IEEE/ EG Symposium on Volume and Point-Based Graphics (2008)
H.-C. Hege, D. Laidlaw, R. Pajarola, O. Staadt (Editors)

Harmonic Colormaps for Volume Visualization

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Abstract

Color design forms a crucial part in visual aesthetics, and it has been shown that a visually aesthetic visualization will be looked at more carefully. An important role plays here the choice of a colormap that is composed of harmonic colors. This paper presents an interface that allows users to choose harmonic colors in volume visualization applications. In addition, it describes mechanisms by which non-harmonic colormaps can be converted to harmonic ones, but keeping lightness constant to preserve the original contrast relationships. Finally, we also show how harmonic colors can be used for the highlighting of important volume features.

Categories and Subject Descriptors (according to ACM CSS): I.3.3 [Computer Graphics]: Display Algorithms.

1 Introduction

In visualization and volume graphics, image and volume datasets typically come in form of 2D and 3D arrays of scalar densities, which are mostly obtained via simulations or scanning (CT, MRI, etc). Due to the human visual system's excellent sensitivity to variations in brightness, greyscale displays are already quite adequate to perceive the inherent variations of densities, at least in a local sense, using the lightness contrast to delineate small feature detail. However, the range of grey levels distinguishable by humans is limited to only about 100 [17], and thus delineating (labeling) many different objects or features in a global sense can be quite difficult with greyscale alone. In addition, such greyscale displays often also lack aesthetic appeal, which may lead to a reduction of interest as well as recall in the human observer – after all, the world around us is in color. Mapping the densities to color can help overcome these problems. In volume rendering this color mapping is provided by the transfer function which provides a general mapping of the volume densities (we shall assume here that these are scalars) into visual parameter values. Much work on transfer function design in volume graphics has concentrated on the specification of the A (opacity) portion of the transfer function, in order to capture shapes and contours of isosurfaces at great fidelity. On the other hand, the RGB portion of the transfer function has in most cases been guided by personal preferences of the system user, or even just by random assignments. Various insightful contributions in these regards have been made in [3][11][18][19][23], but that work has focused mostly on accomplishing perceptually uniform color scales (colormaps). The research presented in [9] specifically addressed the lightness component of these colormaps, devising a simple method to specify such colormaps on commodity non-calibrated displays. Other work [5] described how to best partition the color space to accommodate the best object differentiation (labeling). A number of general books on the subject of color and perception are also available [20][22][24][25].

Aesthetics in the choice of color, on the other hand, has played less of a role in volume graphics so far. However, good visual aesthetics is an important component in visualization. It makes the data exploration task a more enjoyable one and therefore reduces stress. As the work of [16] shows, products designed for use under stress must follow good human-centered (pleasant, aesthetic) design, since stress makes people less able to cope with difficulties, less flexible, and less creative in problem solving tasks. Furthermore, [8] has conducted a set of very interesting experiments to show that objects considered beautiful stimulate different areas in the brain than those considered unattractive. One popular design aspect in terms of aesthetics is *color harmony*. Color harmony is a fairly old concept, already expressed by Goethe and other greats of that epoch, and a quantitative representation was described by Moon and Spencer [13]. This representation was based on the Munsell color-order system [14], which consists of three perceptual coordinates: hue, value (lightness/brightness), and chroma (colorfulness/vividness). In search of an intuitive 2D representation for visual designers, Itten [6] then arranged the harmonic colors into a color wheel, which reduced (flattened) this color space to mostly variations in hue. Matsuda [12] employed Itten's color wheel, in conjunction with extensive psycho-physical studies, to introduce a set of 80 harmonic colors schemes. These were the basis of the recent automated image color harmonization system by Cohen et al. [4], which allowed users to transform a given (possibly ill-chosen) scene colorization into a harmonious one. This can be useful, for example, in image composition tasks, when foreign image objects, such as logos, are inserted into an image. Furthermore, the system also gives users a good mechanism to modify scene colorizations and still ensure that the result follows harmonic guidelines.

