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Somewhere over the Rainbow: How to Make Effective Use of Colors in Meteorological Visualizations

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Abstract

Results of many atmospheric science applications are processed graphically using colors to encode certain parts of the information. Colors should (1) allow humans to process more information, (2) guide the viewer to the most important information, (3) represent the data appropriately without misleading distortion, and (4) be appealing. The second requirement necessitates tailoring the visualization and the use of color to the viewer for whom the graphics is intended. A standard way of deriving color palettes is via transitions trough a certain color space. Most of the common software packages still provide palettes derived in the RGB color model or "simple" transformations thereof as default. Confounding perceptual properties such as hue and brightness make RGB-based palettes more prone to misinterpretation. Additionally, they are often highly saturated, which makes looking at them for a longer period strenuous. Switching to a color model corresponding to the perceptual dimensions of human color vision avoids these problems. We show several practically relevant examples using such a model, the HCL color model, to explain how it works and what its advantages are. Moreover, the paper contains several tips on how to easily integrate this knowledge into software commonly used by the community, which should help readers to switch over to the new concept. The switch will result in a greatly improved quality and readability of visualized atmospheric science data for research, teaching, and communication of results to society.

Keywords: color palettes, HCL colors, RGB colors, HSV colors, perceptually-based color space.

1. Introduction

Working in atmospheric science has a lot of different facets. One important task is to deal with big data sets. that are mostly highly complex. One way to gather the information and better understand it, is to graphically visualize it. Visualizations may be as simple as one-dimensional plots (e.g., time series plots) and as complex as multidimensional charts (e.g., from numerical weather prediction model output). One is confronted with such visualizations daily in all different areas. As a scientist, an important part of daily work is to create plots and graphs that visualize results and outcomes earned trough weeks and possibly months of work. The key feature of visualizations is to help the reader to capture the information as simple and fast as possible. This reader can be a colleague, a customer, or even you.

Often colors are used to improve graphics. For highly complex visualizations there is mostly no way around. Imagine a spatial weather forecast map with three or more dimensions. Therefore, an good color mapping is important to create effective plots and graphs. Most common software already supply methods create different types of plots with different color maps (or color palettes). The default color map is often an RGB rainbow palette. This is probably the most famous color map and leads many people to use it uncritically as default for their visualization although it has been show to be difficult or even harmful (Borland and Taylor 2007).

Although using colors appears to be very simple, the selection of inappropriate colors can cause a variety of problems. The frequently-used RGB color space has some crucial disadvantages. RGB-based color mappings often contain highly saturated colors leading to perceptual distractions. One step towards perception-based colors was the HSV color space which is a "simple" transformation of the RGB color space (Smith 1978). However, even though they work slightly better if used correctly, HSV-based palettes do not solve the basic problems of RGB. Fully saturated HSV colors degenerate to pure RGB colors with all their disadvantages. As an alternative, we will introduce you to a color space called HCL. The HCL color space is based on how the humans perceive color while the RGB color space is based on a technical demand of TV and computer screens. Using a perception-based color concept can strongly improve the visual reception – with very little additional effort.

At the moment, RGB-based color palettes are still often used heedless, even within our community (Borland and Taylor 2007). In other scientific fields, the alternative HCL model is already better known and much more frequently used (Zeileis, Hornik, and Murrell 2009; Silva, Sousa Santos, and Madeira 2011). The use of misleading and distorting RGB colors maps is not necessary as the HCL model helps to avoid the RGB drawbacks. The HCL advantages: simple choice of effective colors maps; improved readability; avoidance of color-dependent distortions; improved suitability of teaching with good visual material; support for understanding complex graphical patterns; etc.

2. Color challenges

A core question for effective color mapping is to define the needs of colors. Effective colors have to fulfill a variety of requirements. Although these requirements are rather guidelines than rigorous rules, breaking them can rapidly deteriorate the effectiveness of the corresponding display.

Simple and natural: The content of most visualizations is complex enough. Colors should not amplify that. Using only few different colors can make the appearance much simpler. A figure with countless colors makes it harder to gather the important information. Furthermore, our visual system is familiar with nature's colors. Those natural colors fulfill a widely accepted harmony to how we perceive colors and they have a natural coherence. In contrast, highly saturated vivid colors shine out – on the other hand they can produce a lot of "colorjunk" (Tufte 1990). As he wrote: "Large area background or base-colors should do their work most quietly, allowing the smaller, bright areas to stand out most vividly, ...".

Guiding: One major task of colors is to guide the reader to the areas of interest. This can be done by setting highlights. One way is to colorize areas of interest while the surrounding has a less conspicuous sensation. A second way is to vary the luminance level. Our perception is trained to gather differences in luminance quiet fast. An area of low luminance (i.e., a dark color) on a bright background (e.g., on white or light gray) helps the reader to identify the most important information quickly.

