

Do No Harm: Are Rainbow Colormaps Dangerous?

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Abstract

This document addresses the controversies and contradictions surrounding colormaps in data visualization. Colormaps are used to display complex data sets by representing data points as colors on a continuous color scale. 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 ability to interpret data correctly. Data visualization is a process of constructing visual representations of data that allow the data to be interpreted quickly so that decisions can be made. For example, a radiologist determines the type and severity of a bone fracture by looking at an image representation of X-ray data. This allows her to make decisions on what treatments will be most effective for the fracture. While most bone fractures are easy to see using X-ray technology, some data insights are harder to find. For complex data sets, color can be used to highlight important features of the data by turning data points into colors. While the benefits of using color are clear, scientists disagree over how colors should be used when representing data, especially regarding the choice of colormaps.

A colormap is a function that assigns data points to an ordering of colors. Nathaniel Smith calls colormaps “an interface between the data and your brain [1].” 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 [2], [3]. Doctors rely on visualization software to interpret medical data correctly and properly diagnose and treat disease. Citizens and politicians vote on public health policy based on data presented in visual form. Each scientific discipline has developed standards that determine how to perform rigorous, consistent, and reproducible data analysis. However, there is debate among scientists about colormap standards in data visualization—or whether there should be colormap standards at all.

Of all the colormaps available, none draws more criticism and debate than colormaps that use a rainbow color scheme. The canonical example of a rainbow colormap is MATLAB’s ‘jet’ colormap. This and other rainbow colormaps are commonly the default colormap in scientific computing software [1], [4]. Despite research showing that rainbow colormaps visually distort data, many scientists prefer a rainbow color scheme for its aesthetic appeal and history of use in scientific publications. This literature review explores the advantages and disadvantages of rainbow colormaps, why they are pre-

ferred by some scientists and discouraged by others, and how spectral color schemes are used in applied data analysis. First, I will give a basic summary of the color theoretic properties of rainbow colormaps. Then, I will address color perception issues of spectral color schemes, including color vision impairment. Finally, I discuss rainbow colormap applications in medical imaging and cartography.

II. COLORMAP FUNDAMENTALS

Colormaps assign data points to colors. While seemingly straightforward, this precise assignment depends heavily on sophisticated mathematics and research in human perception. Color is both a physical phenomenon and a perceptual illusion. When light reaches our eyes, photoreceptors called cones detect wavelengths of light. The cones send signals to the brain, which interprets the information, and generates the perception we call color [1]. Not all humans perceive the same colors equally however. In fact, the question of whether two colors are equal has motivated research in color theory for decades and continues to play a central role in colormap evaluation—especially rainbow colormaps.

A. Color Models and Spaces

To avoid ambiguity when talking about color, scientists use color models—abstract mathematical representations that describe a color as a collection of numbers. 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. The color produced by digital screens with the RGB model is a color space. Another important example is the CMYK model, which describes color as combinations of cyan, magenta, yellow, and black. Printers produce colors using this model. [5]. The different combinations of cyan, magenta, yellow, and black ink used by a printer constitutes a color space.

Most color spaces produce a similar set of colors. However, some colors do not translate well between color spaces. Consider the following list:

- Blue
- Red
- Green
- Orange

When this document is viewed digitally, the colors will look somewhat different than the colors on a printed copy. This represents a transformation from an RGB color space to a CMYK color space [6]. Color may not appear the same when transformed from one color space to another. This is problematic if color needs to be consistent across different media when presenting data visualizations. Issues such as these led to the development of sophisticated color models. To understand why there is so much debate over colormaps today, it is helpful to understand a brief history of color model development.

B. Color Model Development

Much of the early work in color theory was focused on describing light as a physical phenomenon. The first of these was the trichromatic theory of color. Developed by Thomas Young in 1802 and extended quantitatively by Hermann von Helmholtz in 1894, the theory revealed that photoreceptors in the retina of the eye responded to long, medium, and short wavelengths of light, roughly corresponding to red, green, and blue color [?].

Shortly after, the first breakthrough in color perception came when Albert Munsell developed the Munsell Color Specification System by performing experiments using colored paint chips. This system describes color as made up of three independent variables—hue, chroma, and value or lightness. This development led to the more widely known HSL/HSV model which describe the perceptual attributes of color as combinations of hue, saturation, and value or lightness [?], [5]. “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. [5]” 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. [7].