The RGB portion of the transfer function is the effective instrument for scene colorization in volume graphics. In addition to labeling, color also can be used to highlight certain densities intervals and density contrasts, guiding the viewer to these (visually salient) areas. This quality of color is called *pop-out* [1]. Pop-out exploits the property of the low-level human visual system that causes an involuntary awareness of a feature within an ms-time interval. This awareness may or may not occur at a conscious level, which is a finding that presents a departure from the widely used notion of 'pre-attentive processing' (see for example [10]). The pop-out effect is strongly connected to the vividness and lightness of the color, so a switching among harmonic color schemes should not impair these properties.

In our work, we have strived to give visualization researchers a tool that allows them to design harmonic color transfer functions, following the rules established by Matsuda. However, in contrast to computer graphics (at least in a more general sense), we also need to take into account the mission of visualization, that is, to give users insight in to data. In that mission, not only hue, but also chroma and lightness play important roles as they support the aforementioned pop-out effect. This prohibits a simple flattening of the hue channel to switch among the various harmonic color schemes, colorizing the scalar densities. Thus, a further contribution that our paper makes is how harmonic colorizations can be achieved that preserve existing lightness contrasts and salience.

Our paper is structured as follows. Section 2 presents theoretical concepts. Section 3 describes our color-harmonized volume rendering system and explains how we achieve the desired lightness-controlled color harmonization. Section 4 presents results, and Section 5 ends with conclusions and pointers to future work.

2 Theoretical background

In this section we first present relevant background on the human visual perception of color and on color harmonization. Then we proceed to discuss the interplay of hue, chroma and lightness, which is not supported by the present color harmonization scheme.

2.1 Some notes on human color perception

Let us first review a few concepts from visual perception, and then put these into context of the work presented in this paper. The amount of light incident on a surface is called *illuminance*, while *reflectance* is the proportion of the illuminance that is reflected from this surface towards the eye. *Luminance* then is the amount of visible light that arrives at the eye from the surface, and it is the product of illuminance and reflectance. We note that all these are physical properties that can be measured using physical devices. On the other hand, *lightness* is the perceptual correlate of reflectance, that is, the perceived reflectance, while *brightness* is the perceptual correlate of luminance, that is, the perceived luminance. To put our work into proper context we assume an idealized light source. Therefore lightness is equal to brightness, since in volume visualization we are mainly interested in conveying the reflective properties of an object as a visual manifestation for its structure. We shall therefore use the term lightness in the remainder of this paper. This model also fits settings in which components of the visualized object themselves act as emissive light sources. In that case, we shall also assume that these light sources are ideal and, for our purposes, behave like the scene reflectances.

Color vision can be studied with two rather different goals in mind: *aperture color* and *surface color* [24]. Aperture color takes a more physics-based, wavelength-oriented approach to color vision, conducting experiments in very controlled laboratory settings. Test subjects compare small patches of color, embedded on black backgrounds and under exclusion of all other effects, such as lighting and surrounding scene. These types of experiments can explain the fundamental color matching properties of the human visual system very well. However, they are less suitable to explain the effects and interaction of colors within a more general, less controlled scope, as embodied by real-world viewing conditions. Studies that operate in these settings explore the aspects of surface color, which is more complex, varied, and medium constrained than aperture color. As a distinguishing example may serve the situation where one visits a paint store, armed with a carpet swatch, seeking to select a matching wall color by ways of a set of similarly-sized store-provided paint swatches. In many cases the anticipated interplay is vastly different from the actual one, once the wall has been painted. This can be due to varied lighting conditions, but also to the different actual proportionate sizes of the two matched color surfaces, and the effects of other colored items resident in this living space, in this example. Color harmony, and color design in general, are and embrace principles rooted in surface color.

2.2 Some notes on color harmonization

As mentioned, the concept of color harmony is well known and goes back to Art theorist Johannes Itten (a co-founder of the Bauhaus movement in the Arts). In 1960, he introduced a new type of color wheel, mainly based on hues and their relative position, giving rise to 26 different

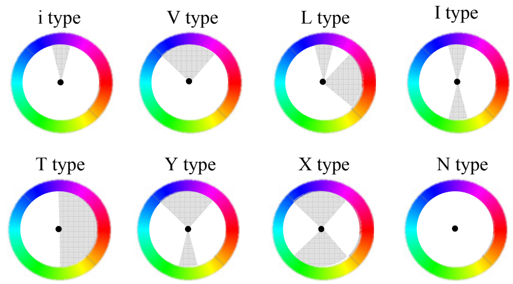


Figure 1: *Harmonic hue wheel templates. The grey sectors indicate the possible spaces that a histogram of hues may occupy. The templates can be rotated by an arbitrary angle. See the appendix of [4] for the exact sizes of these areas.*

combinations of harmonic color relationships. Two decades later, based on Itten's work, Matsuda then devised the set of 80 color schemes, combining several types of hue and tone distributions. Cohen et al. used the eight harmonic hue templates given in Figure 1.