Supportive: Effective color maps support the reader beyond merely pointing out the highlights. The key is that the used color map represents the data. For a continuous variable (e.g., temperature) a sequential color scheme can give this support. Going from light blueish colors (on the cold side) to dark reddish colors (on the warm side) can help the reader to gather the overall information quickly. For centered data (e.g., for anomalies) a scheme that diverges from a neutral central color (e.g., light gray) to two different colors with the same perceptional impact (e.g., dark blue and dark red) can be employed to avoid visual distortions.

Appealing and relaxing: One may argue that being appealing is not the most important property for scientific figures. However, readers can easily loose interest if a figure or plot looks unappealing. In addition, colors should be relaxing. Garish colors and wide vibrant areas can be very strenuous for the human eye, especially when having to look at them over a prolonged time, e.g., in an operational forecasting setting. Not to loose the reader with unappealing colors is an advantage and should be of of the aims.

Customized: (End-)users demand and deserve products customized to their needs. This is also valid for colors. Who will use it? Are there visual constraints to regard? For what purpose do I produce this figure? Based on these questions it is self-evident that figures for a scientific article and a popular product for an internet platform do have different framework conditions.

Work everywhere: In an ideal case, colors work everywhere including screens, data projectors, and printers (grayscale and colorized).

3. Color models and human color perception

Human color perception: To choose the "best color scheme" one has to understand the characteristics of the receiver and processor. The human eye contains two classes of cells which are responsible for our visual perception: rod and cone cells, respectively. The former serve vision at low luminance levels while the latter are wavelength-sensitive. Three subclasses of cone cells are responsible for long, medium, and short wavelengths, respectively. Although most properly referred to as L, M, and S cones, the names R, G, and B cells are also frequently used albeit somewhat misleadingly. The RGB annotation suggests that the cells refer to red, green, and blue which is not the case. In fact, the LMS cones have broadly overlapping scopes. This design strongly differs from the "color-separation" often built into physical imaging systems (Fairchild 2013b).

Under low luminance conditions, the rod cells allow us to gather our surrounding with a limitation to capture differences in luminance only (monochromatic; scoptic view). Under moderate to high luminance conditions, the rod cells are fully saturated and our visual systems switches from a rod to a cone view (trichromat; photopic view). The spectral sensitivity also changes between these two views. Rod cells are more sensitive to shorter wavelengths. The appearance of two objects, say red and blue, changes under different luminance conditions. While they have the same lightness under high luminance conditions, the red one seems to

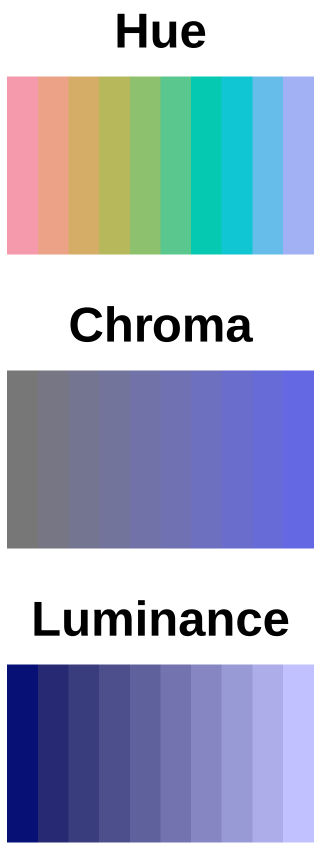

Figure 1: The three dimensions of the Hue-Chroma-Luminance (HCL) color model: hue, chroma, and luminance. In each subfigure, one dimension (see heading) changes linearly across the corresponding axis while the others are held constant.

look nearly black under low luminance conditions while the blue still looks quite light. This is caused by a lack of sensitivity to longer wavelengths (red) in the scoptic view. As one can see, the human perception is a complex system with different behaviors. These reasons make it difficult, if not impossible, to represent colors that can be accurately perceived by humans in all settings/contexts.

Current theories describe that at least three dimensions are necessary to code a specific color. Typically, color models with three dimensions are employed (Knoblauch 2002) while one can argue that more dimensions would be required. For example, Fairchild (2013a) describes that five perceptual dimensions are necessary for a complete specification (brightness, lightness, colorfulness, saturation, and hue). But as typically only the relative appearance of the colors is of interest and not all five dimensions have to be known. Hence, the three perceptual dimensions hue, chroma, and luminance are typically sufficient for most purposes.

