

# Interactive Creation of Perceptually Uniform Color Maps

M. Lambers<sup>1</sup> 

<sup>1</sup>Computer Graphics Group, University of Siegen, Germany

## Abstract

*A large number of design rules have been identified for color maps used in Scientific Visualization. One of the most important of these is perceptual uniformity, which at the same time is one of the hardest to guarantee when color maps are created from user input. In this paper, we propose parameterized color map models for a variety of application areas. To allow interactive creation of color maps, these models are based on few intuitive parameters, and at the same time guarantee approximate perceptual uniformity.*

## CCS Concepts

• *Human-centered computing* → *Visualization toolkits*;

## 1. Introduction

Color mapping is a central technique in Scientific Visualization. Toolkits typically include a selection of prefabricated color maps to choose from (e.g. Matplotlib, Matlab, Paraview). In the categorization used by the popular Color Brewer tool [BH], there are *sequential* color maps for ordered values progressing from low to high, *diverging* color maps for ordered data around a central value with extrema in both directions, and *qualitative* color maps that do not imply magnitude differences between values.

While choosing a prefabricated color map is straightforward, creating a custom color map is a demanding task. Bujack et al. summarized color map design goals [BTS\*18]. The most important ones are *order*, *discriminative power*, and *uniformity*. A natural or intuitive order of color map entries is relatively straightforward to achieve, for example by ensuring a monotonically increasing lightness. Uniformity, on the other hand, requires perceptually equidistant differences in color map entries, which limits the available color choices for a color map designer.

Few methods exist that allow interactive creation of color maps. The most prominent one is the model derived by Wijffelaars et al. [WVVV08] from the Color Brewer techniques [HB03]. However, sequential color maps in this model use a single hue, whereas there is a need for multi-hue sequential color maps for some applications, as evidenced by the selection of prefabricated color maps available in typical visualization toolkits. The Cube Helix model of Green [Gre11] uses multiple hues, but always as a variation of going through the complete hue cycle. The ColorMoves tool [SKR18] allows to adapt and manipulate color maps during exploration of specific data sets; its focus is not on the creation of generic maps.

In this paper, we propose parameterized models for interactive creation of color maps that are approximately perceptually uniform

by construction. These models are based on a limited set of intuitive parameters, but still give the user some artistic freedom, and allow for the creation of multi-hue sequential color maps as well as color maps with constant lightness.

## 2. Related Work

In this section, we review parameterized color map models suitable for interactive creation of color maps.

McNames [McN06] introduced a model for sequential color maps based on increasing lightness. The color maps are designed to contain monotonically increasing gray values when desaturated (for use in print), but use different hues when used in full color mode for increased discriminative power. However, the maps produced by this model are not perceptually uniform.

Wijffelaars et al. [WVVV08] derived parameterized models for sequential, diverging, and qualitative color maps from the Color Brewer techniques [HB03; BH]. The set of parameters is intuitive. However, there are several limitations. Sequential color maps are based on a single hue varying in lightness from dark to light; multiple hues, which can increase the discriminative power of sequential color maps, are not supported. Color maps with constant lightness, which are useful in 3D visualizations because they do not interfere with additional shading, cannot be created. Furthermore, while the resulting color maps are often approximately perceptually uniform if parameter values near the recommended defaults are chosen, this property is not enforced, and it is easy to create maps that are not perceptually uniform.

Moreland [Mor09] proposed a model for a diverging color map based on two hues, meeting in a neutral color in the middle of the map. The results are similar to the diverging maps produced with

the Wijffelaar model. The model enforces perceptual uniformity in each half of the color map via a custom color space based on CIELAB. Sequential or qualitative maps, or maps with constant lightness, are not covered by this model.

Green [Gre11] proposed the Cube Helix model for a sequential color map specifically for astronomical intensity data. It is based on increasing lightness combined with constantly changing hue to increase its discriminative power. The produced color maps are in effect similar to the ones created by the McNames model, but the Cube Helix model is constructed so that its color maps are approximately perceptually uniform. However, the hues are always cycling through the complete hue cycle and cannot be chosen freely. Furthermore, diverging or qualitative maps, or maps with constant lightness, are not covered by this model.

In contrast to the models listed above, our models support sequential, diverging, and qualitative maps, allow multiple custom hues inside sequential maps for increased discriminative power, and allow color maps with constant lightness for applications that require additional shading.

