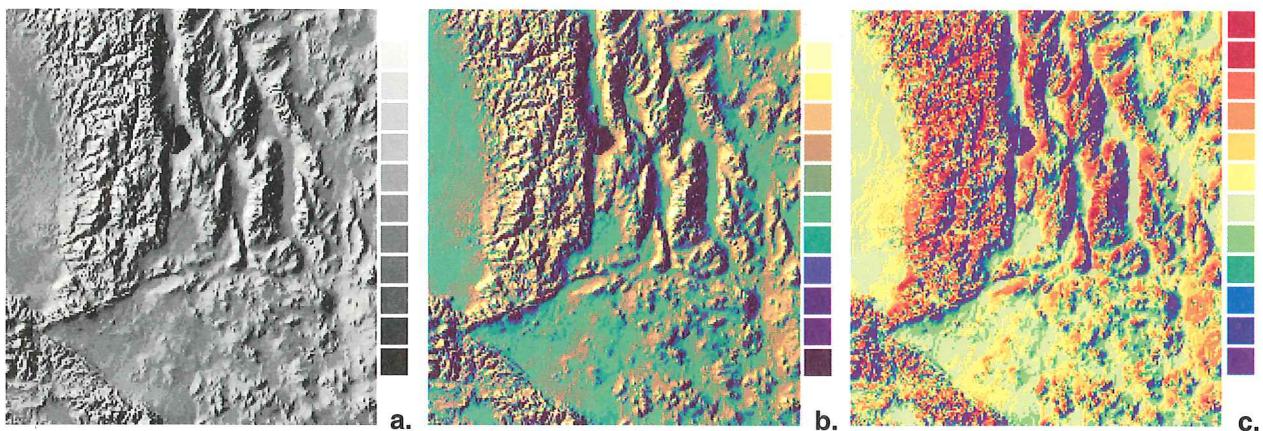
Others have commented as follows:

...there is no logical sequence for ordering colors that differ by very large steps in color space... It is erroneous to assume that we have some hard-wired intuitions for a spectral sequence... If this were true, school children would not find it necessary to learn mnemonics such as "Richard Of York Gains Battles In Vain." Such mnemonics are not required to rank colors in saturation or brightness, or when small steps in hue are considered... [Travis 1991, p. 126 (*Travis's bolds and italics*)]

If the categories are ranked or naturally ordered, assign colors in order of lightness or value, not by hue or wavelength. A color spectrum of pure hues contains two scales of value on either side of yellow... For ordered concepts, never mix the two scales. Value, even within colors, is a stronger ordering force than hue. [Horton 1991, p. 232 (*cites Bertin 1983*)]

A widely used alternative is a scale of rainbow colors, replacing the clear visual sequence of light to dark with the disorderly red, orange, yellow, green, blue, indigo, and violet—an encoding that now and then reduces perplexed viewers to mumbling color names and the numbers they represent... Despite our experiences with the spectrum in science textbooks and rainbows, the mind's eye does not readily give order to ROYGBIV. [Tufte 1990, p. 92]

Kumler and Groop (1990) tested spectral and part-spectral schemes in the context of evaluating continuous-tone representations of smooth and continuous surfaces. In contrast to the above quotes, they found that subjects scored better with spectral schemes than part-spectral (both with isarithms) and that 73 percent of subjects preferred spectral schemes to the other representations used in their test.



**Figure 1.** Demonstration of a map that is difficult to interpret with a spectral scheme. The grayscale (a) and sequential multi-hue (b) versions present the shaded relief well, showing the flat Central Valley (left), the adjacent rugged Sierra Nevada, the beginnings of Basin and Range fault-block topography (right), and the linear Garlock and San Andreas faults (intersecting at the lower left) in the southwestern U.S. Both the (a) and (b) schemes are successful because the light-to-dark sequences are well suited to the mapped data of reflectance of an assumed northwest light source. The spectral scheme in Figure 1c has an approximately diverging lightness organization which is not suited to these data, making the map features difficult to interpret. The map is a segment of the Pike and Thelin shaded relief map (1990-91).

## Graphic Critiques of Spectral Schemes

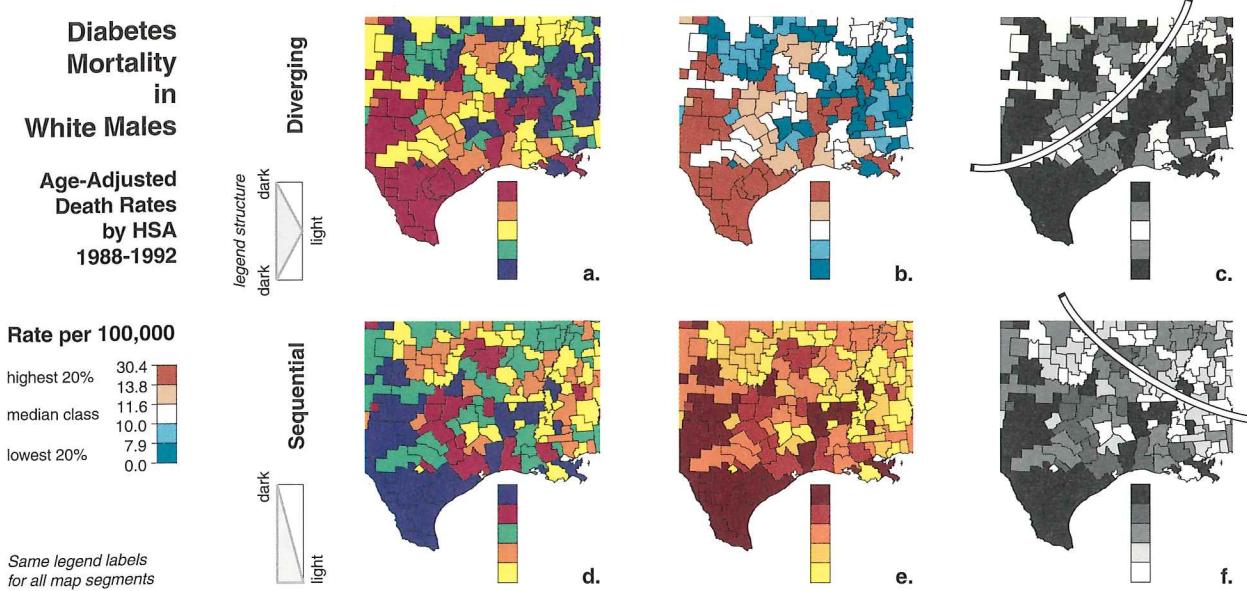
I have seen three similar and compelling graphic demonstrations by Bertin (1981), MacEachren (1994), and Livingstone (interviewed by Grady 1993, p. 63) of how spectral schemes misrepresent distributions. Livingstone presents a photo of Eisenhower's face. With a sequential grayscale representation, Eisenhower is immediately recognizable. The same photo is shown with hues that are ordered sequentially from light to dark: yellow, orange, green, blue, and dark purple. The face is still recognized as familiar, though strangely colorful. With a full spectral scheme applied to the 'data' (dark red, orange, yellow, green, blue, dark purple), the image becomes almost unrecognizable as a face, and certainly not as a familiar one.

Figure 1 presents an example similar to Livingstone's with a shaded relief representation of a readily recognized region of faulted terrain in the southwest U.S. Figure 1a is a standard grayscale shaded relief representation of the area. Figure 1b presents spectral colors in lightness order that produces a strangely colored but recognizable relief. In contrast, Figure 1c presents a diverging spectral scheme that makes the terrain difficult to interpret; larger structures can be seen but the river valleys of the Sierra Nevada, for example, are completely masked. [See Moellering and Kimerling (1990), Brewer and Marlow (1993), and the cover of MacEachren and Taylor (1994) for

examples of effective spectral colors in terrain mapping for slope-aspect representation.

