Patterns

CellPress OPEN ACCESS

Opinion

Navigating color integrity in data visualization

Fabio Crameri[1,2,*] and Sari Hason[1,3]
[1]Undertone.design, Wildermettweg 58, Bern, Switzerland
[2]International Space Science Institute Bern, Bern, Switzerland
[3]Der Energiewender GmbH, Ostermundigen, Switzerland
*Correspondence: fabiocrameri@undertone.design
https://doi.org/10.1016/j.patter.2024.100972

Color is crucial in scientific visualization, yet it is often misused. Addressing this, we think accessible and accurate techniques, such as color-blind friendly palettes and perceptually even gradients, are vital. Accountability and basic knowledge in data visualization are key in fostering a culture of color integrity, ensuring accurate and inclusive data representation.

Introduction

In the vast landscape of scientific data, color serves as a golden key to its comprehension. From the depths of the cosmos to the intricacies of molecular structures, the deliberate use of color in scientific visualization not only enriches our understanding but also delineates the beauty and complexity of the natural world.

As of today, scientific visualization is not generally part of the obligatory curriculum of upcoming researchers. In terms of color use, the scientific community therefore swings back and forth between self-educated science-proof application and peer-endorsed misuse. When misused, data visualization can exclude readers or misguide them.[1] In the worst case, it does both.

From its display on paper and digital screens to its ultimate recognition in the visual cortex, the study of how humans perceive color is extensive and has a long history. As laypeople, we can orient ourselves to the gained facts and quantities and appreciate the handy tools shared with us. The creation of accessible and accurate scientific visualization with color has become easy. All necessary aspects are understood. All necessary tools are given.

Facts and quantities—The legacy of color researchers

Color is not inherent in objects, but instead subjective. It is the portion of light that is reflected from an object and processed into visual information in the eyes and brain. Whether the object's surroundings or the number, distribution, or precision of an eye's light receptors, they all play critical roles in determining the perception of a color.

Unsurprisingly, there is an inherent variation in color perception amongst humans.[2] Some of these differences are subtle and hard to pinpoint. Other shifts in color vision can easily be described by the viewer and observed in their eye's physiology. Different forms of color-vision deficiency (CVD) exist that are obvious and, with almost one in twenty persons showing signs thereof, widespread.[3] The most common forms of CVD can, for example, cause red and green, or red and blue, to appear indistinguishable. Fortunately, total color blindness is rare, but it does exist too.

In general, the total number of colors a human visual system can capture independently is high, on the order of ten million colors,[4] even though the exact number is still uncertain.[5] It is certain though that humans have developed a higher sensitivity for longer wavelengths of light, such as red, orange, and yellow, than for shorter wavelengths. As a result, variable wavelengths along the greenish part of the light spectrum are less obvious than, let's say, along the reddish part. Today, this variability in human color perception across the light spectrum is so well understood that we can now quantify the color difference between two individual colors.[6]

Re-evaluating color practices

In data visualization, uneducated color selection causes not one but two critical pitfalls.[1] First, the color combinations in a figure must be distinguishable also with color-deficient vision or else readers are excluded from the figure's message. Second, if colors are used for a scale (e.g., for a color bar), the uneven human sensitivity to different parts of the color spectrum must be accounted for or else all readers will be misled.

Creating and distributing widely *inaccessible* figures is not only unethical but also hinders the figures' message from spreading. As such, accessible figures are in everyone's interest.

Creating and distributing widely *inaccurate* figures is not only unethical but makes the figure creator appear as if they had purposefully tuned their message instead of letting the data speak for itself. In other words, the figure becomes a (false) interpretation instead of a representation. As such, accurate figures are in everyone's interest.

Whether as an author, editor, or communicator, not enforcing accessible and accurate figures is a statement against them, corrupting the scientific method and harming science.

Recommendations and best practices

It is in everyone's interest to visualize data accurately and in a way that it is accessible but also intuitive to all viewers. This can only be achieved with color-blind friendly color palettes and perceptually uniform color gradients.[1]

"Perceptual uniform" are sets of colors in which all neighboring colors have the same color contrast to each other as perceived by the human viewer (see Figure 1). Only when this is the case and the color gradient appears to change evenly from one side to the other, it can be used to scale a data range accurately. While it is not easy to create perceptually

Figure 1. Accurate color palettes
The open-access Scientific color maps (Crameri, 2018)[7] are a wide variety of perceptually-even color gradients as illustrated by the local color contrast of neighboring color values along the individual gradients.

even color gradients, it has been done and it is now straightforward to use them for accurate data visualization (see resources).

Ensuring visually accessible color figures is similarly easy and a matter of preventing the wrong color combinations. The fastest and most reliable way of checking for CVD issues is to desaturate the figure or, in other words, convert it to gray scale (see Figure 2). If all colors within a palette have unique relative lightness values, it is not only CVD proof but also color-blind proof. To avoid having to create and test certain color combinations, a wealth of pre-built accessible categorical color palettes is available (see resources).