While the Munsell color system was a good way to describe the appearance of color, it did not prescribe a way to create the same colors consistently. This required rigorous and more precise color models. In the early twentieth century, The

Commission Internationale de l’Eclairage (CIE) began developing robust color models that allowed for color consistency. It was CIE who first developed the first reliable RGB color model and they continue to develop color models [?].

After the RGB model, CIE developed the CIEXYZ model in 1931 which became widely accepted. It is still used today [1]. Its development was focused on converting measurable, physical properties of light into a model that represented human color perception by way of color matching experiments [?]. The model compared various colors with different light wavelengths and tested them to see if humans could distinguish between colors with these different wavelengths. This model allowed us to determine precisely which wavelengths humans are capable of seeing, thereby leading to a rigorous definition of the rainbow color spectrum.

This was a large advance in color theory. However, the CIEXYZ color model is not a model of color distance. Thus, CIE set out to create a model of color distance. In 1976, CIE produced two uniform color models, CIELUV and CIELAB [?]. In 2002, CIE released new developments in perceptually uniform color models with the CIECAM02 model family. One of the primary differences between CIELAB and CIECAM02-UCS is that the latter is more perceptually uniform between similar colors than distant colors. CIELAB is a good model of perceptual color distance for very different colors, but it is not as good a model of the distance between similar colors. CIE now recommends using the CIECAM02-UCS model as it is the best perceptual model of color distance to date [8].

The motivation for developing perceptually uniform color models is to produce consistent colors across different media. Good models of color distance may not preserve absolute color, but perceived color difference tends to remain the same across all media [8]. Perceptually uniform colormaps can be produced using these models [1].

C. Color Schemes and Colormaps

Which color is bigger: red or blue? This illustrates the main problem when designing a colormap: there is no natural ordering of the colors from least to greatest. Some argue that there is a natural ordering, namely by light wavelength. The brain’s interpretation of this ordering produces the familiar

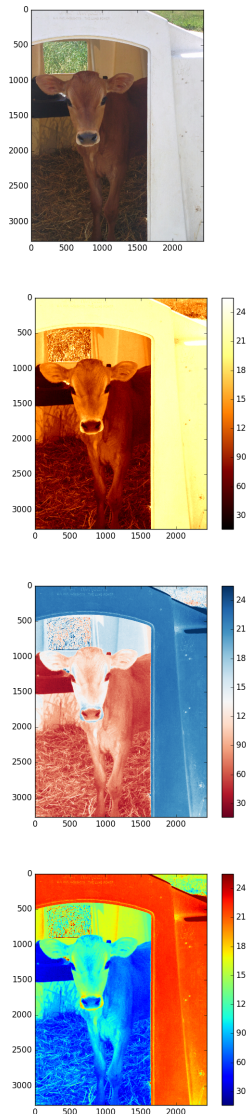


Fig. 1. An image of a calf. The calf image plotted with a sequential, diverging, and rainbow colormap. These images were created by the author.

rainbow spectrum of color hues starting with red, then orange, yellow, green, blue, and so forth [5]. 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 [4], [9]. However, this colormap was not created for data representation. It was designed based on accurately representing light waves, not data.

Other colormaps take a different approach. Color ordering can be constructed by choosing an appropriate color scheme. 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 [5]. The rainbow colormap uses a continuous, qualitative color scheme. It is also known as a spectral scheme [10]. The images in Fig. 1 are examples of image data plotted with sequential, diverging, and rainbow colormaps.

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. Since CIELUV is a model of color distance, designed to equally spaced colors on a colormap is considered good. The second variable is Linear separation. This refers to the ability to separate targets from non-targets in the colour model being used [11]. For example, suppose a doctor wants to identify a tumor and uses a colormap to display the data. If the colors are not linearly separable, it will be more difficult to identify the tumor even if the colors are mathematically different. The third variable is color category, which refers to color regions where there are both target and non-target elements [11]. 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 [12]. The specific criteria of the color model and color space must reflect the attributes of the colormap.

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 [3], [10], [13]. The variety in hue also can show relationships in the data better than a sequential, single-hue colormap. The rainbow colormap also has a long history of use in scientific publications

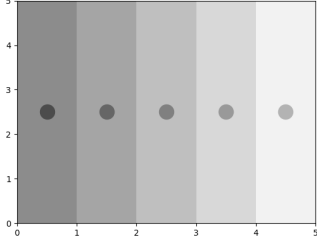


Fig. 2. An example of simultaneous contrast.

and many are already used to reading data from this colormap.