The Livingstone and Figure 1 demonstrations are effective because it is only appropriate to represent the original data (high to low reflectance from a face or landforms) with an ordered lightness sequence to understand the 'distribution.' Emphasis on mid-range reflectance with light yellows is not suitable because this is not an important range in the data (unlike a median mortality rate, Figure 2). These reflectance data are suited only to a sequential scheme, and an application of a diverging spectral scheme makes them difficult to interpret.

Bertin (1981, p. 220) presents a map of France with a variant of a spectral scheme (black, blue, green, yellow, orange, red, dark purple). The look of the hypothetical distribution is dominated by an east-west band of light colors for mid-range data values. He rearranges the same legend colors into a light-to-dark sequence (yellow, green, orange, red, blue, dark purple, black) and maps the same distribution, which then is dominated by a dark north-south band of medium-to-high data values across this same map. Bertin's objective is to use this spatial arrangement of data values to demonstrate the importance of ordering lightness rather than hue. MacEachren (1994, p. 117) provides an updated example of Bertin's demonstration with a more standard spectral scheme (blue, cyan, green, yellow, orange, red, purple) that is then rearranged into



**Figure 2.** Color scheme demonstrations with a portion of a choropleth map of diabetes mortality in white males from Brewer et al. (1997) and Pickle et al. (1996). The map subset shows a portion of the southern U.S. that includes hospital service areas for Arkansas, Louisiana, and Mississippi, and most of Texas and Oklahoma. The same data distribution is shown in all six small maps. The top-row maps have diverging schemes (a-c) and the bottom-row maps have sequential schemes (d-f). The left-column maps use the same colors with spectral order in Figure a and lightness order in d. The middle-column maps show more standard diverging (b) and sequential (e) schemes. The maps in the right column (c and f) summarize the lightness structure of each row with the primary trends for the lightest colors sketched. Maps a, b, e, and f show example schemes used in the experiment reported in Brewer et al. (1997). The overall message of this figure is that diverging spectral schemes are suitable for data that are conceptualized as diverging.

approximate lightness order (yellow, green, orange, cyan, red, purple, blue). The two schemes reveal opposite diagonal trends in a mapped distribution of hypothetical data for Pennsylvania. The map distributions for the Bertin and MacEachren examples are both carefully constructed with a homogeneous band of mid-range data values flanked by an intermixture of high and low data values.

MacEachren (1994) includes a grayscale version of his map figure (p. 24) as a place-holder in the text with reference to the color-plate version (p. 117). This grayscale version is equally effective in demonstrating the opposite trends in the distribution that each scheme emphasizes. The figure, therefore, makes its point equally well for comparison of any sequential and diverging schemes (not just for sequential versus spectral). Does this extension of the demonstration suggest that all diverging schemes are poor choices?

Figure 2 presents mortality data from Brewer et al. (1997) that may be conceptualized as both sequential and diverging. It shows a southern U.S. portion of the death-rate map for diabetes for one of

four groups (mapped in Pickle et al. 1996). The map pattern in this region is partly caused by high death rates in Mexican Americans from *diabetes mellitus*. The data are mapped with similar pairs of schemes as those presented by Bertin and MacEachren. Figure 2a is spectral and 2d has the same colors rearranged into approximate lightness order. Figure 2e shows a more usual sequential scheme with a hue gradation and, correspondingly, 2b is a more standard two-hue diverging scheme with brown and blue-green sequences diverging from a light median class. The grayscale versions of the lightness structures of these schemes are shown in Figures 2c and f. Though a distinctly opposite pattern is not seen in these real data, the lightest colors on diverging schemes (Figures 2a, b, and c) emphasize a northeast to southwest diagonal of median rates and lightest colors on sequential schemes (Figures 2d, e, f) emphasize a northwest to southeast band of low rates (sketched on Figures 2c and f).

The choice of whether or not to use a diverging scheme is a subjective choice that depends on the purpose of the map (Brewer 1994a and 1994b). It

hinges on whether the cartographer wishes to emphasize both extremes in a distribution and whether there is a critical point within the distribution that the cartographer also wishes to emphasize with light colors. This critical value may be zero, the mean, the median (as in Figure 2), or otherwise relevant to the data mapped (such as 50 percent for yes/no votes on referenda). The Bertin and MacEachren demonstrations are compelling because there is not an interesting spatial distinction between the high and low extremes of the data in these constructed examples. Because these examples have no specific topic, we can not know whether it is more important to emphasize the sequential or diverging nature of the data. Thus, the point that the authors intend is well made—that a spectral scheme interferes with visualizing the structure of ordered data suited to a sequential representation. The demonstrations should not be extended, however, to the conclusion that spectral schemes should not be used for data suited to a diverging scheme as shown in Figure 2.

Mersey (1990) tested sequential, diverging, and multi-hue schemes using numerous types of map-reading tasks. She found that hue differences were important for communicating specific map information and lightness steps were important for understanding map structure. She also concluded that use of both hue and lightness allowed the most accurate recall of map information from memory. She chose a “hue-value” scheme that ranged from yellow through orange to dark brown as the best compromise scheme to suit multiple map-reading objectives. The part-spectral scheme she tested (yellow-green-blue-purple) included less lightness contrast through its range, and subject performance with this scheme type was similar but less accurate than for yellow-orange-brown. Results for Mersey’s diverging schemes are difficult to evaluate because she used red for low data values and deviated from a diverging lightness arrangement for the nine-class map she tested.

I maintain that full spectral schemes are good compromise schemes because they include both hue and lightness sequences that diverge from light yellow. The use and design of a spectral scheme should be tied to the decision to emphasize both extremes as well as a critical point within the data range. Hue variation in a spectral scheme should assist in reading specific information from maps and remembering map patterns. Diverging lightness sequences built into spectral schemes emphasize the diverging structure of the mapped data.

In the sections that follow, I present two reviews of recent research results that demonstrate good map-reading performance with spectral and

multi-color schemes by people with normal and impaired color vision. To preface this discussion of research on color, I begin with an overview of the many examples of research that produce data suited to mapping with a diverging spectral scheme to emphasize the relevance of this work to visualization and communication of research results.