While visual accuracy and accessibility are necessary for sensible scientific data visualization, intuitiveness is great to boost the effectiveness of the resulting figure. This feat can be achieved with color palettes for which the lightness varies gradually and monotonically, forming a clear gradient. Ordering light to dark colors (or vice versa) then becomes easy, which greatly facilitates reading color-mapped data.[8]

Resources

Some scientifically derived and accessible color maps, such as "viridis," "cividis," and "batlow"[1,9] are widely distributed and used. For thorough data visualization practices in the section recommendations and best practices, a complete set of color map gradients and palettes is necessary. For a complete set of accurate and accessible (and intuitive) color maps, we recommend the *Scientific colour maps*,[7] which are built into many key software packages and can be accessed freely on www.fabiocrameri.ch/colourmaps (see also Figures 1 and 2).

The package offers a myriad of different file formats to cover all needs of key scientific visualization tools and an extensive user guide shows you how. The *Scientific colour maps* package is versioned and citable to track additions and improvements while allowing it to be acknowledged. The *Scientific colour maps* package is a community effort with many contributors (see the user guide on www.fabiocrameri.ch/colourmaps-userguide) and citing it promotes a science-proof use of color and supports its development.

For researchers, as mentioned above, we think that holding each other accountable is critical also regarding color misuse. To facilitate doing so in an effective manner, we openly provide template statements (s-ink.org/scientific-colour-use-reminders), answers to commonly asked questions (https://www.fabiocrameri.ch/colourmaps-faq), and promotional material (https://s-ink.org/scientific-colour-map-poster) online.

For science communicators, we advise reusing only science-proof visuals. We think it is better to favor graphics from trusted collections with accurate and accessible content, such as https://s-ink.org, and this goes a long way. Additionally, staying up to date and promoting the latest efforts regarding academic color integrity (see e.g., www.fabiocrameri.ch/usebatlow) further helps the underlying cause.

For software developers, we recommend making science-proof color palettes the default options. Having science-proof default options makes more data visualization accurate and inclusive because they are the most likely choice by non-experts.[10] If included, we think that perceptually uneven and inaccessible color palettes should be clearly marked as unsuitable for scientific purposes because they are.

For publishing editors, we openly provide example templates of an author guideline on https://s-ink.org/figure-accuracy-and-accessibility-guideline that is already part of some scientific journals. Given the background knowledge provided here, we think that any misuse of color that represents data inaccurately or exclusively to only some viewers must be pointed out at the latest

CellPress
OPEN ACCESS

Figure 2. Accessible color palettes
The open-access Scientific color maps (Crameri, 2018)[7] are a wide variety of colour-blind friendly color combinations as illustrated by the colour-blind appearance of the individual colors at the end of the rainbows.

during the editing stage of a submission, but best upon submission.

For university faculty that see the value of acting for color integrity in science, we provide exemplary data visualization and academic graphic design courses.[11] These can act as a blueprint to facilitate building new university-level classes, which we think are key to maintaining accurate and accessible scientific visualization across academia in the long term.

Implementing change

We are convinced that the science community can improve color integrity in data visualization practices, but we need to hold each other accountable—and be open to constructive feedback. From our experience, graphic design expert feedback in most academic settings tends to be disruptive to current applications and comes from the bottom up.

In groups where persistence with traditional matters and hierarchical structures was looser, we have seen improved knowledge and skill transfer. We think educating mid- and late-career academics with their established ways to function in a strict environment is incomparably harder than teaching students or (re-)forming institutions. We are at a loss as to why higher education on a global scale still does not provide mandatory courses on data visualization and other scientific graphic design methodologies. Would including such courses in the upcoming academics' curriculum not be a tremendous step forward? We believe it would act on the problem upfront and avoid having to react to it later.

As of today, we academics still need to react in an effort- and time-consuming manner. However, we see that change is underway despite the challenges regarding methodologic traditions and academic hierarchy. Early-career academics who do not shy away from speaking up thoroughly managed software tools with science-proof default settings, and next-generation journals with the necessary author guidelines are leading the way. A wealth of educated reminders in the form of scientific articles[12] and blog posts[13] as well as freely accessible tools[7] and resources[14] are now effectively promoting the creation and usage of accurate and accessible scientific visuals across the entire academic community. With no solid education in scientific visualization for upcoming academics, we must continue these efforts.

Conclusion

In the realm of scientific exploration, data visualization plays a pivotal role in enhancing understanding and revealing the intricacies of nature. Yet, despite its undeniable importance, we observe scientific visualization—particularly using color—often teetering between self-taught application and peer-endorsed misuse.