However, the advantages can also be disadvantages. A human interpreter might see signal where there is none. These false signals are known as artifacts and they seem to occur more often when the data lie in certain regions (as in between blue, green, and yellow) [11].

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.

Some colormaps, like Matlab’s *perula* colormap, are designed to be perceptually uniform in the CIELAB color space [1]. While not completely uniform, they provided the best notion of perceptual uniformity until the CIECAM-02 models were developed in 2002. The open source colormap *viridis* created by Smith and van der Walt, uses the CIECAM02-UCS color space to provide a perceptually uniform color space more consistent with small differences in data values [1]. There has been little to no research on the effects of using this most recent model on colormap development.

An example of color perception under different conditions is the color-of-the-dress meme that became popular in 2015. The picture was sent on social media sites asking whether the dress was black and blue or white and gold. This effect happens

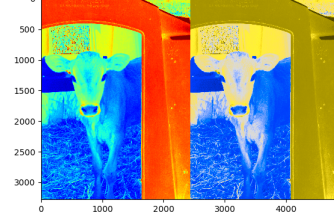


Fig. 3. The rainbow colormap image (left) and a colorblind approximation of the same image (right).

because our eyes perform a kind of normalization under different light conditions. This adjustment alters the perception of what the colors look like [1]. The same shade of gray can appear very different as the surrounding color changes. Even though the colors are the same, they appear to be different because of the context that they are in. This means that sometimes we see color differences even when there are none. Other times, color differences can’t be detected easily or at all. This is especially common among people who have some form of color vision impairment, or colorblindness. Sometimes, when color encodings are converted to grayscale, it can alter the perception of the data [6].

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. 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 colormap to make it perceptually uniform. 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 [14].

A. Colorblindness

Colorblindness results in colors falling on confusion lines—lines in which it is difficult or impossible to distinguish between two colors [5]. People with full color vision also have confusion lines and so in some sense are colorblind because we can’t

see the entire spectrum of light as colors. However, color deficient viewers are special in that they do not see the normal range of colors as their peers. There are multiple kinds of colorblindness. Full color deficiency results in black and white vision and is very rare. The most common form of color deficiency results in confusing shades of red and green [11].

For these genetic color deficiencies, it seems reasonable to design data visualizations with colorblindness in mind. The estimated colorblind population is somewhere around 5-8% and affects mostly males of European descent [5]. Unfortunately for the rainbow colormap, the colors that a colorblind user sees are not the same as those seen by a person with full color vision. Especially for high values, which are displayed in reds, the variation in green is not easy to interpret for colorblind viewers [?]. In fact, though they are aesthetically pleasing, people are slower at interpreting data with large variations in color and make more errors [2]. Yet, colorblind people still seem to get by fine.

Color deficient viewers use clues to distinguish between colors that easily confuse them. Brewer has conducted extensive research into how color deficient viewers interpret color-encoded information. She has suggested several ways in which maps and information visualizations can be designed to help color deficient viewers. A common theme in her research, as well as others, is that colormaps are greatly improved when the dark-to-light variation is controlled and used to show progression [?]. This is the idea behind perceptually uniform colormaps. Even when converted to black and white, the visuals still preserve the nature of the data and are easy to interpret.

IV. APPLICATIONS AND ALTERNATIVES

Readers of scientific literature will recognize the rainbow colormap. It appears often in scientific publications and has broad appeal in the scientific community [3], [9], [10], [13]. Historically, rainbow colormaps like MATLABs jet have been the default colormaps used in data-handling software [4]. Despite its prevalence, many scientists oppose rainbow-gradient representations of data [1], [2], [9], [13]. 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 [2]. 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 [3], [10]. 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 [10]. While the rainbow colormap did not outperform other colormaps, it appears to do no harm. Users can accurately interpret rainbow-colored data visualizations.

The controversy surrounding the rainbow colormap does not appear to be random. Certain industries disagree on how much the rainbow colormap should be discouraged. There is general agreement that rainbow colormaps are not as precise as perceptually uniform colormaps in representing data [6]. However, this does not mean that rainbow colormaps are discouraged in all cases [10]. Among the many uses of the rainbow colormap in the literature, the two most cited are medical imaging and cartography. Both care deeply about the use of color in their respective fields [7], [15]. Even within these applications, the recommended use of the rainbow colormap differs depending on the context.