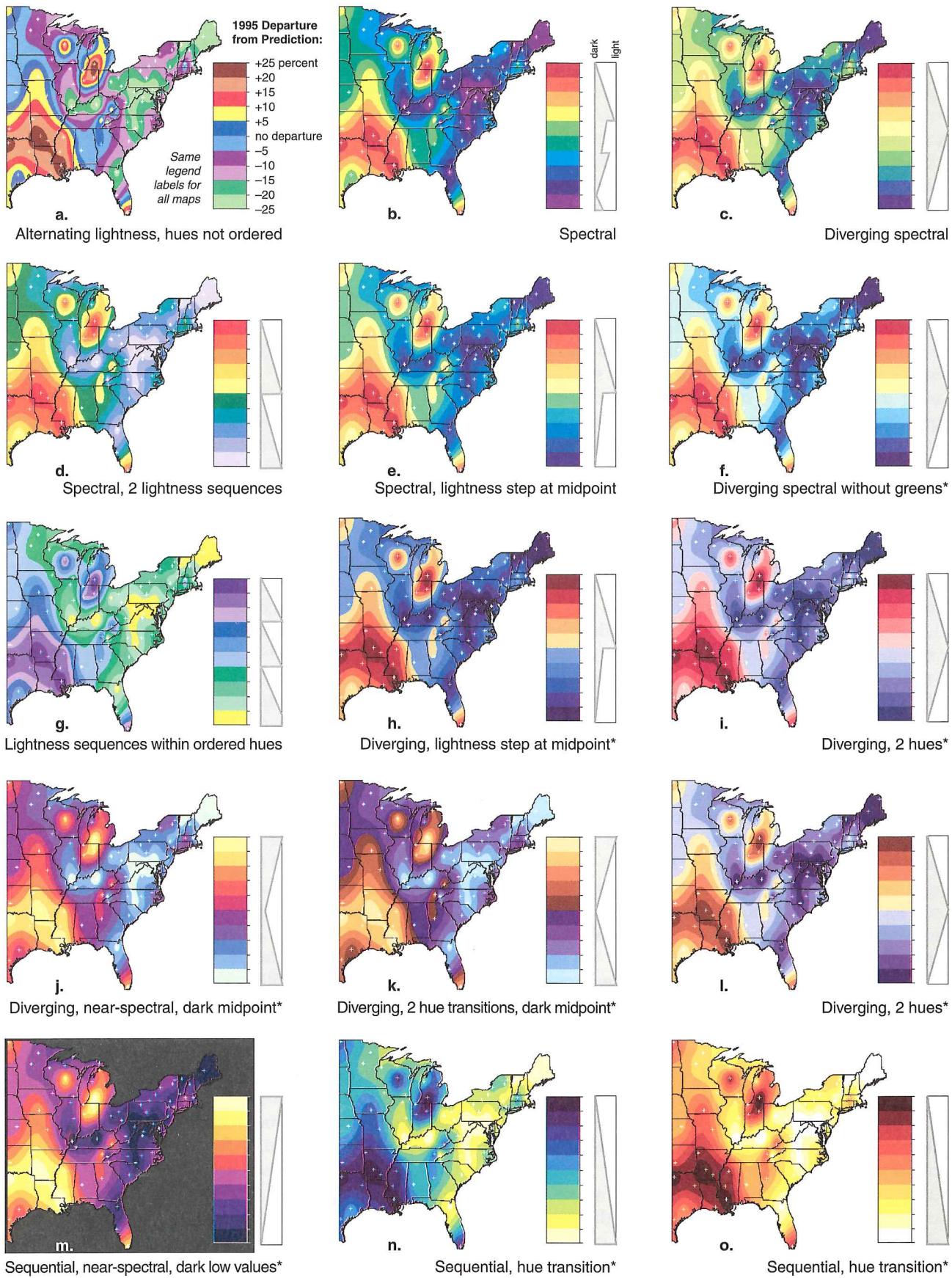
## Mapping Diverging Data

### Use of Diverging Data by Geographers

Data that are conceptually suited to diverging schemes are also frequently used in cartographic and geographic research. Research articles published in the 1990s in *Cartography and Geographic Information Systems*, *Annals of the Association of American Geographers*, and *The Professional Geographer* are representative of the topics that cartographers and geographers study, and the maps in these journals revealed many examples of diverging data (represented in black-and-white).

Statistical analyses often produce diverging data. For example, mapped negative and positive factor scores that diverge from zero were used to describe a fertility/abortion dimension (Morrill 1990, p. 43) and political characteristics (Webster 1996, pp. 385-388). Likewise, various indexes that synthesize multiple characteristics diverge from zero or one, such as positive and negative values of a disparity measure for economic development and human welfare (Holloway and Pandit 1992, p. 61) and values of a retail-sales index above and below one (Lloyd 1991, pp. 341-342). Location quotients also diverge from one and are frequently mapped. They have been used to describe distributions of employment by foreign firms (ÓHullacháin and Reid 1992, pp. 279-280), surgical centers (Lowell-Smith 1993, p. 404), defense services procurement (Crump 1993, pp. 291-293), and membership in environmental organizations (Wikle 1995, p. 44). Maps of positive and negative residuals from regression analyses are inherently diverging and have been used to investigate spatial patterns in model errors for predictions of, for example, acreages owned by full- and part-time farmers (Hart 1991, p. 73) and levels of child-care service (Skelton 1997, p. 231).

Percentage change over time produces diverging data with increases and decreases departing from no change (Monmonier 1990). Example data that have been mapped in the geographic literature are changes in female-headed households below the



**Figure 3.** Color scheme demonstrations with a filled-isarithm map on the topic of acid rain (all 15 maps show the same data with only colors changed). The schemes reflect different conceptualizations of the data. Diverging schemes (c, f, h-l) place emphasis on positive and negative extremes as well as departures of less than 5 percent. Schemes with a midpoint lightness step (d, e, h) emphasize the "no departure" class break. Sequential schemes (m-o) emphasize the positive and negative extremes. Schemes with alternating lightness or repeated lightness sequences (a, b, g) emphasize isarithms. Schemes that include most hues—the colors of the spectrum and the non-spectral purples and magentas—(a-f, j, m) provide good contrast between the ten map classes. With the exception of a and b, all schemes are well suited to the data. Scheme labels marked with asterisks (f, h-o) should be readable by people with red-green color vision impairments. This figure shows that there are many spectral and multi-hue schemes useful for representing diverging data. Some of the schemes (e, g-i, k-o) are examples of schemes described in Table 1, though the different distribution, number of classes, and uncertainties of color printing dictate that they are approximations of the originals. The repeated map represents percent departures of 1995 annual sulfate ion concentrations from predictions of the 1983-94 seasonalized trend model. The digital Internet version of the map was from a U.S. Department of Interior press release dated June 27, 1996. The press release included interpretation of the map pattern: "Significant decreases in sulfate and hydrogen ion concentrations in precipitation in the eastern United States in 1995 — particularly along the Ohio River Valley and in the Mid-Atlantic States—indicate that reductions in sulfur dioxide emissions have resulted in rainfall being less acidic in these areas, according to a report prepared for the U.S. Geological Survey" (quoted from <http://www.epa.gov/acidrain/usgspr.html>).

poverty level (Jones and Kodras 1990, p. 169), changes in total population (White 1994, p. 35), predicted changes in populations by language group (Kaplan 1994, p. 61), and changes in consumption of starchy foods (Grigg 1996, p. 419). Change data may also be analyzed in more sophisticated ways that still yield diverging data. Eytون (1991, p. 102) mapped accelerating versus decelerating increases in mobile-home residency.

Some geographic data are inherently diverging, such as male to female ratios among commuters (Blumen and Kellerman 1990, p. 62), lengthened and shortened travel distances by district with alternate facility locations (Armstrong et al. 1992, p. 161), excesses and shortages of students for school enrollment goals (November et al. 1996, pp. 6-8), and percentage votes above

and below 50 percent on issues such as restricting gay rights (Ormond and Cole 1996, pp. 15, 22-23) and European Union membership (Murphy and Hunderi-Ely 1996, p. 289).

The maps cited above in this section are choropleth maps (like Figure 2), but data represented with filled isarithm maps are also suited to diverging schemes. All of the data examples from the science literature described in the next section (Table 1, Figure 3) are filled isarithms or continuous color scales representing smooth and continuous surfaces. This type of data is also common for physical geography topics: differences in the  $x$ -component of wind stress on a surface (DiBiase 1991, p. 269), positive and negative values of a moisture index (Willmott and Feddema 1992, p. 86), differences above and below a mean temperature (Weber and Buttenfield 1993, pp. 146-147), changes in elevation from erosion and deposition (Gares and Nordstrom 1995, p. 8), and differences in seasonal cyclone frequency between wet and dry periods (Raphael and Mills 1996, p. 259).

Point symbols are also used to represent diverging data on maps. O'Loughlin et al. (1994, p. 366) mapped positive and negative  $z$  values for spatial clustering of high and low votes for the Nazi party, and Liverman (1990, p. 63) mapped summer precipitation deviations from normal. In both cases, the symbols varied in size and were of opposite orientation (pointing up or down to show divergence from a midpoint), which are good design choices for black-and-white production. For colored point symbols, hue and lightness may replace or augment these visual-variations.