Hue-Chroma-Luminance (HCL) model: The HCL model allows to control the three major perceptual dimensions directly. The first one is *hue*, the dominant wavelength (defining the color), the second dimension is *chroma* capturing colorfulness (color intensity compared to gray), and the third is *luminance* pertaining the brightness (“amount” of gray). Figure 1 shows

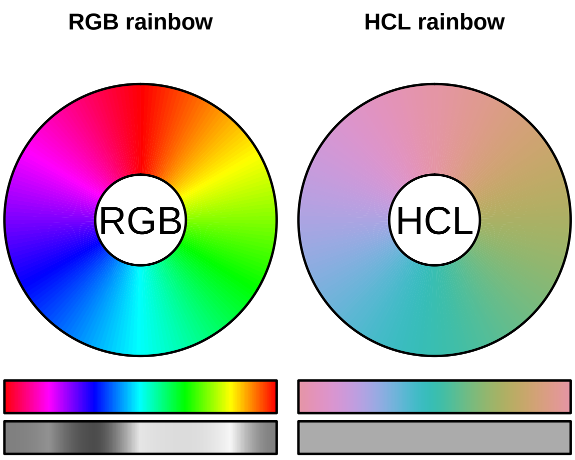

Figure 2: Juxtaposition of the Red-Green-Blue (RGB) rainbow color map, and a Hue-Chroma-Luminance (HCL)-based rainbow. Below the color wheel the same palette is shown as a color bar in the colorized and the corresponding desaturated version, respectively. The RGB rainbow creates unwanted variations in luminance while the HCL rainbow is fully isoluminant.

the three perceptional HCL dimensions. In each of the subfigures one dimension changes linearly across the corresponding axis while the others are held constant. *Hue* changes the color while fixing the lightness and chroma level across colors. Increasing the *chroma* dimension increases the colorfulness compared to gray and the *luminance* dimension changes the colors from dark to light.

Red-Green-Blue (RGB) model: Historically, the RGB model is based on how screens work. Cathodic ray tubes, LED, and plasma screens attached to TVs, computer monitors, and projectors all use the same technique: Images are created by additive color mixing. Each image consists of hundreds to thousands of pixels where each pixel emits a mixture of red, green, and blue light. Each single RGB color is defined by a triplet of intensities for those three primary colors. Appropriate mixing produces a wide range of colors. Three zero-intensities result in black while maximum intensities for all three primary colors yield white and, in between, all other colors can be defined. The RGB color space can be easily transfered into the HSV color space which is a polar coordinates representation of the cubic RGB gamut. However, while the HSV dimensions attempt to capture the three perceptual axes (hue, chroma/saturation, luminance/value), the dimensions of HSV are actually confounded. For example, as shown for the RGB rainbow below, both chroma and luminance vary substantially across hues.

Desaturated: To focus on the luminance dimension of a color palette, it can be desaturated, e.g., by transforming to HCL space, removing all chroma (so that hue does not matter), and transforming back to the original color space. This just removes hue/chroma information but keeps luminance fixed. Thinking in HCL dimensions: changes in hue or chroma do not influence the underlying luminance information.

Comparison of HCL and RGB: Figure 2 shows a juxtaposition of the (in)famous RGB rainbow color map and an alternative HCL rainbow. Both rainbows go from red over green and blue back to red. Below the color wheel, the same color maps are shown as colorized and desaturated color bars, respectively. As one can see, the luminance is highly discontinuous