A. Cartography

Maps are used to show public health information, the spread of disease, weather forecasts, and other demographic data. This information is important to public policy and public awareness. This information is almost always shown using color. Choosing an appropriate color scheme is not a trivial task. In her article *Mapping Mortality: Evaluating Color Schemes for Choropleth Maps*, Cynthia Brewer shows that a judicious choice of color is “worth

the extra effort and expense” because “it permits greater accuracy in map reading [3].” For public understanding of data, the rainbow colormap seems to do no harm and users tend to prefer it.

Rainbows are not always good for maps, however. An assortment of colormaps were developed and shown to be superior to rainbow schemes when used for oceanography. Sea level is an important metric in these contexts and a rainbow colormap poorly represents the coastline where land and sea meet. In this context, customized colormaps outperform most other colormaps [16]. In contexts where the data are in a particular form that the scientist knows, it is best to create a customized colormap that gives more accurate results.

B. Medical Imaging

The consequences for color misuse in medical imaging are more severe. Research already shows that the potential for diagnostic errors increases when rainbow color schemes are used [2]. In this research, color may not be necessary and only used for convenience. However, some procedures require medical images that must be interpreted using color. In this case, it is especially important that hardware components be standardized so that color can be interpreted effectively. Since there are many manufacturers that produce image processing software and display hardware, there is no consensus which color models or color mappings should be used by the medical community. The Summit on Color in Medical Imaging met to reach a consensus on how to standardize color use [15]. Images that are important to medicine but not exclusively part of the community would not be held to these standards.

Bioinformatics and genetics are two fields related to medicine that could be exempt from the standards set in medical imaging. In fact, many tools are being created now to analyze the vast amount of data that can be collected in genetics. One such tool uses clustering techniques to find biomarkers in gene data. This software is written in Matlab and designed to run on Microsoft Windows and Linux x86 [17]. This specific choice of software uses an older version of Matlab and uses the *jet* default colormap. Software updates and hardware limitations make it difficult to change the visualization system. This may be another reason why doctors prefer the rainbow visualization—it is just too difficult to change.

C. Alternative Colormaps

Many recognize that change is not easy. Some recommend changing colormap defaults instead of setting standards [1]. That way, some consistency can be maintained while still allowing a little variation in the implementation. This is the goal of visualization studies like the one carried out in the development of the HemoVis medical imaging program [2]. This is especially important because it is not feasible for every software to be written independently without dependencies on other software.

V. CONCLUSION

Color is an essential attribute of data visualizations. Representing data with color is best done through a colormap designed specifically for the data in mind. Colormaps require a vast amount of knowledge to be thoroughly constructed. It involves disciplines as different as engineering, computer science, graphic design, and psychology. The recent development in color rendering technology has made it possible to develop and test many different colormaps. In particular, it seems clear the rainbow colormap has many undesirable properties when trying to represent data. It takes more time for viewers to interpret data with this colormap and they tend to make mistakes when the data fall in areas where the color changes do not match equivalent changes in the data. There does not seem to be a problem in cartography and people tend to prefer the rainbow colormap because it is familiar and aesthetically pleasing. Despite these preferences, there is an increasing movement to replace the rainbow colormap as the default colormap in scientific software [4]. Recommended alternatives are colormaps that are more perceptually uniform than the rainbow colormap. The variety of colors is diminished and the darkness-to-lightness progression is more consistent with human perception of color change.

When data must be represented using color, most recommend using a perceptually uniform colormap because it more accurately represents the data and is more friendly to colorblind or color impaired individuals. When colors cannot be changed to accommodate for color impairment, redundancy can be added to the visualization so as to encode the same information the color represents as a small icon or by using a different visual variable such as

position or size. In contexts where data interpretation is to be precise and time-efficient, scientists are discouraged from using the rainbow colormap. In applications where user preferences are valued over representational accuracy, the rainbow colormap is acceptable. However, scientists are encouraged to use perceptually uniform colormaps to phase out the rainbow colormap as a default and replace it with a colormap that more accurately represents a larger variety of data.

We need more research in how to create custom colormaps. No good tools exist except for the things the viridis guys use, and that's only for perceptually uniform colormaps.

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