The maps by Liverman (1990), DiBiase (1991), Eytون (1991), Hart (1991), Armstrong et al. (1992), Weber and Buttenfield (1993), Kaplan (1994), O'Loughlin et al. (1994), Gares and Nordstrom (1995), Grigg (1996), Ormond and Cole (1996), and Murphy and Hunderi-Ely (1996) used diverging symbolizations to represent their diverging data. In other figures, the diverging data were represented with sequential schemes. This mismatch may have occurred because the mapmakers did not choose to emphasize the diverging structure of the data or because the challenge of producing a monochrome diverging scheme was not readily accomplished with the tools available. In a black-and-white diverging scheme, differences in hue are replaced with differences in texture for the two lightness sequences. For example, a lightness sequence of a fine dot pattern may diverge from a sequence of coarser line patterns. Sequential schemes for these diverging data do not emphasize the critical midpoint in the data and map versions with diverging schemes may

Color Scheme	Reference (with page)	Example
<b>1. Sequential Schemes with Multiple Hues</b>		
<ul style="list-style-type: none"> <li>◆ Amplitude recovery for lithospheric slab model using well controlled lightness sequence of light yellow, green, blue, and dark purple-blue for 0 to 60 percent recovery</li> <li>◆ Light yellow, orange, and dark brown lightness sequence for increasing seismic wave scattering gradients</li> <li>◆ Lightness sequence of yellow, orange, red, magenta, purple, and blue representing high to low elevations on Venus, with an overlay of terrain shading' scheme also used for low to high intensities of scattered neutrons</li> <li>◆ Sequence from light pink through yellow-greens to dark brown overlaid on three-dimensional shaded representation of increasing friction near atoms</li> </ul>	Widiyantoro and van der Hilst (1996, p. 1568) Revenaugh (1995, p. 1345) Naeye (1993, p. 79) Kes (1995, p. 730) Anonymous (1995, p. 20)	Figure 3n Figure 3o Figure 3m Figure 3n Figure 3n
<b>2. Two-hue Diverging Schemes (accommodate readers with impaired vision)</b>		
<ul style="list-style-type: none"> <li>◆ Spatiotemporal evolution of chains of coupled pendula using white for still pendula (0 velocity) and lightness sequences to dark red for increasingly negative velocities and to dark blue for increasingly positive velocities</li> <li>◆ Seismic wave phase velocity anomaly models with light orange to dark brown sequence for negative velocity anomalies and light purple to dark purple for positive anomalies. The light orange/purple boundary marks 0 velocity anomalies on the maps</li> <li>◆ Oranges and purples are also used with an opposite organization of lightness on maps of scattering potential for seismic waves; scattering potential is symbolized with light blue for 0 through purple, dark brown, orange to light yellow for 1</li> </ul>	Braiman et al. (1995, p. 466) Trampert and Snieder (1996, p. 1259) Revenaugh (1995, p. 1345)	Figure 3i Figure 3l Figure 3k
<b>3. Lightness Step for Visual Emphasis Midway Through Data Range</b>		
<ul style="list-style-type: none"> <li>◆ The radial component of Earth's magnetic field is mapped with light orange to dark red representing outward-directed fields, medium-light blue to dark purple representing inward-directed fields, and the lightness step between orange and darker blue emphasizing the shift from outward to inward</li> <li>◆ Spectral maps of cortex activation during finger movement mapped with red, orange, yellow, green, blue, and purple representing standard deviations above and below the mean response, with the mean (<math>-2 &lt; Z &lt; +2</math>) marked by an abrupt lightness change from light yellow to dark green</li> <li>◆ The same yellow/dark green lightness step within a spectral scheme marks zero mean annual change on world maps of radiative forcing and temperature change</li> </ul>	Glatzmaier and Roberts (1995, p. 205) Ungerleider (1995, p. 772) Mitchell et al. (1995, p. 503)	Figure 3h Figure 3e Figure 3e
<b>4. Variation on Spectral Scheme</b>		
<ul style="list-style-type: none"> <li>◆ Progression through bands of red-purple, red, orange, yellow, green, blue, and purple with colors grading from light to dark <i>within</i> each hue band. This use of repeating lightness sequence squeezes a large range of discernible differences from the hue progression. Adjacent lightest and darkest colors mark hue changes, rather than critical thresholds in the data, and the transitions form visually prominent 'isarithms' through the distribution. This variation on a spectral scheme is used in two articles to represent decreasing sodium brightness surrounding the moon and concentration gradients of Bodipy-PC molecules.</li> </ul>	Mendillo and Baumgardner (1995, p. 405) Hwang et al. (1995, p. 613)	Figure 3g

**Table 1.** Use of color schemes in scientific visualization. Descriptions of example color maps and images from *Science*, *Nature*, and *Discover*.

have communicated different messages or yielded different insights for these examples.

Because the academic geographic journals publish mostly black-and-white, spectral schemes do not appear for either sequential or diverging data representations, though spectral representations are common in research journals with larger circulations, such as *Science* and *Nature*. Color representations are also common in our presentations at conferences, in classrooms, over the World Wide Web, and on our desktop computer screens.

## Diverging Data and Color Use by Scientists

An excellent map example of appropriate use of a spectral scheme from *Science* is a representation of anomalies in seismic *P*-wave velocities with dark red, orange, light yellow, green, blue, and dark purple-blue. Yellow is centered on zero difference (as in Figure 3c) from a reference velocity, with smooth lightness and hue progressions to red for slower velocities and to purple-blue for faster velocities in cooler subducting slabs (Widiyantoro and van der Hilst 1996, p. 1568). Additional good examples of varied spectral and multi-hue schemes are listed in Table 1 and these examples are illustrated in Figure 3.

Not all spectral schemes, however, are used well or to full advantage in the science literature. In an example from *Nature*, maps of *S*-wave velocity anomalies show velocities ranging from -2.4 to zero to +2.4 and the yellow of the spectral scheme forms visually bright ribbons of color that twist across the maps (Van Decar et al. 1995, p. 27). Unfortunately, the yellow marks approximately -0.8 on the anomaly scale, and not the zero transition, so the most prominent patterns on the maps are mismatched with the diverging data logic (Figure 3b).

The example graphics listed in Table 1 have made their way into the popular and scientific media. They show evidence of excellent color selection decisions and suggest that scientists are willing to augment and rearrange the prevalent spectral scheme. Spectral schemes are standard choices, but sequential schemes with hue transitions and two-hue diverging schemes are used.

Each example map described in Table 1 has the characteristic that the data represent a smooth and continuous surface with color classes occurring in a consistent order throughout the display, as in Figure 3. This constraint produces a simpler representation challenge than that of the typical choropleth map familiar to geographers (Figure 2) because colors are

always shown in their ordered progression on the map. An example of the reduced importance of logical color order when data are always ordered is seen on maps of the development of a shock-wave front of a supernova represented with purple-blue, light blue, green, red, orange, and light yellow (Chevalier 1995, p. 1452). These colors are not in spectral or lightness order, but the color symbols do permit comparison of the shock wave five times during the year because the maps show simple concentric isarithmic distributions. I do not recommend these sorts of representational idiosyncrasies for choropleth maps and other symbol forms for visualization of discontinuous or stepped distributions that produce more complex displays. A more disorderly scheme is shown with the relatively intricate acid rain data in Figure 3a to compare the interpretability of this type of scheme to other representations in the figure.

A case study (Brewer et al. 1997) of spectral, diverging, and sequential representations for mortality maps is described in the next section. This research was conducted in preparation for the production of the *Atlas of United States Mortality* (Pickle et al. 1996) and involved inherently geographic data (like the examples of geographic research above) and full-color production (as seen in the science journals). The majority of examples in this paper are taken from journals and magazines rather than atlases, however, to represent the current variety of topics in research to which spectral diverging schemes may be applied.

## Mortality Maps with Spectral Schemes

In Brewer et al. (1997) we tested how color schemes affect map reading with choropleth maps of death rates for eight mortality variables. The quintile-based data classifications could be interpreted as sequential or as diverging from median national rates. Our maps of the conterminous U.S. showed 798 health service areas (HSA), which are aggregates of counties. Half of the mortality distributions were clustered and the other half were dispersed. The maps were presented at two scales with eight color schemes.

