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 [1]." 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 [1]. 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. [2]. 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 [3]. 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 [4]. Perceptually uniform colormaps can be produced using these models [1]. 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. [2]" 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. [5]. 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 [6].

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 [2]. The rainbow colormap uses a continuous, qualitative color scheme. The images in Fig. 1 are examples of image data plotted with sequential, diverging, and rainbow colormaps.

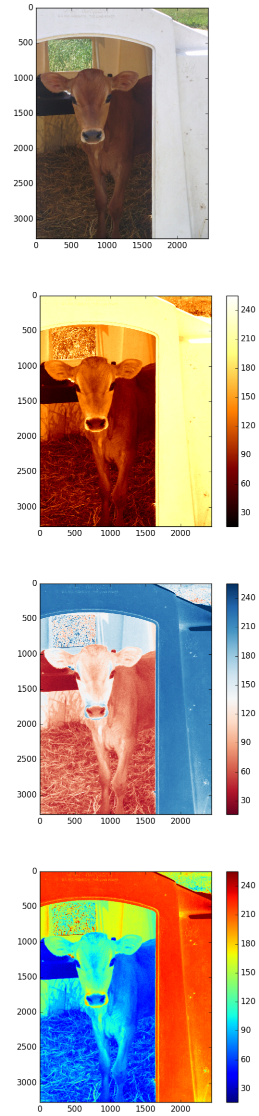

Fig. 1. An image of a calf. The calf image plotted with a sequential, diverging, and rainbow colormap. These images were created by the author.

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 [2]. 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 [7], [8]. 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 [9]. 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 [10]. 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 [11]–[13]. 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) [9].

Readers of scientific literature will recognize the rainbow colormap. It appears often in scientific publications and has broad appeal in the scientific community [7], [11]–[13]. Historically, rainbow colormaps like MATLABs jet have been the default colormaps used in data-handling software [8]. Despite its prevalence, many scientists oppose rainbow-gradient representations of data [1], [7], [13], [14]. 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 [14]. 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 [11], [12]. 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 [11]. 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.

A. Choosing Colors

Mark Rothko and Josef Albers are notable artists who explored the human relationship with color perception. Some colors blend together while others almost appear to be in conflict with each other, causing a perceived vibration in the colors.

Another 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

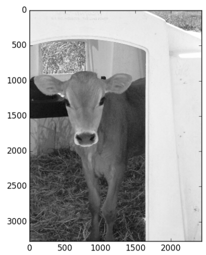

Fig. 2. An Example of colorblind deficiency

because our eyes perform a kind of normalization under different light conditions. This adjustment alters the perception of what the colors look like [1]. Other examples from psychology place the same color in two images with different colors surrounding the color being studied. 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.

B. Perceptual Uniformity

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, as in colorblindness. The estimated colorblind population is somewhere around 5-8% and affects mostly males of European descent [2].

Colorblindness results in colors falling on confusion lines—lines in which it is difficult or impossible to distinguish between two colors [2]. 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 [9].

C. Colorblindness

For these genetic color deficiencies, it seems reasonable to design data visualizations with colorblindness in mind. 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 [14]. 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

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 [**?**]. However, this does not mean that rainbow colormaps are discouraged in all cases [11]. 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 [5], [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 [12]." 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 oceaonography. 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 [14]. 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.

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 [14]. 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 still 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 [8]. 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 accomodate 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 exists except for the things the viridis guys use, and that's only for perceptually uniform colormaps.

VI. Appendix

The following is useful for understanding the development of colormaps and how the rainbow colormap came to be outdated. It also provides some context for colormaps that have been designed using perceptually uniform color models and what advantages they might have over a rainbow colormap.

A. Trichromatic Theory

This theory was developed by Thomas Young in 1802 and extended quantitatively by Hermann von Helmholtz in 1894. This was the first time that the photoreceptors in the retina of the eye responded to three different wavelengths of light—long, medium, and short [**?**]. They were thought to respond to red, green, and blue light.

One reason why the rainbow colormap may be aesthetically pleasing is that it triggers responses in all the photoreceptors in the eye. The rainbow contains many different wavelengths.

B. Munsell Color Specification System and HSV/HSL

This was developed by Albert Munsell in the early 20th century using paint chips. This was one of the first systems to develop the concept that color is made up of three independent variables—hue, chroma, and value or lightness. Later developments added to this model and made the perception of color via these attributes more concrete [2]. The model relies on cylindrical coordinates of colors arranged by these variables. This development led to the more widely known HSL/HSV model [**?**]. These models draw inspiration from the Munsell system and describe the perceptual attributes of color as combinations of hue, saturation, and value or lightness.

