Do No Harm: Are Rainbow Colormaps Dangerous?

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Abstract

This document addresses the controversies and contradictions surrounding colormaps using a rainbow color scheme in data visualization. Colormaps are used frequently in science and its applications to display complex data sets by representing data points as colors on a spectrum. The scientific community is divided on whether the default 'jet' or rainbow colormap is best for data visualization. Some point to evidence in medical imaging that suggests the rainbow colormap distorts data, resulting in slower and less accurate data interpretation. Others have shown that the scientific community is used to reading graphics with rainbow color schemes and are no less accurate than others who use a different color scheme. This document finds that rainbow colormaps are generally inferior to perceptually uniform colormaps. However, it seems that rainbow colormaps are not the main cause of diagnostic error, though there is sufficient evidence showing that diagnostic errors do occur. To avoid errors in data interpretation, some scientific software programs have changed their default colormap away from the rainbow scheme. Nevertheless, many find the rainbow colormap to be aesthetically pleasing and continues to be used extensively in medical imaging.

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I. Introduction

Scientific progress depends on the proper evaluation of evidence from data. The evaluation process usually starts by visualizing data produced from an experiment or procedure. For example, a radiologist determines the type and severity of a bone fracture by looking at an image representation of X-ray data. Data sets with one or two variables are generally easy to visualize. When a data set has three or more variables, it is much harder to show all the variables on one visualization. Color is commonly used to show three or more variables in one visualization.

A common way to represent data with color is by using a colormap—a function that assigns data points to an ordering of colors. Nathaniel Smith calls colormaps "an interface between the data and your brain [?]." A scientist interested in visualizing a data set must choose a colormap that reflects the nature of the data. When judiciously chosen, colormaps reveal hidden structure that would go unnoticed otherwise. A careless colormap selection, on the other hand, may distort the data and lead viewers to misinterpret the data. This can have serious consequences, especially in medicine and public health. Doctors rely on visualization software to interpret medical data correctly and properly diagnose and treat disease. Public health policy is also decided based on data often presented in visual form. While scientists agree that data analysis should be rigorous, consistent, and reproducible, many disagree over the proper use of color in data visualization—especially rainbow colormaps.

Despite visually distorting the data, many scientists prefer a rainbow color scheme for its aesthetic appeal and historical use in scientific publications. This literature review explores the advantages and disadvantages of rainbow colormaps, why they are preferred by some scientists and discouraged by others, and how spectral color schemes are used in applied data analysis. First, this review gives a basic summary of the color theoretic properties of rainbow colormaps. Then, it will address color perception issues of spectral color schemes, including color vision impairment. Finally, rainbow colormap applications are discussed in medical imaging and cartography.

II. Colormap Fundamentals

To represent data as color, the data must first be converted into RGB values by way of a colormap. The computer then turns the RGB values into light, projected from a screen. When the light reaches our eyes, photorecpetors called cones detect certain wavelengths of light and send that information to the brain. The brain then interprets the information and generates the perception we call color [?]. To avoid ambiguity when talking about color, scientists use color models—abstract mathematical representations that describe a color as a collection of numbers.

A. Color Models and Spaces

When a color model is used to produce color on a specific medium, the resulting set of colors is called a color space. For example, the RGB model describes color as the combination of red, green, and blue light. A computer screen renders color using the RGB model, thus the color produced by digital screens with the RGB model is a color space. Another example is the CMYK model, which describes color as combinations of cyan, magenta, yellow, and black. Printers produce colors using this model. [?]. The combination of cyan, magenta, yellow, and black ink on a specific printer constitutes a color space. The selection and modification of color models and spaces happens before colormaps or data visualizations can be created.

Most color spaces produce a similar set of colors. However, there are some colors that do not translate well between color spaces. For example, consider the image shown in Figure 1 and Figure 2. When this document is viewed digitally, the colors will look different than the colors on a printed copy. This represents a transformation from an RGB color space to a CMYK color space [?]. Color changes when transformed. This is the motivation for developing perceptually uniform color models, as in the CIECAM02-UCS color model. Good models of color distance may not preserve absolute color, but perceived color difference tends to remain the same across all media [?]. Perceptually uniform colormaps can be produced using these models [?]. In general, rainbow colormaps are not perceptually uniform because the lightness is not consistent.

This has not stopped some from attempting to modify—and therefore preserve—the rainbow colormap. The adjustments refer to the Munsell color specification system, which describes color with hue, saturation, and lightness. "This system divides up the colors humans are capable of perceiving into equal perceptual divisions of color lightness and color saturation for each color hue. [?]" Hue refers to the attribute generally associated with the color name (i.e. red, orange, yellow, green, blue). On a color wheel, hue is the position of the color on the color wheel. Saturation is the intensity of the hue. In physical terms, it is the purity of the light wave frequency. Lightness is the amount of light emitted by a color. Low lightness results in a darker color; high lightness results in a lighter color. [?]. Sisneros et al created a colormap modification framework that smooths the variation in luminance (or lightness) and chromaticity, which is a combination of saturation and hue. Their method can be applied to any perceptually non-uniform colormap. However, they focused their efforts on improving the rainbow colormap, since it is still widely used in science. Their improved rainbow colormap contains subdued colors that better represent image data [?].