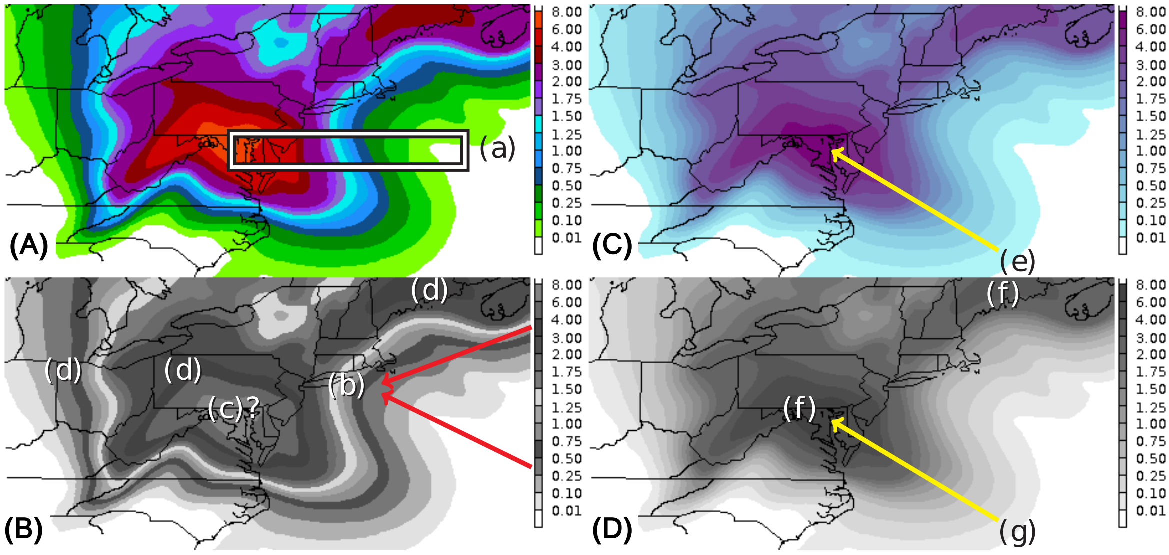

Figure 3: A rainfall amount forecast during the landfall of hurricane Sandy on the October 29, 2012, over the East Coast of the United States. The data are shown in inches accumulated over 120 hours. Panel A shows the original version as provided by the NOAA. Below, the desaturated version thereof is plotted (B). On the right hand side an alternative HCL-based color scheme is shown (C) along with its desaturated representative (D). The markers shown on the panels are discussed in the paper. Source: National Oceanic and Atmospheric Agency (2012).

creating unwanted gradients throughout the RGB rainbow map. The discontinuity is caused by the fully saturated garish colors in the RGB rainbow map. In contrast, the HCL version shows an isoluminant gray in the desaturated version. This is no surprise, because one of the three dimensions of the HCL color space directly controls the luminance. Nevertheless, many common software packages provide the RGB rainbow scheme as default. As Borland and Taylor (2007) wrote: "…the rainbow color map is the most widely used color map in the visualization community", "…even if the RGB rainbow is a poor choice". Because of its lack of perceptual ordering it does not only confuse the reader, but also obscure data through its inability to present small details, and might even actively mislead the reader.

3.1. What can go wrong with inefficient color maps?

We would like to show you the potential problems of RGB-based colors in a first real-world example. Figures like this can be found by the thousands on meteorological websites and products. Figure 3 shows a 120 hour rainfall amount forecast during the landfall of hurricane Sandy in 2012. Panel 3A shows the original colors as provided by the NOAA website (National Oceanic and Atmospheric Agency 2012). The first conspicuity: the selected colors are mostly fully saturated. This leads to plenty intensive color gradients (see marker (a) in Panel 3A). Furthermore, the colors along the color map go from bright to dark and back several times. Comparing this to the guidelines established in Section 2: The colors are neither simple nor natural, do not support the reader, and especially the varying brightness is rather misleading than guiding. The corresponding desaturated Panel 3B emphasizes several misleading patterns: association between colors and values is no longer unique (marker (b)); the most important areas are barely identifiable (marker (c)); our eye automatically focuses on the dark "artefacts" which are not the areas of interest (active misleading of the reader; marker (d)).

As an alternative, we added a HCL-based color map in the second column along with its desaturated counterpart (Panel 3C and D). We took blueish colors to reproduce a known pattern familiar in nature (natural: water looks blue) and reduced the number of different colors (simple: range from blue to violet). In comparison to the original color map, we have a smooth transition from low to high values without irritating gradients (marker (e)). The monotonic change in luminance represents the data (a continuous variable). Furthermore, the decreasing luminance with increasing rainfall amount automatically guides the reader to the most important areas making the colors guiding and supportive. Even in the desaturated version the rainfall pattern and the area of maximum rainfall can be identified easily.

3.2. Customization and guiding the end user

Color blindness, or color vision deficiency, is another important aspect when choosing effective colors. In Europe, about 8 percent of the male population do have visual constraints (see Miles 1943, Wong 2011, Fairchild 2013b). Far more men than women are affected. Besides the relatively rare monochromacy (light/dark contrasts only) two main types of dichromacy or constrained trichomacy are observed among the male population: Either there one of the cone cell subclasses is lacking entirely (about 2 percent) or is anomalous (about 6 percent). The most frequent of these is the deuteranomaly, also known as red-green blindness and caused by an anomaly of the M cone cell. The medium-wavelength pigment aesthesia (green) is shifted towards longer wavelengths (red). People with this type of anomaly are poor at discriminating small changes in hues in the red/yellow/green spectrum.

Again, we would like to show you a real world example to illustrate what can happen if visual constraints are not considered. Figure 4 shows a warning map for Austria in 2013 for severe precipitation amounts. The left column shows the original image while the right one shows an alternative HCL-based color palette, both traversing from green via yellow, orange, and red to purple. The top row shows the colorized version followed by a desaturated version thereof and emulated deuteranope vision in the bottom row.