### 3. Perceptually Uniform Color Maps in CIELCH

We consider perceptual differences using the euclidean distance measure in the perceptually linear CIELUV color space, as Wijffelaars [WVVV08], Moreland [Mor09] and others [BTS\*18] did.

In order to arrive at intuitive parameters, we use the CIELCH representation of this color space based on lightness  $L \in [0, 100]$ , chromaticity  $C \in [0, 100]$ , and hue  $H \in [0, 2\pi)$ . Using  $C = L \cdot S$ , we can furthermore replace the chromaticity parameter with a more intuitive saturation parameter  $S$ .

CIELCH is related to CIELUV through  $U = C \cos H$  and  $V = C \sin H$ . Formulating the euclidean distance in CIELUV using the CIELCH representation leads to the distance measure  $d$ :

$$d(\text{LCH}_0, \text{LCH}_1) = \sqrt{(L_0 - L_1)^2 + C_0^2 + C_1^2 - 2C_0C_1 \cos(H_0 - H_1)} \quad (1)$$

The color map models described in the following all compute a color  $\text{LCH}_t$  for each  $t \in [0, 1]$  based on their individual set of parameters.

In the following subsections, we introduce *sequential*, *diverging*, and *qualitative* color map models. The individual models names are highlighted in the text *in bold italics*; each has an example in Fig. 1.

#### 3.1. Sequential Color Maps

Variation in lightness has been identified as the main factor for discriminative power of a sequential color map [Kov15], and when it increases monotonically it also guarantees a natural order of colors [BTS\*18].

An obvious approach is therefore to base sequential color maps on monotonically increasing lightness. This is consistent with all other parameterized models described in Sec. 2. However, some applications require color maps of constant lightness in order to combine them with shading in 3D rendering. In the following, we describe models for both cases.



Figure 1: Example results for all methods from Sec. 3.

##### 3.1.1. Varying Lightness

Linearly increasing lightness is modeled with a lightness range parameter  $R_L \in (0.5, 1]$ :

$$\begin{aligned} L_0 &= (1 - R_L) \cdot 100 \\ L_1 &= R_L \cdot 100 \\ L(t) &= (1 - t)L_0 + tL_1 \end{aligned}$$

This leaves chromaticity (or saturation) and hue as free parameters. To let the user choose one or more hues freely, the chromaticity parameter is the one we use to enforce perceptual uniformity.

With linear increasing lightness, saturation is typically low at both the dark and the light ends, and stronger in the middle of the color map. Using a parameter  $R_S \in (0.5, 1]$  for the saturation range and a parameter  $S \in [0, 5]$  for the overall saturation of the map, we define:

$$\begin{aligned} S_0 &= 1 - R_S \\ S_{0.5} &= SR_S \\ S_1 &= 1 - R_S \end{aligned}$$

Note that the distances  $d(\text{LCH}_0, \text{LCH}_{0.5})$  and  $d(\text{LCH}_{0.5}, \text{LCH}_1)$  are only exactly equal for single-hue maps. However, both distances are dominated by the lightness differences in the multi-hue case. Because  $C_0 = L_0S_0$  and  $C_1 = L_1S_1$  are small, the difference in hue does not have much effect (see Eq. 1). Therefore, the difference



**Figure 2:** Test pattern for the sequential color map with varying lightness and multiple hues. The pattern details are visible nearly uniformly throughout the color map.

between the distances, and therefore the deviation from perceptual uniformity, is small.

In between these points with fixed saturation and therefore chromaticity, the chromaticity is computed so that the resulting colors are perceptually uniform. This is done as follows: For two colors  $LCH_A$  and  $LCH_B$  with distance  $D$ , an interpolation parameter  $s \in [0, 1]$  leads to two conditions for the chromaticity  $C_s$ :

$$\begin{aligned} d(LCH_s, LCH_A) &= sD \\ d(LCH_s, LCH_B) &= (1-s)D \end{aligned}$$

Solving Eq. 1 for  $C_s$  for both of these conditions leads to two quadratic equations with a total of four solutions. Of these, we consider only those that fulfill  $\min(C_A, C_B) \leq C_s \leq \max(C_A, C_B)$ , and choose the one that produces the smallest absolute error with regard to the two conditions. In some pathological cases, it may happen that no valid solution exists, in which case we fall back to  $C_s = \frac{1}{2}(C_A + C_B)$ .