The spectral schemes tested (the five-class example is shown in Figure 2a) were carefully designed with light yellow symbolizing death rates near the national median, yellow-orange-red steps for the progression of high rates, and yellow-green-blue steps for low rates. We also tested four diverging schemes, with lightness steps of two hues diverging from a light gray median-rate class (Figure 2b is an example), and three sequential schemes. One sequential scheme was part-spectral (yellow-orange-

red; Figure 2e) which is recommended by cartographers as better than a full spectral scheme (Mersey 1990; MacEachren 1995, p. 292). Another sequential scheme ranged from light blue to dark purple, and the third was an achromatic sequence of grays (Figure 2f). Altogether, 128 people answered questions about the maps. An equal number of each gender participated, and subjects were mostly undergraduate students with a wide range of academic specializations.

Subjects were asked to describe the mortality rates for individual health service areas and mean rates for regions (census divisions). They were asked to rate, on seven-step scales, the number of clusters and overall clustering of regions and of entire maps. Subjects were also asked to evaluate the ease-of-reading and pleasantness of color schemes. Results are detailed in Brewer et al. (1997), and those specific to spectral schemes are briefly reviewed below.

Responses to map-reading questions revealed few significant differences between the spectral scheme and diverging or sequential schemes. Responses for HSA rate retrievals (legend matching) were significantly more accurate with the spectral scheme than for the gray sequential scheme, and they were significantly less accurate for the spectral scheme than for two of the diverging schemes. Rate-retrieval accuracies for the spectral scheme were not significantly different from accuracies for the remaining two sequential and two diverging schemes. Importantly, responses with the spectral scheme were not significantly different than with other schemes for accuracy of selecting higher-rate regions from pairs of regions or for estimates of average rates for single regions.

Compared to other schemes, the spectral scheme did not produce different mean ratings of levels of clustering for single regions and entire maps, or of number of clusters for single regions and entire maps. Subjects also did not select different regions with distinct high- and low-rate clusters with spectral schemes. The only significant difference in region and map pattern ratings was significantly greater complexity of distributions seen with the spectral scheme in comparison with one of the four diverging schemes (purple/green). In addition, both spectral and diverging schemes caused dispersed patterns to be rated as less clustered than the same distributions seen with sequential schemes.

The spectral scheme was rated as the most pleasant and easy to read of all eight schemes, echoing Kumler and Groop's (1990) results. This top rating in pleasantness was not significantly different than the slightly lower ratings for one diverging (purple/green) and two sequential (red-yellow and purple-blue) schemes. The purple/green diverging

scheme was the only scheme with an easy-to-read rating not significantly lower than that of the spectral scheme. In final comparisons among the spectral and sequential schemes, subjects selected spectral as the best scheme for a planned mortality atlas. Of 63 subjects who evaluated spectral and sequential schemes, 56 percent selected spectral as the best; the next best scheme was selected by only 22 percent (diverging schemes were judged by a different group of subjects). These evaluations were made after completing numerous map reading tasks with the schemes and were thus well informed comparisons.

We had expected the spectral scheme to interfere with map-reading accuracy and with understanding map patterns, but this did not occur. Our subjects preferred the spectral scheme and performed well with it. This surprise can be attributed to the careful arrangement of lightness within the spectral scheme we tested. The red, orange, yellow, green, and blue steps were well matched with the diverging nature of the mortality data. Well designed diverging spectral schemes appear to be logical.

## Perception of Spectral Schemes

### Reading Colorful Maps with Impaired Color Vision

MacEachren (1995, p. 390) and Brewer et al. (1997) have suggested that spectral schemes should not be used because they do not accommodate map readers with red-green color-vision impairments, who make up approximately four percent of the population. Red, orange, yellow, and green are all used in typical spectral schemes, and they are potentially confusing colors. These hues may look the same to people with impaired vision if they are presented at approximately the same lightness, which is common for the oranges and greens that straddle light yellow in a typical spectral legend. However, I re-evaluated my blanket condemnation of spectral schemes as confusing after a conversation with a self-described colorblind researcher. He stated a preference for spectral schemes because he could *better* see differences between the map colors. That encounter prompted me to reconsider results from an experiment with people with impaired color vision (Olson and Brewer 1997).

Olson and Brewer (1997) tested 32 people with color-vision impairments and 32 with normal color vision using seven thematic maps. Each map was seen with two renditions of a color scheme—one with

Scheme Set	Vision	Confusing	Accommodating
		Rendition	Rendition
<b>a. Percent correct responses to content questions (Figure 4a)</b>			
1: Sp, 2V	Impaired	74	70
	Normal	83	71
2: Qa, Qd, D, B	Impaired	45	74
	Normal	76	74
<b>b. Percent correct responses to matching questions (Figure 4b)</b>			
1: Sp, 2V	Impaired	87	97
	Normal	98	92
2: Qa, Qd, D, B	Impaired	70	96
	Normal	99	99
<b>c. Percent choosing rendition as easier/better (Figure 4c)</b>			
1: Sp, 2V	Impaired	38	62
	Normal	60	40
2: Qa, Qd, D, B	Impaired	3	97
	Normal	35	65

**Table 2.** Results of color scheme testing by Olson and Brewer. (Source: Olson and Brewer (1997), Tables 3, 4, and 9.)

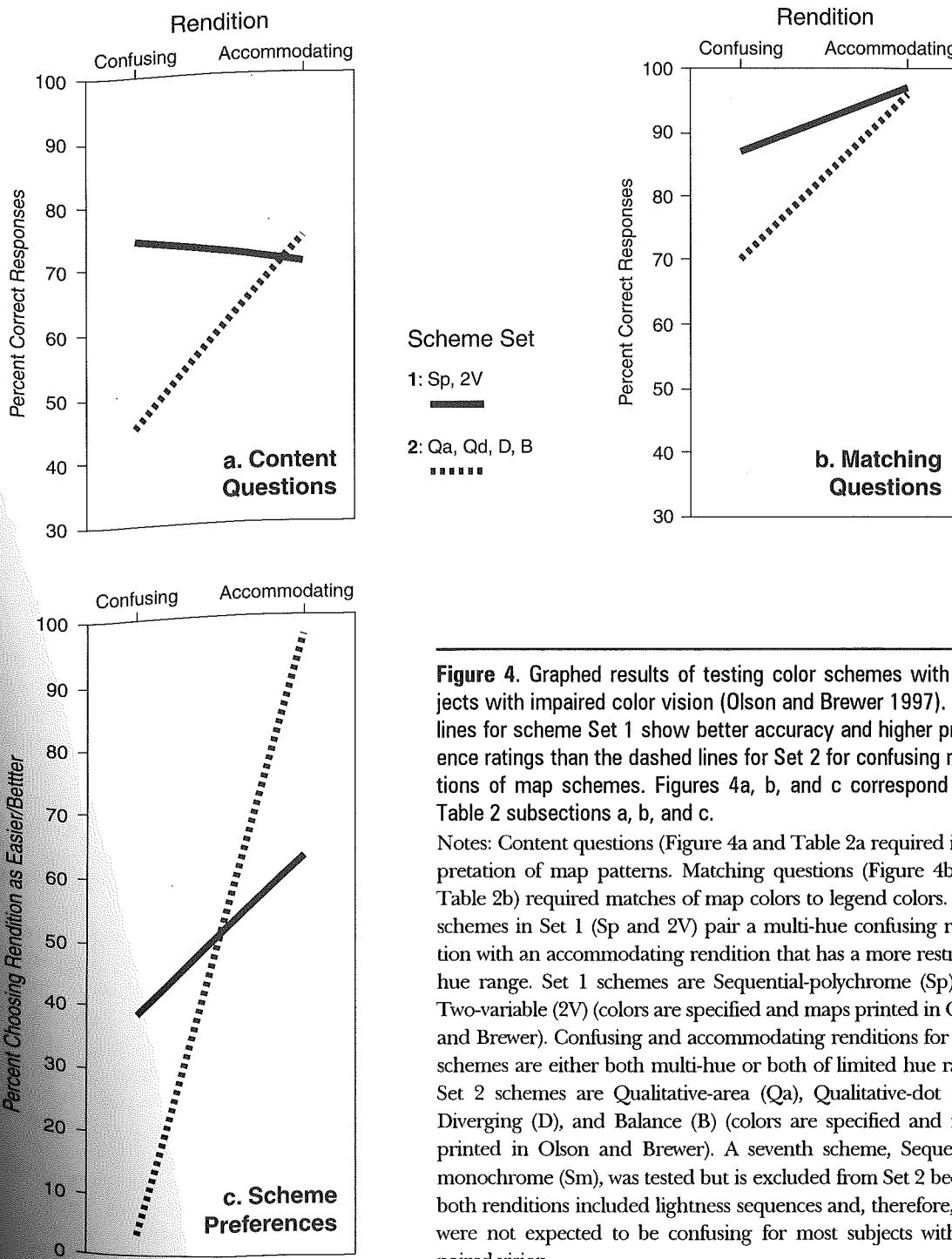
colors purposely chosen to be difficult to distinguish for people with red-green color-vision impairments and the other with colors chosen to accommodate their impairments. Both renditions were intended to be easy to read for people with normal vision. We hypothesized that "confusion lines" determined in vision research could be used to select colors for thematic maps to be read by people with impaired vision. We found that subjects with impaired vision responded more accurately and more quickly to questions about the maps when using the accommodating renditions. Likewise, they selected these accommodating renditions as easier to use on 87 percent of trials. In contrast, people with normal vision answered questions with similar accuracy and reaction times for both renditions, and their preferences for renditions were not significantly different than a 50-percent split between accommodating and confusing. Thus, aggregate results supported our initial hypotheses about designing maps to accommodate people with impaired vision.