B. Color Schemes

There are three main types of color schemes that define a colormap. Sequential color schemes vary in lightness but do not vary in hue. If two sequential color schemes have different hues and are connected at their lightest ends, it is called a diverging color scheme. Qualitative color schemes vary in hues with little variation in lightness and saturation [?]. The rainbow colormap uses a continuous, qualitative color scheme. The images in Fig. 2 are examples of image data plotted with sequential, diverging, and rainbow colormaps.

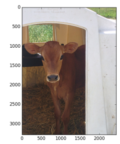

Fig. 1. An image of a calf. This and corresponding images were created by the author.

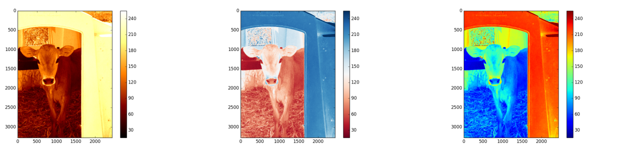

Fig. 2. The calf image plotted with a sequential, diverging, and rainbow colormap.

C. Colormaps

The main problem when designing a colormap is that there is no natural ordering of the colors from least to greatest. Some might argue that there is a natural ordering—the brain's interpretation of the electromagnetic spectrum. Based on light wave frequency, this color ordering is rainbow-like with respect to the color hues [?]. It starts with red and on to orange, yellow, green, blue, and so forth. This is the foundation for the rainbow colormap. It was especially popular among physicists and soon grew to become the default in many scientific software applications [?], [?]. However, this colormap was not created for data representation. It was designed based on accurately representing light waves, not data.

What are the criteria for evaluating a colormap? Several authors have created methods to evaluate color choice. In one paper, color schemes are evaluated by three variables of the CIELUV color model. The first is color distance. The CIELUV model is designed to measure distance between colors. If the distances are equally spaced, thats a good thing. Linear separation is the second variable. It refers to the ability to separate targets from non-targets in the colour model being used. For example, suppose a doctor wants to identify a tumor and uses a colormap to display the data. If the colors are not linearly sepparable in the color model, it will be more difficult to identify the tumor even if the colors are mathematically different. The third variable is color category. This refers to color regions in which there are both target and non-target elements [?]. These characteristics do not account for multidimensional data projected into two-dimensional space. CheckViz attempts to account for this problem by using a perceptually uniform color coding so that distortions such as those described above are accounted for when scientists want to visualize multidimensional data [?]. The specific criteria of the color model and color space must reflect the attributes of the colormap.

Sometimes, when color encodings are converted to grayscale, it can alter the perception of the data. There are many algorithms to cast a color encoding to grayscale.

Colormaps have a variety of properties that make them unique and potentially useful. However, there is controversy among scientists and visualization experts over certain properties of the rainbow colormap. First, the rainbow gradient is not a perceptually consistent ordering of colors. Similarly, it is not perceptually uniform as the variation in lightness is inconsistent. Finally, the rainbow colormap traverses through many highly saturated colors in color space.

There are multiple advantages to using rainbow colormaps. For one, it is clear that users tend to prefer it over other colormaps for its aesthetic appeal [?], [?], [?]. The variety in hue also can accentuate relationships in the data than a sequential, single-hue colormap. History is an advantage.

However, the advantages can also be disadvantages. When accentuating relationships, a human interpreter might see signal where there is none. This seems to be what happens when the data lie in certain regions (as in between blue green and yellow) [?].

Readers of scientific literature will recognize the rainbow colormap. It appears often in scientific publications and has broad appeal in the scientific community [?], [?], [?], [?]. Historically, rainbow colormaps like MATLABs jet have been the default colormaps used in data-handling software [?]. Despite its prevalence, many scientists oppose rainbow-gradient representations of data [?], [?], [?], [?]. In one study, medical students were asked to identify risk factors for heart disease in visualizations of artery data. On average, the participants using rainbow-colored visualizations took more time and made more errors than participants using divergence-colored visualizations. Furthermore, the participants thought they did well using the rainbow color map even when in reality they did not perform as well as the participants who used the diverging color map [?]. This compelling evidence suggests that the rainbow colormap is clearly inferior to other colormaps.

Others disagree. They claim that users have learned to read data with the rainbow colormap and prefer its aesthetic appeal [?], [?]. One experiment tested data interpretation accuracy under diverging, sequential, and spectral (rainbow) color schemes. Of 63 subjects who evaluated spectral and sequential schemes, 56 percent selected spectral as the best...We had expected the spectral scheme to interfere with map-reading accuracy and with understanding map patterns, but this did not occur, Brewer writes. Our subjects preferred the spectral scheme and performed well with it [?]. While the rainbow colormap did not outperform other colormaps, it appears to do no harm. Users can accurately interpret rainbow-colored data visualizations.

III. Color Perception

One of the advantages of using perceptually uniform colormaps is that they show the data accurately even if the colors do not appear the same. Color perception can change for a number of reasons. When colors are placed near each other, it changes the way our eyes see that color. The brain adjusts the amount of light that enters the eyes based on external conditions. For example, colors appear more bright under diffused light. Competing bright colors also diminishes the overall perception of their brightness.