A harmonic distribution of hues has a histogram that only occupies the grey sectors in any of these eight templates The N-type is only composed of grey hues. The templates may be rotated by an arbitrary angle but they cannot be resized. The algorithm of Cohen et al. accepts any image (or an image collage) with a possibly non-harmonic hue distribution (histogram), finds the closest (rotated) harmonic hue template, and then uses an optimization algorithm to re-colorize this image (or image collage) to have a hue distribution that fits this nearest harmonic template. The algorithm only considers hue, but not saturation or lightness. However, pixels with higher saturation receive more weight in the template matching procedure because their hue is perceptually more salient.

Other notable work on computational color harmony is that of [15] which presents a color design tool with a knowledgebase derived from a large ongoing user study spread over more than three decades. They find that maximal hue harmony is achieved by using pair-wise hue distances of around 12, 35, 130, and 180 degrees (on the hue wheel), while separations of around 21, 80, and 153 degrees are not recommended. In addition, they also offer perceptually-based rules for choosing the saturation and lightness of color pairs. An interesting finding in this regard is that the most harmonious lightness contrast of a color pair is obtained when their lightness differs by 17 to 45%, independent of hue and saturation. Further, there are also a number of well and ill-chosen saturation combinations, which are a function of the angular hue distances on the color wheel. These are more expressed for saturated colors. The worst angular hue distance here is 80°.

2.3 The interplay of hue, chroma, and lightness

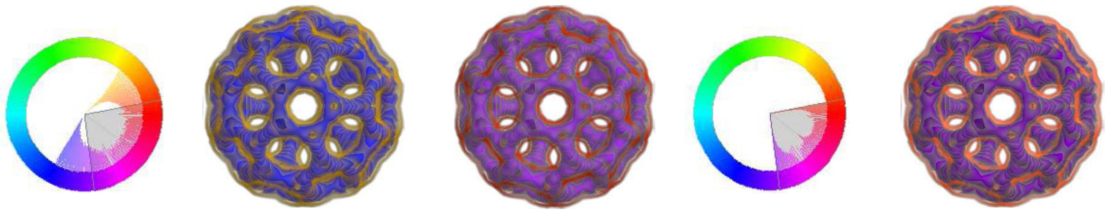
As mentioned, apart from harmonization, another design goal addresses the need of visualization to guide the observer to the most important features of the data. A recent paper in that regard is that of [7] who employed an emphasis function based on the center-surround mechanism of the human visual system to enhance the visual saliency of features important within the visualization task. While color is not the only way to encode the visual field, show similarity and difference relationships, and direct viewer attention, it is generally the best and fastest. Such a system will embrace a strong interplay of the three perceptual color parameters, that is, hue, chroma and lightness, and therefore an associated color harmonization method must also support all of these. However, in order to achieve this, a suitable extension to Itten's hue-based color wheel needs to be devised, which in turn also requires an extension to the automated color harmonization algorithm by Cohen et al. Since the concept of a color wheel is convenient and intuitive – which was most likely the reason it was invented for – this extension should be formulated as a post-process to rectify any imbalances of chroma and lightness during the harmonization process. This is most suitably executed in a perceptual color space, such as CIE LAB (also known as CIE L*a*b*, or more informally, Lab color space).