For two schemes, a multi-hue rendition that was intended to be confusing was paired with an accommodating rendition that had a more limited hue range (Figures 3 h, i, n, and o printed in color on page 113 in Olson and Brewer, 1997). This pairing is analogous to comparing spectral

and two-hue diverging schemes in the mortality map experiments (Figures 2a and b; Brewer et al. 1997). These are the only two scheme pairs for which the rendition preferences of subjects with impaired vision were not significantly different than 50 percent. In both cases, the preference percentages were 62 percent for the accommodating rendition and 38 percent for the confusing, multi-hue rendition (Table 2c), which are percentage splits similar to the preferences of subjects with normal vision.

This deviation from the overall results occurred only with multi-hue 'confusing' renditions. Results for aggregate sets of schemes (Figure 4; left side of each graph) also show that the average accuracies of the impaired-vision group for responses to confusing renditions are better for the two multi-hue renditions (Set 1: Sp, 2V) than for four other renditions (Set 2: Qa, Qd, D, B; see Figure 4 notes for descriptions of schemes). With the confusing renditions for both sets of schemes, the responses of subjects with normal vision remained more accurate than those of subjects with impaired vision (Table 2a and b). Comparison of results for only two multi-hue schemes does not provide an adequate sample for drawing conclusions about how well people with impaired vision read multi-hue or spectral maps. The results do, however, prompt me to reconsider criticism of spectral schemes as confusing to people with impaired color vision.

The explanation I offer for the higher-than-expected accuracies with, and preferences for, these multi-hue schemes is based on nuances in types of color vision impairments. The Olson and Brewer (1997) experiment was designed to test, as a group, people with four types of impairment that can collectively be labeled red-green impairments. People with more severe impairments are called dichromats and those with less severe impairments are called anomalous trichromats. The latter group have three types of cones (retinal receptors), but one of these has anomalous sensitivity, rather than being a missing or lacking function as with dichromatic vision. Anomalous trichromatic vision (deutanomaly and protanomaly) produces a continuum of impairment severity and affects approximately six percent of men and 0.4 percent of women (Table 3). Anomalous vision reduces map readers' sensitivity to color differences, though they may still be sensitive to large hue differences that span color space and confuse dichromats. Thus, fully saturated



**Figure 4.** Graphed results of testing color schemes with subjects with impaired color vision (Olson and Brewer 1997). Solid lines for scheme Set 1 show better accuracy and higher preference ratings than the dashed lines for Set 2 for confusing renditions of map schemes. Figures 4a, b, and c correspond with Table 2 subsections a, b, and c.

Notes: Content questions (Figure 4a and Table 2a) required interpretation of map patterns. Matching questions (Figure 4b and Table 2b) required matches of map colors to legend colors. Both schemes in Set 1 (Sp and 2V) pair a multi-hue confusing rendition with an accommodating rendition that has a more restricted hue range. Set 1 schemes are Sequential-polychrome (Sp) and Two-variable (2V) (colors are specified and maps printed in Olson and Brewer). Confusing and accommodating renditions for Set 2 schemes are either both multi-hue or both of limited hue range. Set 2 schemes are Qualitative-area (Qa), Qualitative-dot (Qd), Diverging (D), and Balance (B) (colors are specified and maps printed in Olson and Brewer). A seventh scheme, Sequential-monochrome (Sm), was tested but is excluded from Set 2 because both renditions included lightness sequences and, therefore, they were not expected to be confusing for most subjects with impaired vision.

colors of a spectral scheme may be identified by anomalous trichromats. They may even prefer to work with a full-saturation spectral scheme, which would generally be rated as potentially confusing because colors align with confusion lines that characterize red-green impairments as a group (see Figure 5).

### Variation in Color Vision Impairment

I expect that many people with anomalous vision will prefer fully saturated colors that may fall along confusion lines but lie beyond their shortened range of confusion. They may be critical of color choices planned for them because they are

Red-green Impairment	Percentage occurrence among	
	males	females
<b>Dichromatic vision:</b>		
protanope	1.0	0.02
deutanope	1.0	0.01
<b>Anomalous trichromatic vision:</b>		
protanomaly	1.0	0.02
deuteranomaly	4.9	0.38

**Table 3.** Frequency of color vision impairments. (Source: Wyszecki and Stiles 1982, p. 464).

not aware that we are attempting to accommodate different types of impairments and different degrees of impairment as a group on maps designed to be accommodating. Because of the variation in impairment, displays that are not customized for a particular individual and are intended to be read by many people with red-green impaired color vision should be designed for dichromats, who are the most severely impaired. These schemes will also accommodate anomalous trichromats, even though they may prefer more colorful schemes.

The research of Regan et al. (1994) demonstrated variation in red-green impairments, and their results assist in estimating whether spectral schemes accommodate color-vision impairments. They described the range of chromaticities that look the same to people with impaired color vision. Their sample included dichromats (protanope, deutanope, and tritanope) and anomalous trichromats (protanomaly and deuteranomaly). Deuteranomaly is the most common type of impairment, affecting 4.9 percent of men (Table 3). Unfortunately, deuteranomaly varies widely in severity, so schemes must either be customized for individuals in an interactive environment or designed for the worst-case impairment which is equivalent to that of deutanopes.

Regan et al. (1994) examined confusions between CRT colors in 20 directions from three separate colors using CIE 1976  $u'v'$  color specifications. Ellipses were fit to the scatter of points for colors that subjects were just able to discriminate from each of three test colors. Ellipses drawn on  $u'v'$  diagrams were used to summarize their results (Figure 5). Each ellipse encircles a range of colors that are not discriminated by an individual subject. Ellipses for subjects with the complete range of red-green impairments align in the directions of protan and deutan confusion lines, and the major axes of these ellipses vary greatly in length. Thus, some subjects diagnosed with extreme anomalous vision made the same wide range of confusions as dichromats, and some with anomalous vision could discriminate

between the test colors as accurately as could subjects with normal color vision. The continuum of ellipse lengths in Figure 5 illustrates the continuum of severity of impairment that characterizes anomalous trichromats. Ellipse widths also provide guidance on the general width of confusion lines, and that permits mapmakers to estimate how far away from a confusion line colors should be to look different.

