Color Coding for Data Visualization

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Simone Bianco
Università degli Studi di Milano-Bicocca, Italy

Francesca Gasparini
Università degli Studi di Milano-Bicocca, Italy

Raimondo Schettini
Università degli Studi di Milano-Bicocca, Italy

INTRODUCTION

Visualization is a process of mapping data onto visual dimensions to create a pictorial representation. A successful visualization provides a representation which allows the user to gain insight into the structure of the data or to communicate aspects of this structure effectively, The use of color for encoding information can greatly improve the observer's understanding of the information depicted by image and his/her capacity for remembering it. However, many aspects of color itself and of its use are unknown to both users and system designers. Users are often allowed to choose colors that can not be reproduced, that can not be distinguished by the human eye, or are easily misinterpreted. The broad range of variables involved, as well as the interactions and the trade-offs among them, pose difficult problems in selecting specific colors, in predicting their appearance when they are seen in relation with others, and in predicting the observers' interpretation and reaction to them. These problems can not be solved without a working knowledge about color reference systems, color reproduction technologies, mechanism of color perception, users' cultural and emotional reactions. The goal of this paper is to critically discuss how a color scale should be designed to effectively represent both qualitative and quantitative information. Color coding requirements, with regard to the task at hand, the characteristics of the media, and the characteristics of data to be coded are therefore analyzed providing examples and references to related works.

BACKGROUND

A color coding scheme can be characterized by a color mapping function $f: D \rightarrow C$ that maps data values D to colors from the color palette C. In case of univariate data, each value is mapped to a single color, with multivariate data, each combination of values is mapped to a single color.

In the following we make a distinction only between qualitative (nominal) and quantitative (ordinal, interval and ratio) data values.

Associating a set of colors with a set of items to express the significance of each is called "nominal color coding." Examples of nominal data values are: water, vegetation, and urban. There is no logical ordering in this sequence.

Color can be also used in a quantitative fashion, i.e. to convey information about ordered data set. We can distinguish here among "ordinal, interval and ratio color coding." In ordinal coding the data values are in some way ordered, i.e., the data values can be put into a sequence but no distance is defined between data values. Examples of ordinal data values are: very bad, bad, average, good, very good. In interval coding data one can define a distance between two data values, but the zero point is arbitrary. The hue by itself can be seen as interval data values, we can say that the distance between red and yellow is 90° but we can not says that yellow is bigger than red. Periodic functions typically produce interval data values. Data sets with both positive and negative values can have a zero point representing no change, average, or expected value. In such data, deviation from zero is what is interesting. In ratio coding a zero point is therefore defined. Data values that represent the temperature are ratio data, in

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this case the zero point is defined at 0 Celsius degrees and we can state that a temperature of 20 Celsius degrees is twice a temperature of 10 Celsius degrees.

For nominal and ordinal data types discrete palettes must be used. For interval and ratio data one can use both discrete and continuous palettes, according to the data structure and to the visualization aims. If a discrete palette is used to code interval and ratio data, those values must be a-priori quantized into a finite number of ranges.

MAIN FOCUS OF THE ARTICLE

The goal of this paper is to critically discuss how a color scale should be designed to be effectively adopted to obtain a successful visualization. For instance, adding a color which does not add additional insight to the visualization can sometimes cause confusion as users try to understand its meaning and should, therefore, be avoided. So, it is particularly important to perform the right choice in order to build visualizations which depict the desired information in a clear way. The color scales and methods used for encoding information depend on several factors. They certainly depend on the data type involved in terms of information carried (qualitative and quantitative) and dimensionality of the representations (univariate or multivariate). The goal of a specific visualization is also an important issue when choosing a color scale. Different tasks and goals require different color coding schemes. Certain goals may require specific subsets of data to be highlighted. This can be achieved for instance by using bright, warm, and fully saturated colors. Within this context, Bergman et al. (1995) have proposed to select the appropriate color scales according to four specific tasks, while Tominski et al. (2008) have presented a task-driven color coding. Different color perception of the viewers must also be considered. An estimated nine to twelve percent of the male population and less than 1% of females suffer from some form of color vision deficiency. The degree to which a person may have an abnormal color vision ranges from slight difficulty in recognizing color shades to a complete loss of color vision. The most prevalent type is a deficiency in perceiving red/green differences (approximately eight to ten percent of the male population), while one to two percent of men are blue/yellow color blind. VisCheck (http://www.vischeck.com/vischeck) is a web tool base on based on SCIELAB which shows how an image is seen by a user with some kind of color blindness. Apart from its aesthetic appeal, we can use image processing techniques to try to make information in images available to color blind people (http://www.vischeck.com/daltonize/) without distorting the color balance to an unacceptable degree. Color schemes that accommodate red or green-blind dichromats will accommodate most other forms of color deficiency.