3 Color harmonized volume rendering

We initially used a system similar to that of Cohen et al. to define and convert transfer functions (colormaps) for use in volume rendering applications. For this, we simply converted the RGB transfer function to HSV coordinates, transformed the hue (H) channel to fit the nearest harmonic template (Figure 1), converted the result back to RGB, and rendered the object with this new harmonized transfer function. To demonstrate, we shifted the color transfer function of a volume rendering of the Buckyball dataset into a harmonic configuration. This is shown in Figure 2a and b where to the right and left of the two images, respectively, we show the image hue histograms embedded into the hue wheel. Figure 2a is a rendering with the original color transfer function, while Figure 2b is a rendering with a harmonized transfer function, using just the hue wheel. The degradation in lightness of the thin boundaries is dramatic, making it difficult to see small detail and also pushing its visual salience into the background. This is due to the reduced lightness of the thin boundary's red color (as opposed to the brighter yellow color used in Figure 2a). In contrast, Figure 2c shows a harmonized image (with the same hue histogram than Figure 2b) that preserves lightness and thus restores the lightness contrast of the non-harmonic image of Figure 2a. We now describe our framework that extends the method of Cohen et al. to lightness-preserved color harmonization and then apply this method for volume visualization (demonstrated in Section 4, Results).

3.1 Lightness-preserving color harmonization

As discussed before, the original color harmonization scheme of Cohen et al. shifts the hues on the color wheel into a (new) harmonic color configuration. Since only the hue is varied, if the shifting angle is not small, the lightness and contrast will change. We shall now describe our



(a) (b) (c)

Figure 2: *Color harmonization without lightness-preservation (Buckyball dataset). (a) Original rendering with corresponding hue wheel; (b) Rendering with colormap harmonization using just the hue shifting (hue wheel on the right); (c) Rendering with hue harmonization, but with our lightness-preservation scheme applied after hue shifting (same hue wheel than (b)).*

scheme to preserve lightness after hue shifting. The hue wheel used in the standard color harmonization is simply the circumference of the top-level of the HSV color space, somewhat compensated for saturation. The interior (the lightness) is not represented. Thus it is a 1D compression of the 3D color space. As is well known, the HSV color space is not a perceptual color space, but the CIE LAB space is (within certain tolerance levels). The HSV space gains its high popularity since it is intuitive to interact with. However, we can see its inappropriateness for lightness preservation when plotting the iso-lightness curves (derived from CIE LAB) of different hues into their corresponding HSV hue-slices (note that these curves are monitor-specific and require a prior sRGB conversion step, using the monitor's white point, followed by a mapping to CIE XYZ). Two of these HSV hue slices with their iso-lightness curves mapped onto them are shown in Figure 3. In this figure, each such curve reflects a trajectory in CIE LAB space, formed of points of the same hue and lightness, but decreasing chroma (see [21] for more detail on the derivation of these curves). We observe that from the bottom curve to the top curve, the lightness increases gradually, and we also note that for different hues, the lightness values of the most vivid colors (the top-most outside points on the hue slices) are quite different.

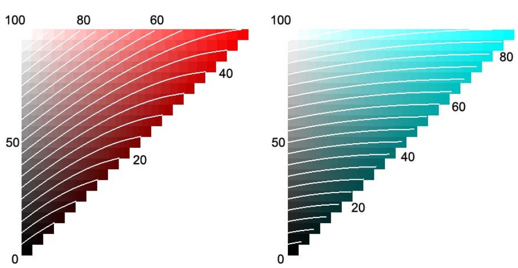


Figure 3: *Iso-lightness curves for two different hue-slices (red, cyan) in the HSV colors space. The numbers indicate the lightness value.*

From these curves we see that in order to preserve lightness when shifting from one hue to another, we must use the same lightness curve on the new hue. We achieve this by first converting the RGB transfer function to an HSV transfer function. We also plot the histogram of hue (H) values into the color wheel (shown in Figure 2). Then, when the user employs the hue wheel for a harmonized transfer function modification, we map each transfer function HSV triple to CIE LAB space, and locate the LAB triple with the target hue and saturation and the source lightness. Since it is not always possible to increase lightness without sacrificing saturation (see the iso-lightness curve in the red HSV slice in Figure 3), we prefer to reduce saturation (over lightness). We then convert the triples back to obtain the RGB transfer function for rendering. This scheme was used to generate the Buckyball rendering in Figure 2c. Next, Figure 3 compares our lightness and contrast preserved color harmonizations with the original color harmonizations of Cohen et al. We observe that our method keeps the contrast and details significantly better. For example, in Figure 4c, the left-most person's silhouette is almost blending into the