Understanding the nuances of color perception is essential to navigate this landscape successfully. First, the human perception of color is subjective and varies greatly, with differences ranging from subtle to profound, including various forms of color vision deficiency. Second, our sensitivity to different wavelengths of light further complicates matters, highlighting the need for meticulous attention in the use and application of color scales. Academia's bold ignorance of these two well-founded facts poses significant challenges, as poorly chosen color schemes can exclude or mislead readers, ultimately impeding the dissemination of scientific knowledge.

Addressing the widespread misuse of color requires a concerted effort to reevaluate and improve color practices in data visualization. Accessible and accurate visualization techniques not only uphold ethical standards but also strengthen the integrity of scientific inquiry. We therefore made strides in this regard, with the development and open distribution of color-blind friendly palettes and perceptually uniform gradients. Building these resources into our workflow enables us researchers to create visualizations that are not only trustworthy but also cater to diverse audiences.

Moreover, by making the availability of resources such as scientifically derived color maps and comprehensive user guides available, we empower researchers, software developers, and publishing editors alike. By embracing these tools and advocating for their widespread adoption, we can foster a culture of integrity in data visualization across the scientific community.

However, achieving a lasting change requires a multifaceted approach. It entails not only overcoming entrenched norms and hierarchies within academia but also educating future generations of researchers on the importance—and the most important basics—of scientific visualization. By embracing accountability and continuous improvement, we are convinced that we will continue paving the way into a future where accurate and accessible scientific visualization is the norm not the exception.

ACKNOWLEDGMENTS

We thank Grace E. Shephard and Philip J. Heron for contributing to many of the resources, and the science community for their contribution to the Scientific colour map initiative, promoting science-proof use of color, and holding each other accountable.

AUTHOR CONTRIBUTIONS

F.C. conceived the manuscript structure, wrote the manuscript, and created the figures. S.H. conceived the figures and read and improved the manuscript.

DECLARATION OF INTERESTS

The authors offer color consulting, graphic design, and training services through https://undertone.design and www.fabiocrameri.ch/masterclasses, respectively.

REFERENCES

1. Crameri, F., Shephard, G.E., and Heron, P.J. (2020). The misuse of colour in science communication. Nat. Commun. *11*, 5444.
2. Emery, K.J., and Webster, M.A. (2019). Individual differences and their implications for color perception. Curr. Opin. Behav. Sci. *30*, 28–33.
3. Neitz, J., and Neitz, M. (2011). The genetics of normal and defective color vision. Vision Res. *51*, 633–651.
4. Judd, D.B., and Buc, G.L. (1953). Color in business science and industry. Appl. Spectrosc. *7*, 90–91.
5. Masaoka, K., Berns, R.S., Fairchild, M.D., and Moghareh Abed, F. (2013). Number of discernible object colors is a conundrum. J. Opt. Soc. Am. Opt Image Sci. Vis. *30*, 264–277.
6. Lindbloom, B. (2018). Delta E (CIE 1976). http://www.brucelindbloom.com/index.html?Eqn_DeltaE_CIE76.html.
7. Crameri, F. (2018). Scientific colour maps (Zenodo). https://doi.org/10.5281/zenodo.1243862.
8. Thyng, K., Greene, C., Hetland, R., Zimmerle, H., and DiMarco, S. (2016). True Colors of Oceanography: Guidelines for Effective and Accurate Colormap Selection. Oceanography *29*, 9–13.
9. Nuñez, J.R., Anderton, C.R., and Renslow, R.S. (2018). Optimizing colormaps with consideration for color vision deficiency to enable accurate interpretation of scientific data. PLoS One *13*, e0199239.
10. Moreland, K. (2016). Why We Use Bad Color Maps and What You Can Do About It. ei. *28*, 1–6.
11. Crameri, F. (2023). Use of colour in scientific visualisation. https://www.fabiocrameri.ch/masterclasses/.
12. Kaspar, F., and Crameri, F. (2022). Coloring Chemistry—How Mindful Color Choices Improve Chemical Communication. Angew. Chem. Int. Ed. Engl. *61*, e202114910.
13. Crameri, F. (2017). The Rainbow Colour Map (repeatedly) considered harmful. http://blogs.egu.eu/divisions/gd/2017/08/23/the-rainbow-colour-map/.
14. Crameri, F., Shephard, G.E., and Straume, E.O. (2022). Effective high-quality science graphics from s-Ink.org (Preprint at *EarthArXiv*). https://doi.org/10.31223/X51P78.

About the authors

Fabio Crameri is a geoscientist with a PhD, science communicator, and graphic designer at Undertone.design and the International Space Science Insititute in Bern, Switzerland. He develops and shares the open-access Scientific color maps and promotes accurate and accessible scientific visualisation.

Sari Hason is a graphic designer and color enthusiast and promotes accessibility with Undertone.design in Bern, Switzerland. She creates visually appealing artwork, clothes, and other products, and also works with photovoltaic systems at Der Energiewender GmbH in Ostermundigen, Switzerland.