Many colors have certain qualities associated with them because of their natural occurrence, cultural usage or technical norms. However color also depends on, and is constrained by, the cultural traditions or technical experience of the users. We commonly associate green with vegetation, for an USA audience the color green is associated with the color of money.

Thus in this paper the color coding requirements, with regard to the task at hand, the characteristics of the media, and the characteristics of data to be coded are therefore analyzed providing examples and references to related works.

Color Space Selection

Several approaches to color description, whatever based on device-dependent data, colorimetry, or some other empirical organizations give rise to various color spaces. The use of RGB color spaces seems unrealistic for man-machine communications since its metrics does not represent color differences in a uniform scale and the colors are not organized in a manner intuitive for human observers. Color spaces, such as RGB and derived color spaces, are device-dependent and therefore do not univocally describe colors. If colors were identified only by their device-dependent coordinates it might be difficult to reproduce the same image on another device (display, printer, projector….) or worst still, an image that differs from the one intended is generated.

Device-independent color description, perceptual addressability, and the capability of representing color differences in a uniform scale can be achieved by specifying colors in the CIELUV or CIELAB color spaces. In our opinion CIELAB space represents the best that can be achieved with a space of Euclidian metrics. However, as it does not take into account all factors determining color response, it should not be used as an absolute standard for color appearance description.

Obviously, other color spaces can be used for selecting colors in particular for nominal color coding. One could, for example, define a color atlas by sampling the color solid obtained by mapping the RGB color cube of the device to the CIELAB color space. Campadelli et. al (2001) have preferred to use the Munsell Atlas for nominal color coding mainly for two reasons:

- The classified images may not only be displayed on the screen but also printed. Since the gamut of feasible colors of common displays and color printers differ considerably, a "good," high contrast, color coding on the screen may be drastically modified when printed. Many colors (in the ranges of blues and greens in particular) cannot be reproduced in print. Restricting the selection of color to the Munsell color atlas greatly limits this drawback.
- Munsell specification can be associated with the ISCC-NBS standard color naming system providing a simple way of verifying whether the colors selected, either manually or automatically, have similar linguistic descriptions. This is very helpful in preventing undesirable conceptual linking between unrelated classes in the classified image, or, viceversa, in creating those links when necessary.

To map the colors in RGB values for reproduction on a given output device, the user must provide the color profile of the display device, a well-defined tool enabling color conversion in cross-media color reproduction. The International Color Consortium (ICC) has defined the rules for coding in ICC profiles, the functions for the conversion of colors from a device-independent to a device-dependent color space, together with information about the viewing conditions and media characteristics recommended for Color Management Systems, which can be used to ensure faithful color reproduction on different media or devices. If the user cannot supply the ICC profile, a default display device set to the Standard RGB color space and corresponding color profile should be assumed. For a more complete discussion of color reproduction and Color Management Systems, interested readers may refer to http://www.color.org/index.xalter.

Qualitative Color Coding

Color is pre-attentively observed and used to segment the visual environments into objects. This characteristic makes it particularly effective in coding qualitative information. In nominal color coding all colors should be distinguishable, the palette should display no clear ordering and all colors should be perceived as equally important. There should be no perceptual ordering in the representation. The number of colors used to represent nominal data should be restricted to seven or less. The problem is that we have often more items to represent than easily discriminable colors. Moreover in the design of a coding, colors may be used not only to permit the recognition or discrimination of information items, but also to convey high-level information at local (e.g. areas are evaluated) and/or global level (e.g. apparent conceptual linking between different items) as well, (Wang et al. 2008).