Let us start with the colorized version in Panel 4A: Like in the example before, all colors are on maximum saturation to attract the attention of the reader. Warning maps, or warning products in general, are often colored similarly to replicate the colors of a traffic light. Basically this is a good idea. Our brain is trained to capture established pattern quickly. The disadvantage of the chosen colors: it is hard to capture the most important areas. The garish colors all over the color map coerce us to scan the whole image. We keep the traffic light concept for the HCL version in Panel 4D. However, in comparison to the original colors, we simultaneously increase chroma and decrease luminance along with increasing warning level. The range of colors from light green to dark purple guides the user to the areas of interest (highest warning level). The rest of the color palette has to lie on a path between those two anchor colors. If we try to go from one highly saturated color to another it is possible that this path runs out of the defined HCL color space. Therefore, it is necessary to pick more "pastel" colors. In return, we can strongly improve the reader-support and guidance of the product.

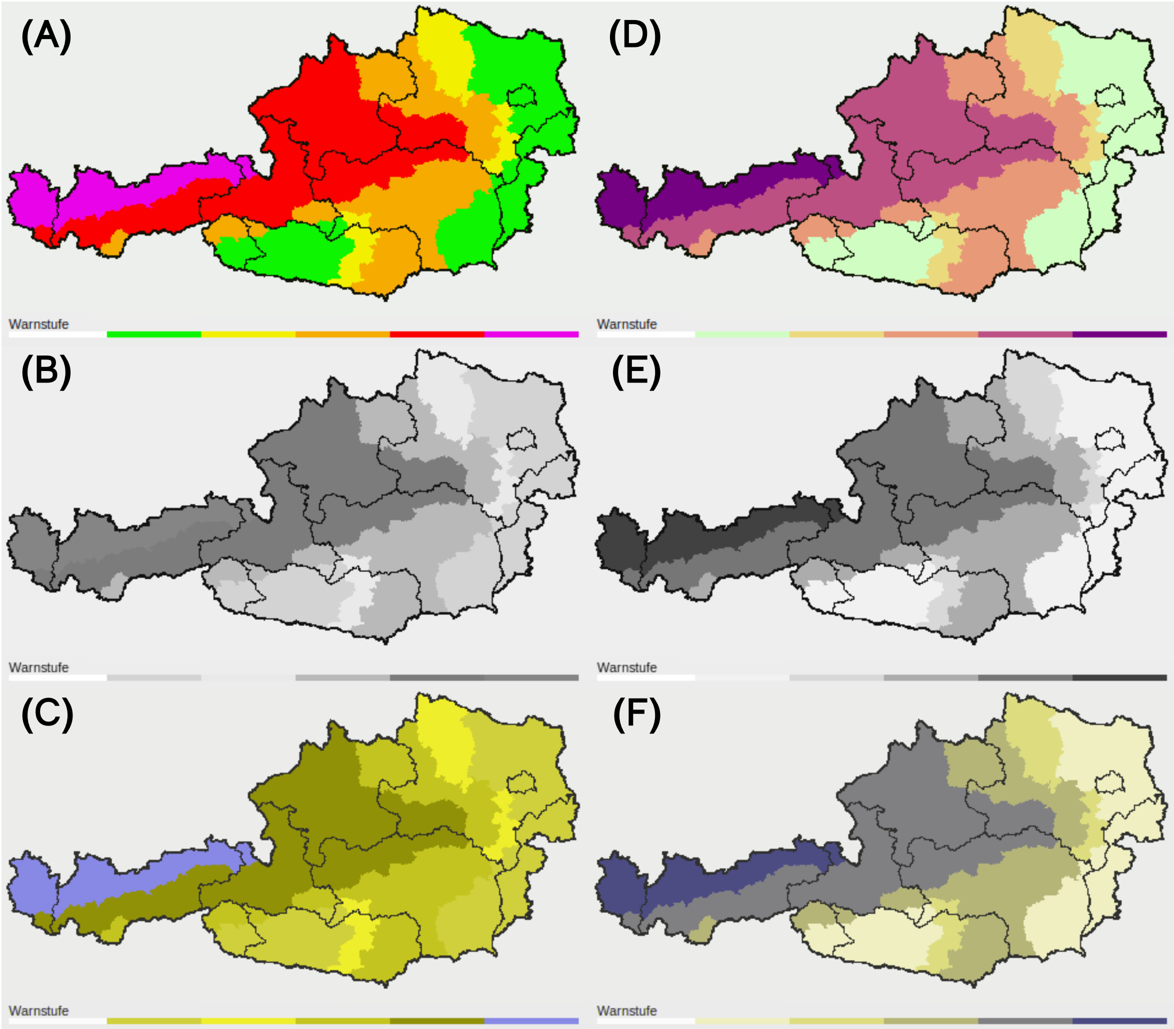

Figure 4: A severe weather advisory for Austria published on May 31, 2013. Panel A shows the original image as published by UBIMET GmbH (2013); slightly modified due to further postprocessing steps. In the second column a modified version with HCL-based colors is shown (D). Second row: desaturated version of the first row. Bottom row: simulation of the appearance for people with deuteranomaly (red-green weakness). Because of the lack of perceptual representation of the RGB color space, different distortions can be found in the left column.