C. Commision Internationale de l'Eclairage (CIE)

While the Munsell color system was a good way to describe the appearance of color, there was no rigorous way to define a consistent way to create color. The Commision Internationale de l'Eclairage (CIE) developed the RBG color specification system and continued to develop reliable color models [**?**].

After the RGB color specification system, CIE developed the CIEXYZ model in 1931 which became widely accepted. It is still used today [1]. It's development was focused on converting measurable, physical properties of light into a model that represented human color perception by way of color matching experiments [**?**]. Since humans do not see all light as color, the model collapsed a large variety of light waves into a smaller spectrum that humans could see as color. This is the model typically used in generating a rainbow colormap.

The CIEXYZ color model is not a model of color distance. Thus, CIE set out to define color distance and create a uniform color model based on that notion. In 1976, CIE produced two uniform color models, CIELUV and CIELAB [**?**]. 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.

In 2002, CIE released new develpments in perceptually uniform color models with the CIECAM02 model family. CIE now recommends using the CIECAM02-UCS model [4]. 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 is not as good a model of the distance between similar colors. CIECAM02-UCS 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.

REFERENCES

[1] S. van der Walt and N. Smith, "mpl colormaps," 2015.
[2] A. L. Griffin, *Color, Mapping*, pp. 195–201. International Encyclopedia of Human Geography, Oxford: Elsevier, 2009.
[3] H. Levkowitz, "Color vs. black-and-white in visualization."
[4] M. R. Luo and C. Li, "Ciecam02 and its recent developments."
[5] C. A. Brewer, "Guidelines for use of the perceptual dimensions of color for mapping and visualization," vol. 2171, May 9, 1994.
[6] R. SisnerosB, M. Raji, M. W. V. Moer, and D. Bock, "Chasing rainbows: A color-theoretic framework for improving and preserving bad colormaps."
[7] D. Borland and R. M. T. II, "Rainbow color map (still) considered harmful," *IEEE Computer Graphics and Applications*, vol. 27, no. 2, pp. 14–17, 2007.
[8] S. Eddins, "Rainbow color map critiques: An overview and annotated bibliography."
[9] C. G. Healey, "Choosing effective colours for data visualization," pp. 263–270, 1996.
[10] S. Lespinats and M. Aupetit, "Checkviz: Sanity check and topological clues for linear and nonlinear mappings," *Computer Graphics Forum*, vol. 30, pp. 113–125, Mar 2011.
[11] C. A. Brewer, "Spectral schemes: Controversial color use on maps," *Cartography and Geographic Information Science*, vol. 24, pp. 203–220, Oct 1997.
[12] C. A. Brewer, A. M. MacEachren, L. W. Pickle, and D. Herrmann, "Mapping mortality: Evaluating color schemes for choropleth maps," *Annals of the Association of American Geographers*, vol. 87, pp. 411–438, Sep 1, 1997.
[13] B. E. Rogowitz and L. A. Treinish, "Data visualization: the end of the rainbow," *IEEE Spectrum*, vol. 35, no. 12, pp. 52–59, 1998.
[14] M. Borkin, K. Gajos, A. Peters, D. Mitsouras, S. Melchionna, F. Rybicki, C. Feldman, and H. Pfister, "Evaluation of artery visualizations for heart disease diagnosis," *IEEE Transactions on Visualization and Computer Graphics*, vol. 17, no. 12, pp. 2479–2488, 2011.
[15] A. Badano, C. Revie, A. Casertano, W. C. Cheng, P. Green, T. Kimpe, E. Krupinski, C. Sisson, S. Skrvseth, D. Treanor, P. Boynton, D. Clunie, M. J. Flynn, T. Heki, S. Hewitt, H. Homma, A. Masia, T. Matsui, B. Nagy, M. Nishibori, J. Penczek, T. Schopf, Y. Yagi, and H. Yokoi, "Consistency and standardization of color in medical imaging: a consensus report," *Journal of Digital Imaging*, vol. 28, no. 1, pp. 41–52, 2014.
[16] K. Grove, "Oceanography," Feb 14, 2017.
[17] A. Kaever, T. Lingner, K. Feussner, C. Gbel, I. Feussner, and P. Meinicke, "Marvis: a tool for clustering and visualization of metabolic biomarkers," *BMC bioinformatics*, vol. 10, no. 1, p. 92, 2009.