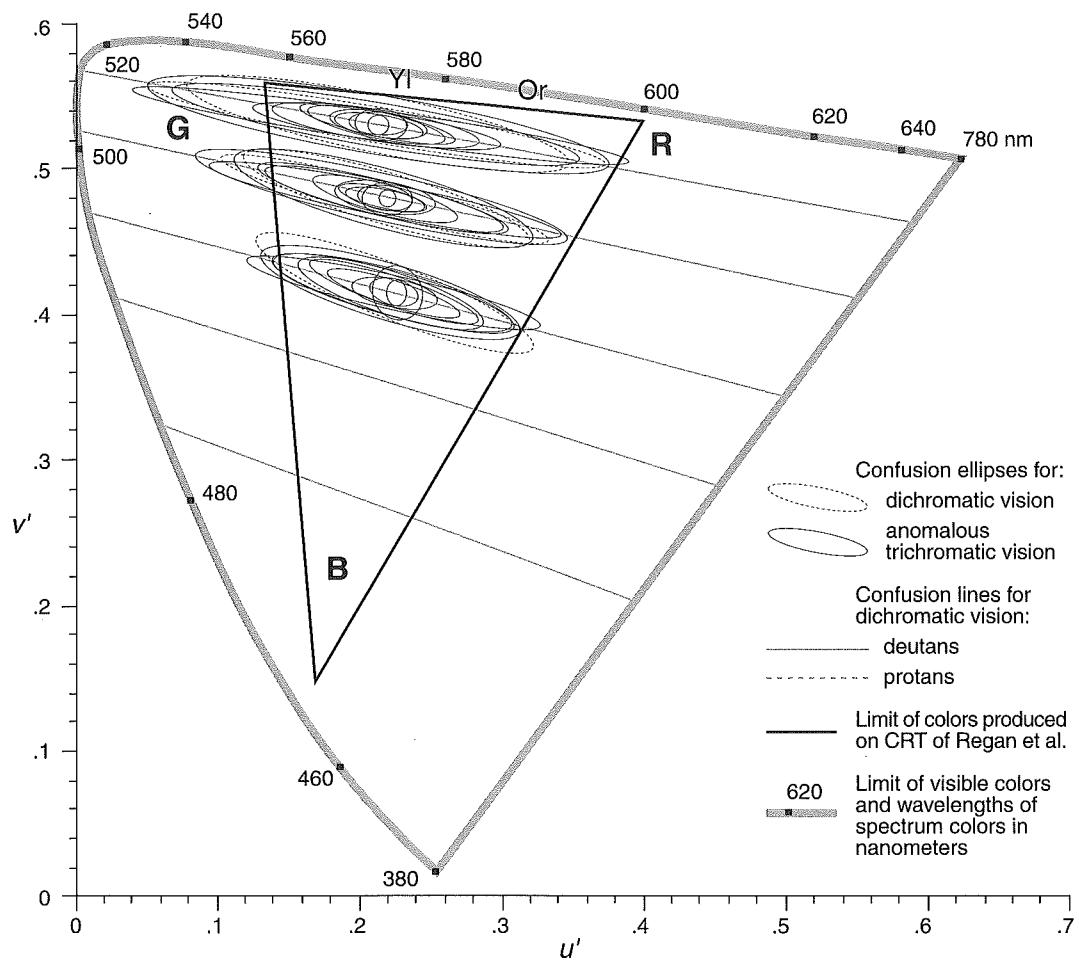
## Recommendations on Color Use

### Spectral Schemes for Impaired Vision

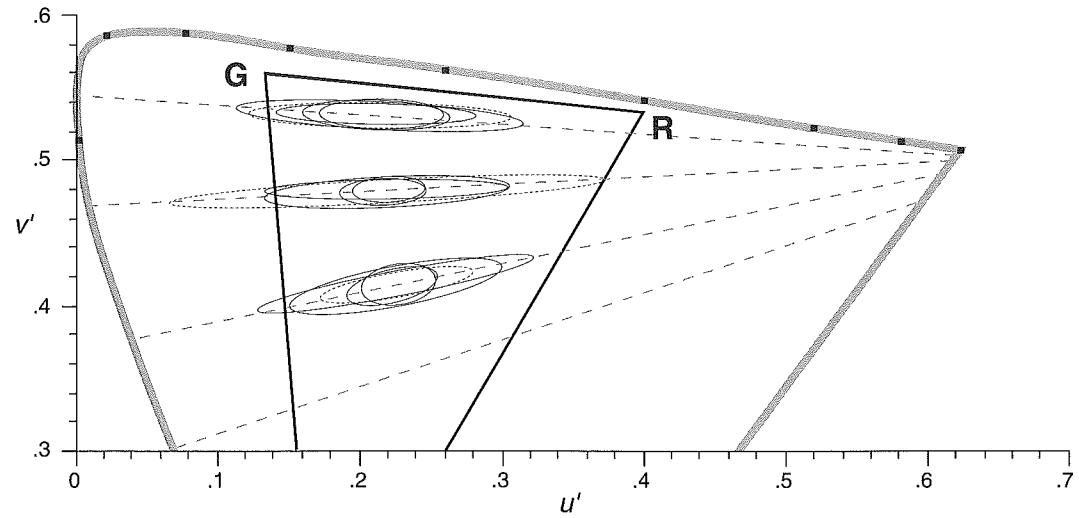
Based on both the width and orientation of these confusion ellipses (Figure 5), I can recommend a spectral color scheme that should accommodate all red-green color-vision impairments (Figure 6). The yellow-orange-red sequence is aligned with confusion lines, but this sequence can be designed to include a lightness sequence while also maintaining color saturation for readers with normal vision. Different anomalous trichromats will see different amounts of hue within this range, but all readers with red-green impairments should be able to interpret the lightness differences in this sequence. Protanopes have difficulty seeing reds, but this aspect of their impairment should not interfere with map reading because it increases the lightness contrast within the sequence, which would then appear to range from a light color to an even darker color.

As mentioned earlier, yellow-green is likely to be confused with orange. The key, therefore, is to omit yellow-green from the sequence of hues. Stepping from yellow to a light bluish-green shifts far enough from the confusion line that runs through orange to produce a hue difference visible with impaired vision. The lightness sequence from yellow through blue-green, blue, and purple-blue runs perpendicular to the direction of the confusion lines and therefore includes hue differences visible with both normal and impaired vision. The recommended spectral scheme of red, orange, yellow, blue-green, blue, and purple-blue (Figures 3f and 6) is akin to a sequence of dark gray, medium gray, light gray, blue-green, blue, and dark purple-blue for map readers with impaired vision. Lightness is organized in an orderly and logical manner and no colors are confusing because lightness differences carefully compensate for hue confusions.

A similar diverging scheme that is not as colorful as a full spectral scheme but also accommodates



a. Confusions with Deutanopic and Deuteranomalous Vision



b. Confusions with Protanopic and Protanomalous Vision

**Figure 5.** Composite of results of Regan et al. (1994). Each ellipse encloses a range of colors that look the same to a person with a red-green color-vision impairment. Dashed ellipses are confusions of dichromats and solid ellipses are confusions of anomalous trichromats. Note the great range in severity of impairment with anomalous color vision. Ellipses are oriented in the direction of confusion lines that connect colors predicted to look the same with dichromatic vision. These are the same confusion lines tested in Olson and Brewer (1997) using the CIE 1931  $xy$  chromaticity diagram. The chromaticity diagram shown here is the 1976 transformation to  $u'v'$ , which has better perceptual scaling than  $xy$  (see Brewer (1996) for further discussion of this transformation). The RGB triangle outlines the range of colors that could be mixed on the CRT used by Regan et al. (1994). (Source: Figures 8, 9, and 10 in Regan et al.).

people with impaired color vision includes the standard red, orange, yellow sequence and then continues with a sequence from light blue to dark blue with no hue transition. Example applications of this scheme observed in literature are maps of changes in monsoon rainfall (Mudur 1995, p. 1922) and tide anomalies with glacial isostatic adjustment (Davis and Mitrovica 1996, p. 848). In both examples, the yellow/light-blue boundary appropriately marks zero change on the maps.