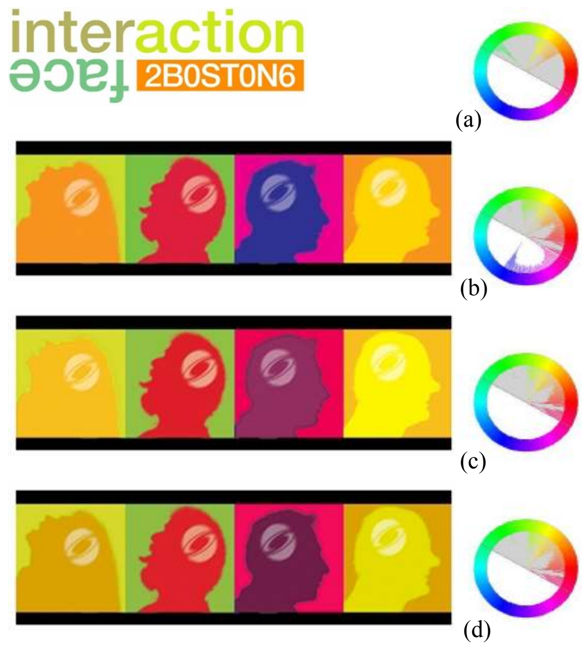


Figure 4: *Lightness preserved color harmonization for an image pair. (a) Image 1, (b) Image 2, which will be color harmonized to image 1, (c) Color harmonization using the method of Cohen et al., (d) Our lightness preserved color harmonization. Shown to the right are the respective color histogram distributions on the hue wheel of the original image.*

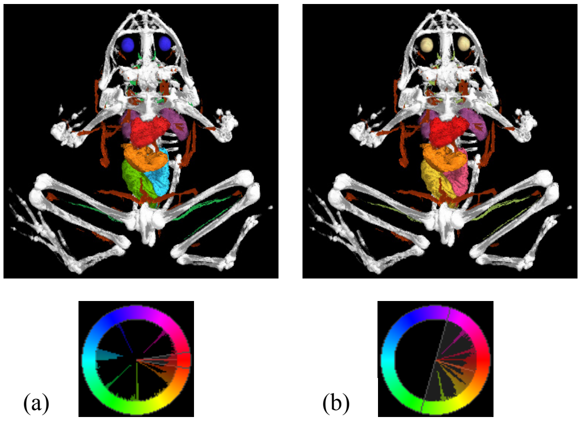

(a) (b)

Figure 5: *Volume rendered segmented frog dataset. (a) Original non-harmonized color transfer function; (b) Harmonized color transfer function (T-type).*

background, but in Figure 4d, it stands out like in the original image, and the contrast between the third person and the background is better preserved as well.

3.2 Lightness-preserving color harmonized volume rendering

A novel issue (as compared to image color harmonization) is that in volume visualization we often make use of semi-transparencies where the resulting color mixing and blending may change all color parameters, that is, hue, chroma, and lightness. While the changes in lightness, and to some extent also chroma, are desirable in the illustration of these partial occlusions, the changes of hue from a harmonic to a possibly non-harmonic hue can be troublesome. In fact, we have addressed these issues in a companion paper [21], where we describe various methods to avoid, or at least reduce, the manifestations of these false color effects. We achieve this by reducing the global or local (in the overlap region only) saturation and blending weight of the background object in the mixture. In this paper, we shall assume that we are able to control the hue in the presence of color mixing of semi-transparent materials and restrict our discussion on achieving lightness-preserving harmonic color scales.

4 Results

We now present a variety of results illustrating the capabilities of our method for application in volume visualization. In Figure 5a we show the volume rendered frog dataset with a non-harmonic transfer function (see the histogram in the hue wheel below). We first use the matching method of Cohen et al. to determine that the closest harmonic template is the T type (compare Figure 1). Then, using the optimization method, we shift the original transfer function to the nearest T type template. Following, we employ our lightness preservation framework to maintain the restore the original lightness levels. Finally, we re-render the dataset with the new harmonized transfer function. The result is shown in Figure 5b.