Based on the linear lightness and the chromaticity that guarantees (approximate) perceptual uniformity, the user can now choose one or more hues.

**Sequential map with varying lightness, single hue.** We simply set  $H(t) = H_{\text{base}}$  for a single hue  $H_{\text{base}} \in [0, 2\pi)$  chosen by the user.

**Sequential map with varying lightness, rainbow hues.** We set  $H(t) = H_{\text{base}} + tr \cdot 2\pi$ , where  $H_{\text{base}}$  is a start hue, and  $r$  defines the number of rotations through the hue cycle; these parameters are consistent with the Cube Helix model [Gre11].

**Sequential map with varying lightness, custom hues.** The user chooses  $n$  hue steps  $H_{t_i}$ ,  $n \in \mathbb{N}_{>0}$ ,  $t_i \in [0, 1] \forall i$ . The hue for an arbitrary  $t \in [0, 1]$  is computed by linear interpolation in this set, with a weight defined by  $t_i \leq t < t_{i+1}$ . It is important to choose the shortest path between  $H_{t_i}$  and  $H_{t_{i+1}}$ , which may require crossing the cycle period at  $2\pi$ .

### 3.1.2. Varying Saturation

Varying saturation while keeping lightness constant provides color maps suitable for combination with shading. Allowing multiple hues in such maps does not make much sense since at low saturation and constant lightness, different hues are hardly discernible.



**Figure 3:** Test pattern for the sequential color map with varying saturation and constant lightness and hue. While the pattern details are visible nearly uniformly throughout the color map, only few details are visible.

**Sequential map with varying saturation.** Based on a user-provided saturation range parameter  $R_S \in (0.5, 1]$ , we define

$$\begin{aligned} S_0 &= 1 - R_S \\ S_1 &= SR_S \end{aligned}$$

With  $L(t) = L_{\text{base}}$  and  $H(t) = H_{\text{base}}$  from user-defined parameters  $L_{\text{base}} \in [0, 100]$  and  $H_{\text{base}} \in [0, 2\pi)$ , we then compute chromaticity  $C(t)$  to enforce perceptual uniformity as described in Sec. 3.1.1.

### 3.2. Diverging Color Maps

Diverging color maps typically use two dominating hues, one for each half of the color map that meet in the middle in a neutral color. They can be constructed by combining two sequential color maps [WVVV08; Mor09].

Such maps include two dominant hues, given by the user parameters  $H_{\text{base}} \in [0, 2\pi)$  for the base hue of the first half, and  $D_H \in [0, 2\pi)$  for the offset to the base hue of the second half. Adding more hues, as in the rainbow and multi-hue approaches in Sec. 3.1, does not make sense as this introduces confusion. Our diverging color map models are therefore based on the single-hue models from Sec. 3.1, resulting in a *diverging map with varying lightness* and a *diverging map with varying saturation* model.

### 3.3. Qualitative Color Maps

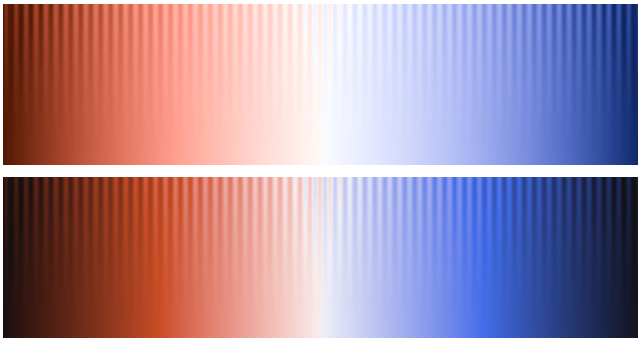
A qualitative map should not imply an ordering of the data [BH], and therefore should have approximately constant lightness. Additionally keeping the saturation constant leads to the following simple *qualitative map with varying hue* model:

$$\begin{aligned} L(t) &= L_{\text{base}} \\ S(t) &= S_{\text{base}} \\ H(t) &= H_{\text{base}} + tD_H \end{aligned}$$

where  $D_H \in [0, 2\pi)$  defines the range of hue values used. Since the hues are equidistant, it follows directly from Eq. 1 that this model produces perceptually uniform maps.

## 4. Results

We implemented our model as an extension to the open source tool gencolormap [Lam], which also provides a web-based demo. Additionally, source code is available as supplementary material to this paper.