## Spectral Schemes in Scientific Visualization

In an interactive visualization environment, researchers should be controlling the color schemes used to represent their data. Often their choices are spectral schemes, which have come to typify scientific data displays. Cartographers can not stop people from selecting spectral schemes and we can not stop programmers from offering these schemes as standard options within visualization software. Certainly few have heeded the many admonitions quoted at the beginning of this paper. Thus, I think we should change our approach, and join in the pleasure of creating vibrant colorful maps. What we can usefully offer is guidance that improves these spectral maps.

Multi-color schemes can be structured to accommodate red-green color-vision impairments and to parallel either sequential or diverging data organizations. Four approaches are listed:

- ♦ The dark-light-dark diverging spectral scheme in Figure 6 is one recommendation: dark red, oranges, light yellow, blue-green, blues, dark purple-blue (Figures 3f and 6).

- ♦ An ordering of light yellow, orange, dark red, magenta, purple, light purple-blue takes advantage of the darker reds seen by protanopes to produce an opposite diverging arrangement of light-dark-light (approximated in Figure 3j). This reversal is similar to using light colors for high data values with a sequential scheme, so it should be used with care.

Examples of light-to-dark sequential schemes that range through many hues are:

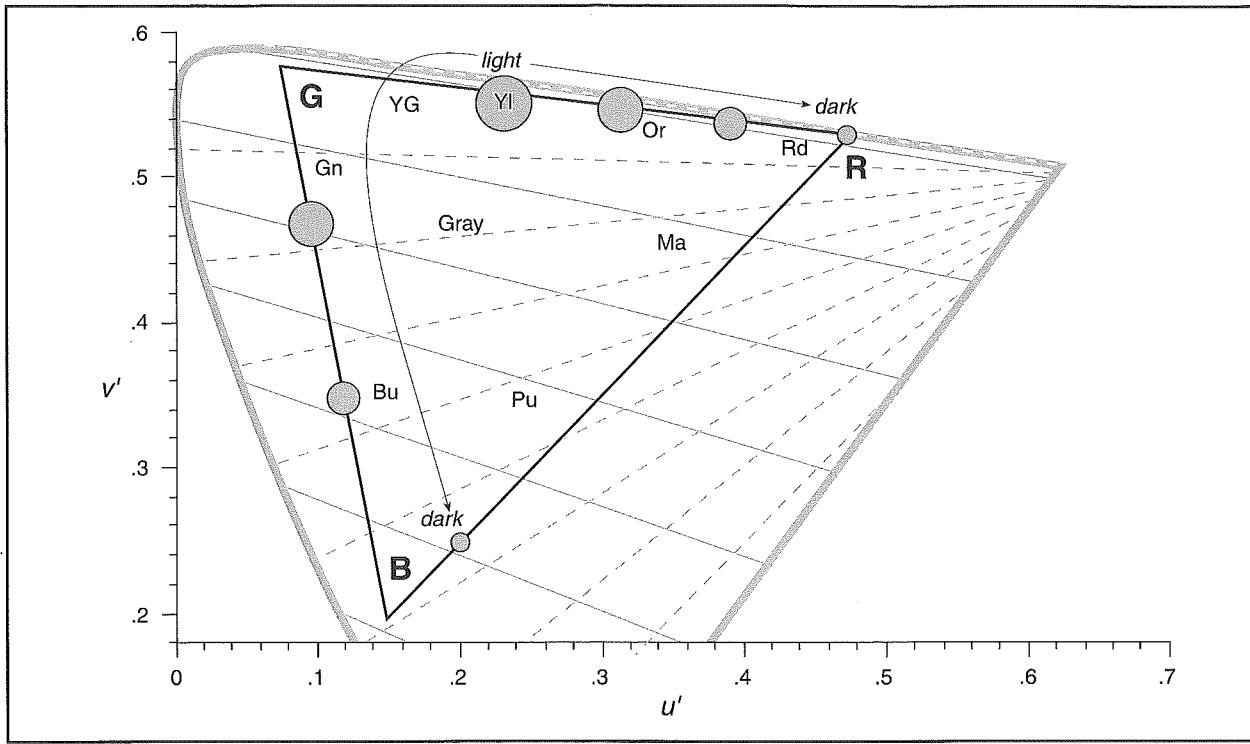
- ♦ light yellow, orange, red, magenta, purple, dark blue (Figure 3m); and
- ♦ light yellow, green, blue-green, blue, purple, dark magenta (Figure 3n).

Research on the perception of lightness sequences that span a range of hues is needed to confirm the effectiveness of these schemes for people with normal and red-green impaired color vision.

It is also possible that warnings that spectral hues are not ordered by adults may no longer be valid. Spectral hues may now be spontaneously ordered in the public consciousness after continuous exposure to popular spectral graphics on topics such as the ozone hole and weather. The contradiction between the lack of perceived order for spectrum colors and the likelihood that the public is learning this code, through its use on most scientific visualizations that enter the public sphere, is a topic ripe for further research.

## Summary

Spectral schemes are logical and effective representations of geographic data distributions which include a mid-range critical value. As with two-hue diverging schemes, both extremes of the data range should be of interest, and a critical point within the data range should correspond with the lightest colors when spectral schemes are used (Figure 3c). Skipping over the yellow-greens in a spectral sequence should accommodate map readers with red-green color-vision impairments (Figure 3f). The light yellow in a spectral scheme is a high-contrast color, and the spatial arrangement of the corresponding portion of the data range marked with yellow will be visually prominent in the image. If this pattern is irrelevant to understanding the distribution, a colorful alternative that maintains a single lightness sequence should be considered (Figure 3m-o). If a critical point in the data range does exist, a spectral scheme should be arranged so that this portion of the data range is symbolized with yellow (like Figure 3c; not like 3b).



**Figure 6.** Proposed spectral scheme that accommodates red-green color-vision impairments. The yellow, orange, red progression includes a lightness sequence so these colors are differentiable by lightness, though they are not differentiable by hue because they fall along confusion lines for all types of red-green deficiency. Yellow-greens are omitted from the scheme because they are on the same confusion line as orange and are similar in lightness. The blue-green used contains enough blue to pull it well below the confusion lines that run through orange and red. The lightness sequence of blue-green, blue, purple-blue also includes hue differences that are seen with color-vision impairments, since these colors do not share confusion lines. The RGB triangle shown is for a generic set of additive primaries. RGB specifications for individual colors are not offered because resulting colors may differ greatly between CRTs. If color measurement is unavailable, producing saturated colors that look like dark red, medium red-orange, light orange-yellow, very light yellow, light blue-green, medium blue, and dark purple-blue will yield a fair approximation of this recommended scheme (see Figure 3f for approximation).

In comparison to choropleth map design, mapmakers have greater design flexibility for color schemes representing data that occur in a predictable order on the map, i.e. a smoothly changing and continuous distribution. If many classes are desired, the mapmaker may use repeating sequences of lightness within multiple hues (Figure 3g), or use alternating lightness differences (light-dark-light-dark... Figure 3a) between adjacent hues to increase contrast. These symbolization choices for data that appear in only one order, as on a map with filled isarithms, reduce the role of color to defining form contours, enhancing memory of the pattern, and aiding reading of specific map information (Mersey 1990). The isarithms then define the structure of the distribution. In this context, though, peculiarities in the perceptual orderings of colors are not overly distracting because memory is not required to understand the color order; the colors are always in order on the map.

The conventional wisdom in cartography is that spectral schemes on maps of quantitative data are inappropriate. This conventional wisdom is based on the assumption that all quantitative or ordered data is sequential in nature, that low-to-high must be paralleled by light-to-dark symbols. The results of recent research indicate that spectral schemes will work well in many contexts by emphasizing the diverging structure of quantitative data. Experimental work in cartography is the most convincing way to challenge conventional wisdoms. I hope that these recommendations encourage further research on color use on maps.

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