Next, we demonstrate our method in a scientific rendering scenario. Figure 6 shows various collage compositions of semi-transparent volume renderings of the shockwave and turbulent jet datasets. Two different transfer functions were used, one for each dataset, and the hue histogram incorporates both. Figure 6a shows a non-hue harmonized rendering, while Figure 6b and c show renderings after the joint histogram was matched to two different templates, T type and V type, respectively. In both cases, the two transfer functions were shifted into the matched template.

The third example points out a limitation inherent to the color harmonization concept, that is, its tendency to reduce the available color gamut. Consider Figure 7 where we show a rendering of the vortex dataset. We see that while the colors in Figure 7a are not harmonic, they are able to show the fine nuances of the data better (see the thin blue layers around the long red structures in Figure 7a) than the harmonized color distribution (although we picked the T type which covers a fairly wide range of colors).

Finally, to demonstrate the impact of highlighting (using color vividness) for pop-out, we devised the following extension. We use the equi-lightness curves of Figure 3 to design color scales. Here, Figure 8 shows two equi-lightness color scales, with vividness changing from high to low. Based on these equi-lightness color scales, we can design a scheme to highlight the features in volume data

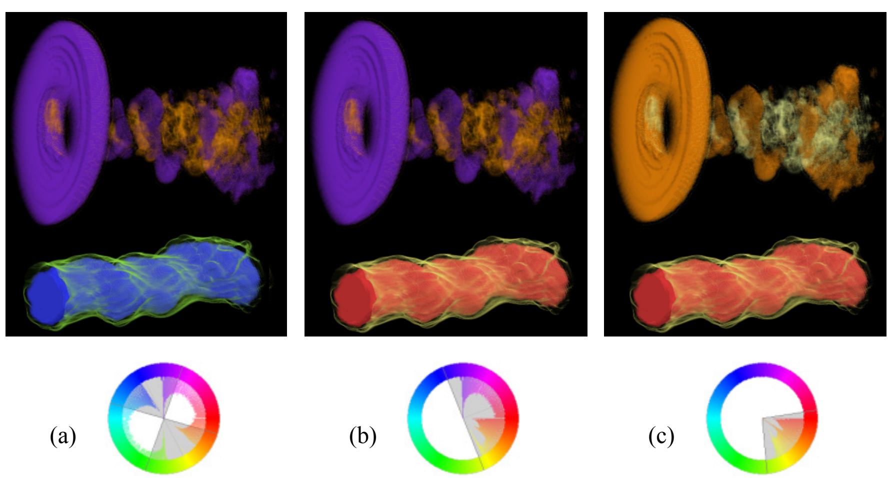

(a) (b) (c)

Figure 6: *Composition of shockwave and jet dataset rendering.(a) Non-harmonic transfer function; (b) Harmonic transfer function (T type); (c) Harmonic transfer function (V type).*

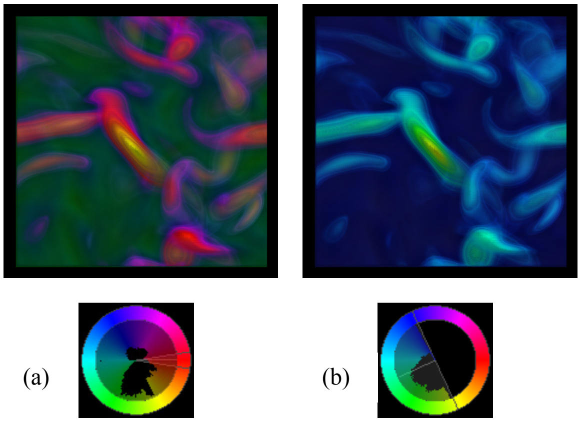


Figure 7: *Volume rendered vortex dataset. (a) Non-harmonized transfer function; (b) Harmonized transfer function (T type).*

one by one. This is shown in Figure 9. All features are always visible since the lightness is not changed, but one feature is highlighted by a more vivid color each time, which draws the observer's attention.

4.1.1 Conclusions

We have extended the method of color harmonization to volume visualization. One significant shortcoming of the current color harmonization framework was that it did not preserve lightness which however is important in visualization tasks since it serves as a means for highlighting, contrast enhancement, and pop-out. We therefore devised a framework that restores the original lightness contrast after the hue harmonization has taken place. A by-product of the framework's equi-lightness curve interface are equi-lightness color scales, which users can employ to select the degree of visual attention, expressed by color vividness, for selected objects or object parts in a dataset, on a continuous scale. In future work we plan to incorporate more rules of human perception into the framework, and create a more sophisticated framework for colorization for illustrative rendering applications.