**Figure 4:** Comparison of test patterns for diverging maps with varying lightness. The top map was created using the Wijffelaars model [WV08] with default parameters except for hue. The bottom map was created using our model and shows stronger discriminative power in the middle of the map.

The tool has an interactive interface that allows to change the parameters of each model using sliders, and the effect is immediately visible. We aimed at intuitive parameters such as “lightness range”, “saturation” etc. so that the effects of parameter changes are as predictable as possible for the user.

Example results for each of the models proposed in this paper are shown in Fig. 1.

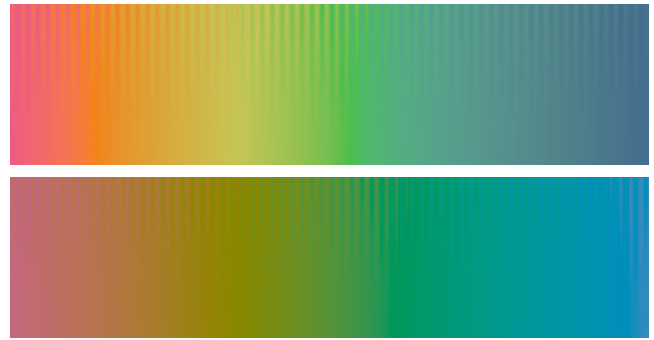
Perceptual uniformity (and many other properties) can be analyzed in detail by the tools provided by Bujack et al. [BTS\*18], available online [BTS\*]. The results of these evaluations cannot be easily summarized in a few numbers and are therefore omitted here for space reasons, but our tool includes a link and an export option for the evaluation web site, encouraging users to validate their custom color maps.

Alternatively, Kovesi designed a simple test pattern [Kov15] that reveals both the perceptual uniformity and the discriminative power of a color map at a single glance. Later, Ware et al. [WTS\*17] designed a very similar test pattern for the same purpose. We include Kovesi’s pattern in our interactive tool to provide immediate feedback on the effect of color map adjustments. Note that its interpretation depends on how well the display device reproduces the sRGB color space.

Fig. 2 shows this pattern for the sequential map with varying lightness and multiple hues. The pattern detail visibility is nearly uniform throughout the image, confirming the approximate perceptual uniformity of the map.

Fig. 3 shows this pattern for the sequential map with varying saturation and constant lightness and hue. This example shows that the missing variability in lightness leads to low discriminative power of the resulting map. Nevertheless, some applications require constant lightness.

Fig. 4 compares test patterns for diverging maps with varying lightness, one created using the Wijffelaars model [WV08], and one created using our model. Our map shows stronger discriminative power in the middle of the map, and therefore an improved perceptual uniformity.



**Figure 5:** Comparison of test patterns for qualitative maps. The top map was created using the Wijffelaars model [WV08]. The bottom map was created using our model and shows weaker discriminative power and weaker perceptual uniformity.

As an example illustrating limitations of our models, Fig. 5 compares test patterns for qualitative maps, one created using the Wijffelaars model [WV08], and one created using our model. Our map shows weaker discriminative power and, despite guaranteeing perfect perceptual uniformity based on the CIELUV distance measure, it shows weaker perceptual uniformity than the Wijffelaars map in the test pattern. One reason for this might be that the standard observer experiments used as a base for the CIELUV color space (on which our models are based) may not be ideal for applications in scientific visualization [Kov15].

Note that the LCH colors generated by our models need to be converted to the display color space for use in visualization applications. This today is mostly the sRGB color space, which can represent significantly fewer colors than CIELCH. Therefore, color clipping may occur, damaging the perceptual uniformity and other properties of the color map. Reducing the overall saturation of a color map typically reduces instances of color clipping considerably, at the cost of reduced discriminative power of the map. Our tool reports instances of color clipping to the user and at the same time allows adjustment of saturation (and other parameters) so that the user can interactively trade off perceptual uniformity against discriminative power where necessary.

## 5. Conclusion

This paper introduces a consistent set of color map models that allow interactive creation of sequential, diverging, and qualitative color maps that are approximately perceptually uniform by construction. Multi-hue sequential maps as well as maps with constant lightness are supported.

The approximate perceptual linearity built into our models is based on the CIELUV color space, and therefore subject to its limitations, in particular those related to the requirements of scientific visualization [Kov15].

The sets of user-definable parameters of our models and the measures taken to enforce approximate perceptual uniformity take some artistic freedom from the user, but on the other hand considerably ease the task of custom color map creation.

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