Let us have a look to the desaturated versions in Panel 4B and 4E. While the HCL version is still conveys the essential information, the desaturated RGB version shows something different. Yellow colors are rather light which results in a lower luminance than the surrounding orange and green (which are rather hard to distinguish). An inappropriate representation of the warning levels is the result. The last row with emulated deuteranope vision (Panel 4C and 4F) exhibits similar problems. While the interpretation of the original RGB version gets difficult or impossible, the HCL version preserves full readability. This aspect is very important for some fields of application. The used example warns the inhabitants of Austria of severe weather situations. Imagine that for 4 out of 100 people it can be very difficult

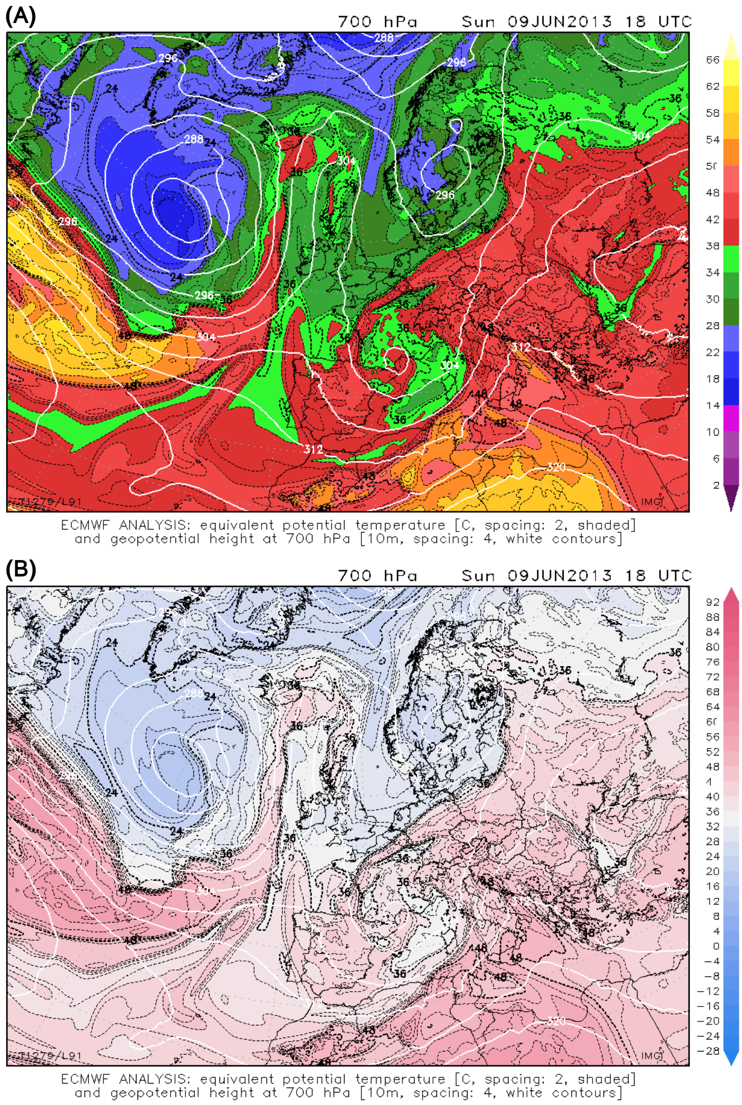

Figure 5: ECMWF analysis of the equivalent potential temperature on 700hPa over Atlantic/Europe. Panel A shows the old product based on highly saturated RGB rainbow colors. Panel B shows the revamped product including a HCL-based color map.

to gather the information just because of inefficient colors. Using more appropriate color palettes can make it much easier for them to interpret the plots and to gain the important information. As you can see, it is important to think about for whom the product should be accessible and to tailor visualizations for the needs of your end-users.

3.3. Supporting and guiding the specialized user

To give you broader idea of how to make use of the HCL we consider a somewhat more complex example. Figure 5 shows an equivalent potential temperature analysis on 700hPa from the European Center for Medium-Range Forecasts (ECMWF) as employed in the internal weather platform at the Institute of Meteorology and Geophysics in Innsbruck. For those who are not familiar with the equivalent potential temperature concept: it is used to identify different air masses and weather fronts. Frontal zones separate two air masses with different properties. The strength of a front depends on the gradient of the equivalent potential temperature. Additionally, the geopotential height is shown in thin white lines to appraise the movement of the air to identify the front types (Steinacker 1992).