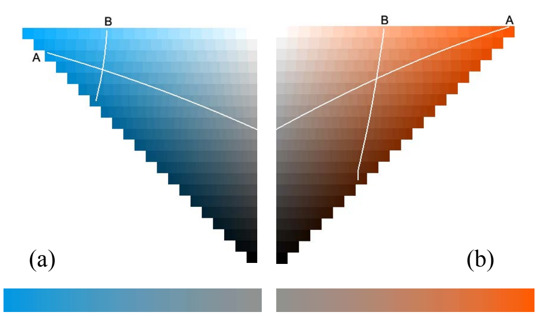


Figure 8: *Color scales. (a) Hue slice with h=20; (b) Hue slice with h=200, A is an equi-lightness curve (B is an equi-vividness curve). Below we show the equi-lightness color scales derived from the equi-lightness curve.*

Finally, we would also like to find better solutions for overcoming the limitations of the color gamut reduction that is inherent to the harmonic color templates. One way might be to compensate for these effects by varying the saturation instead, which is a color parameter we have not considered so far.

Acknowledgments

This work was partially funded by NSF CAREER grant ACI-0093157 and NIH grant 5R21EB004099-02. We also thank the NVIDIA Professor Partnership program for an equipment donation and the reviewers for helpful comments.

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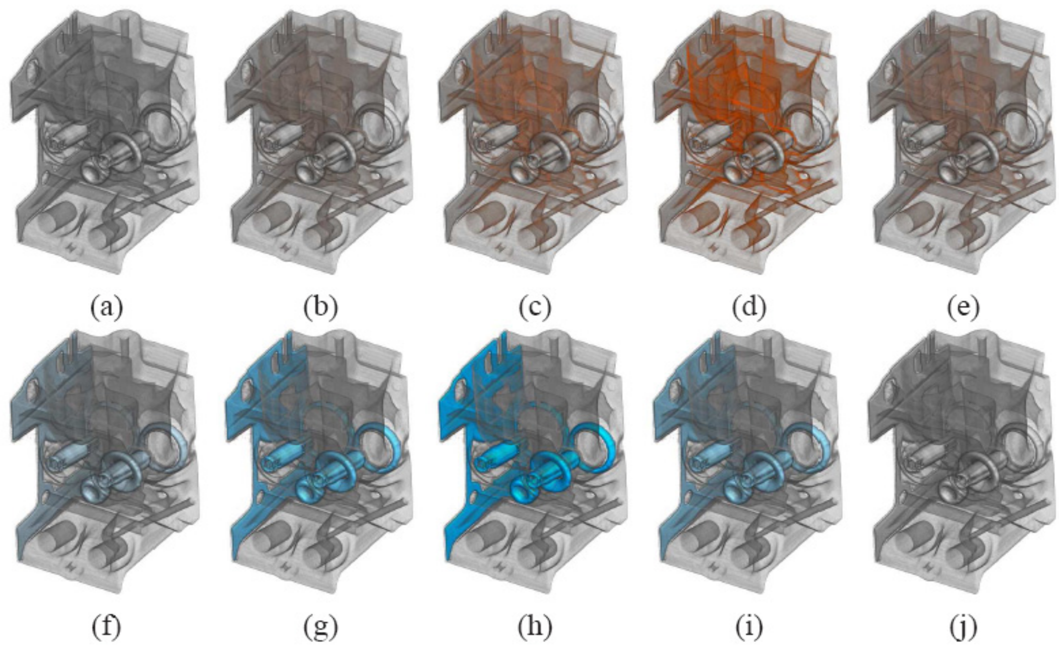

Figure 6*: Features are highlighted one by one: (a) All features are rendered in neutral colors, no feature is highlighted, (b)-(d) The outside feature is highlighted by increasing the vividness of its color gradually, while preserving the lightness, (e) The vividness of the outside feature decreases, (f)-(h) The inside feature is highlighted gradually, (i)-(j) The vividness of the inside feature decreases*.

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