Panel 5A shows the product as it was provided over the last decade using a rainbow-type color map as found in many other meteorological websites and products. The most important feature of this type of product is to identify the physical gradients – not the color gradients. Due to the strong color gradients, especially between red and green (opponent colors), a large proportion of our less-experienced students were mislead. Mostly, fronts were allocated to the ares where red and green encounter each other because the color gradients obscured the physical gradients. The striking quantity of misinterpretations was the main motivation to redesign our products.

Panel 5B shows the new appearance of the same analysis field. The conventional colors for warm and cold are used (red/blue) to identify the overall pattern. The white contours show the geopotential height. To keep this secondary information in the background we decided to retain the white color. In black contours, values of identical equivalent potential temperature are shown. A concentration of black lines leads to an area with lower luminance which can be identified very quickly by our visual system. This helps to gather the most important areas faster than for the old product.

The original RGB-based product is a good example how colors can actively mislead the reader. Since we removed this shortcoming the number of misinterpretations decreased by roughly 50% (empirical value from the daily weather briefing lecture at the Institute of Meteorology and Geophysics, University of Innsbruck, Mayr 2013). Moreover, imagine that you have to look at those products for a longer time. Presumably, most viewers will agree that the overhauled product is less strenuous than the highly saturated one.

4. Tools and further reading

A good concept is worth little without ease of use. To facilitate the first steps towards your personal HCL color palettes, we provide the following hints. It should be emphasized that each HCL color can be converted to the corresponding RGB coordinates with the corresponding hexadecimal representation. Therefore, once the HCL-based color maps have been converted they can be easily used in nearly all software languages.

Onilne tool: We set up an online interface to create customized palettes. The tool "Online HCL Creator" is available on `http://www.wetterleuchte.ch/`. The interface offers some typical examples of statistical maps/graphics and some specifically meteorological chart types. You can easily modify the color palettes and tune them for your personal needs. Furthermore, the tool gives you the ability to emulate the appearance of the chosen colors under different visual constraints (e.g., for deuteranope viewers) or in a desaturated representation (e.g., on a grayscale printer). The interactive examples give a first impression what the color maps look like. Moreover, we developed some export functions for common software languages so that the HCL palettes can be comfortably applied to your own data in your familiar software environment.

Advanced users: The most powerful tool to create HCL palettes for all possible uses is the package *colorspace* (Ihaka, Murrell, Hornik, Fisher, and Zeileis 2013) that provides various types of color space manipulations/transformations. The *colorspace* package is written in R (R Core Team 2013), an open-source programming language which has also been receiving increasing attention within our community. Our online interface mentioned above is based on this *colorspace* package, mimicking its `choose_palette()` graphical user interface.

Other tools: Harrower and Brewer (2003, 2011) developed the online tool ColorBrewer.org that provides predefined color palettes for various purposes with focus on map makers. While their palettes are not directly based on the HCL model, the guidelines used in their creation are very similar resulting in often similar sets of colors. Easy-to-use sets of colors are available in different coding languages (e.g. colorbrewer in Python, RColorBrewer in R, cbrewer in MATLAB, etc.). However, the disadvantage of ColorBrewer.org is that you can only pick from preset color schemes.

5. Conclusion

In this paper, we introduced you to a fully perception-based color model called HCL. Based on how human color vision works, the HCL model captures the three main perceptional dimensions *hue* (dominant wave-length, defining the color), *chroma* (colorfulness, compared to gray), and *luminance* (brightness, amount of gray). With these three dimensions, a broad range of colors can be defined (Knoblauch 2002; Fairchild 2013a), facilitating specification of effective colors for various purposes.

The much more commonly known color model, the RGB color space, on the other hand is motivated by hardware requirements. As most visualization tools offer easy access to RGB color maps a big proportion of our scientific community uses them without much consideration of potential benefits and drawbacks (Borland and Taylor 2007). However, in contrast to the HCL model the RGB model is based on the technical demands of TV and computer screens anc captures poorly the human perceptional dimensions. Hence, colors derived from traversing paths in RGB space can make it difficult to extract the coded quantitative information or even actively mislead the reader. Many alternative color models have been developed for different purposes (e.g., HSV, HSL, sRGB), sharing many disadvantages of the RGB model, while some other models take different approaches at capturing human color perception (e.g., CIELAB, Mhs, Moreland 2009). However, a detailed discussion of these is beyond the scope of this manuscript.

Choosing appropriate colors can strongly increase the power of visualizations. The introduced HCL color model can help you to define effective color maps for all kinds of visualizations. The benefits are: better readability; full functionality in grayscale/luminance; highly supportive and guiding; more effective in transporting complex concepts; more attractive for the reader; and enhanced accessability for people with visual constraints.

We present a few tools to easily adapt the proposed concepts for your own work. In particular, we provide a web interface to the R package *colorspace* where everyone can create personal HCL color maps and export them in different formats for several common software languages.

We have often experienced scepticism about changing familiar color maps when introducing potential users to the HCL colors. However, much more often than not this scpeticism turned into enthusiasm after a few days of using HCL-based products, especially with the availability of tools to ease implementation into one's own workflow.

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References

Borland D, Taylor RM (2007). "Rainbow Color Map (Still) Considered Harmful." *IEEE Computer Graphics and Applications*, **27**(2), 14–17.

Fairchild MD (2013a). "Color Appearance Terminology." In *Color Appearance Models*, chapter 4, pp. 85–96. John Wiley & Sons.

Fairchild MD (2013b). "Human Color Vision." In *Color Appearance Models*, chapter 1, pp. 1–37. John Wiley & Sons.

Harrower MA, Brewer CA (2003). "ColorBrewer.org: An Online Tool for Selecting Color Schemes for Maps." *The Cartographic Journal*, **40**, 27–37. URL http://ColorBrewer.org/.

Harrower MA, Brewer CA (2011). "ColorBrewer.org: An Online Tool for Selecting Colour Schemes for Maps." In M Dodge, R Kitchin, C Perkins (eds.), *The Map Reader: Theories of Mapping Practice and Cartographic Representation*, chapter 3.8, pp. 261–268. John Wiley & Sons, Chichester.

Ihaka R, Murrell P, Hornik K, Fisher JC, Zeileis A (2013). *colorspace: Color Space Manipulation*. R package version 1.2-3, URL http://CRAN.R-project.org/package=colorspace.

Knoblauch K (2002). "Color Vision." In S Yantis, H Pashler (eds.), *Steven's Handbook of Experimental Psychology – Sensation and Perception*, volume 1, 3rd edition, pp. 41–75. John Wiley & Sons, New York.

Mayr GJ (2013). Personal communication.

Miles WR (1943). "Color Blindness in Eleven Thousand Museum Visitors." *The Yale Journal of Biology and Medicine*, **16**(1), 59–76.

Moreland K (2009). "Diverging Color Maps for Scientific Visualization." In *Advances in Visual Computing – 5th International Symposium, ISVC 2009*, volume 5876 of *Lecture Notes in Computer Science*, pp. 92–103. Springer-Verlag, Berlin.

National Oceanic and Atmospheric Agency (2012). "National Oceanic and Atmospheric Administration." Accessed on 2012-10-29, URL http://www.noaa.gov/.

R Core Team (2013). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Silva S, Sousa Santos B, Madeira J (2011). "Using Color in Visualization: A Survey." *Computers & Graphics*, **35**(2), 320–333.

Smith AR (1978). "Color Gamut Transform Pairs." *Computer Graphics*, **12**(3), 12–19. ACM SIGGRAPH 78 Conference Proceedings, URL http://www.alvyray.com/.

Steinacker RA (1992). "Dynamical Aspects of Frontal Analysis." *Meteorology and Atmospheric Physics*, **48**(1-4), 93–103.

Tufte E (1990). *Envisioning Information*. Graphics Press, Cheshire.

UBIMET GmbH (2013). "Österreich – Alle Warnungen." Accessed on 2013-04-31, URL http://www.uwz.ch/.

Wong B (2011). "Color Blindness." *Nature Methods*, **8**(6), 441.

Zeileis A, Hornik K, Murrell P (2009). "Escaping RGBland: Selecting Colors for Statistical Graphics." *Computational Statistics & Data Analysis*, **53**(9), 3259–3270.

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2013-37

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Somewhere over the rainbow: How to make effective use of colors in meteorological visualizations

Abstract

Results of many atmospheric science applications are processed graphically using colors to encode certain parts of the information. Colors should (1) allow humans to process more information, (2) guide the viewer to the most important information, (3) represent the data appropriately without misleading distortion, and (4) be appealing. The second requirement necessitates tailoring the visualization and the use of color to the viewer for whom the graphics is intended. A standard way of deriving color palettes is via transitions trough a certain color space. Most of the common software packages still provide palettes derived in the RGB color model or ßimple"transformations thereof as default. Confounding perceptual properties such as hue and brightness make RGB-based palettes more prone to misinterpretation. Additionally, they are often highly saturated, which makes looking at them for a longer period strenuous. Switching to a color model corresponding to the perceptual dimensions of human color vision avoids these problems. We show several practically relevant examples using such a model, the HCL color model, to explain how it works and what its advantages are. Moreover, the paper contains several tips on how to easily integrate this knowledge into software commonly used by the community, which should help readers to switch over to the new concept. The switch will result in a greatly improved quality and readability of visualized atmospheric science data for research, teaching, and communication of results to society.

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