Several heuristic procedures have been proposed to define high-contrast sets of colors. Kelly (1976) has conceived a list of 22 maximally contrasting surface colors, such that each color of the list is maximally different from the one immediately preceding it. In 1982, Carter and Carter (1982) formulated the first algorithm to compute easily discriminable sets of colors: selecting a subset of highly contrasting colors from a given range of colors means choosing a subset such that in it the minimal distance among all possible couples of colors is maximal. Campadelli et al. (1995) have presented an abstract formulation of the problem of selecting high-contrast color sets, defining it as a combinatorial optimization problem on graphs. They also addressed the algorithmic aspect of the selection of high-contrast color sets. They presented an effective algorithm, which has an innovative feature that could also be useful when one has to take into account visual features such as the shape, size, and texture of the graphical items to be coded. The algorithm does not require that the function used to code the similarity between two colors (or graphical codes obtained by combining color with other visual features) be a distance function; in other words, it works whatever the measure of perceptual similarity selected (Campadelli, 2001). Several authors have devised algorithms that

Figure 1. The sets of colors (with cardinalities from 2 to 25) selected applying the method described in Bianco (2013), rendered in sRGB under the CIE D65 illuminant

can also fulfill a number of ergonomical requirements (Bergman, 1995; Borland, 2011; Della Vantura, 1991).

Bianco and Citrolo (2013) addressed the algorithmic aspect of the selection of high contrast color sets under single or multiple illuminants, and present an effective algorithm based on Local Search, which is fast enough to be used in real time applications. The sets are extracted from the Munsell atlas and have cardinalities from 2 to 25. The method is also generalized to cope with multiple illuminants simultaneously (Figure 1).

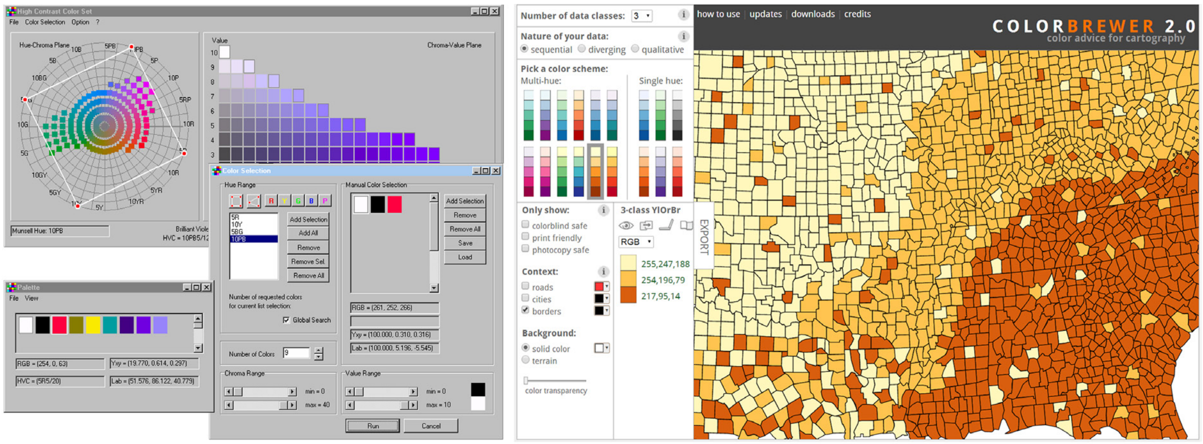
Borland and Huber (2011) argued that designing color maps for domain experts differs fundamentally from designing them for general audiences. Domain-specific knowledge should inform the design choices and domain experts need to understand the design choices, a close collaboration between designers and experts is therefore necessary.

There are some systems aimed to facilitate this cooperation. Campadelli et al. (2001) presented a system for the automatic selection of conspicuous color sets for qualitative data display called Quickcolor. Based on visual interaction, it provides effective tools for browsing the Munsell color space and setting perceptual constraints on the colors the system then selects automatically. This system is available for academic and non-profit purposes. ColorBrewer (is an online tool designed to help people select good color schemes for maps and other graphics. The system informs the user about several important properties of the chosen color representation, such as if it is suitable for color blind people and if can be faithfully color printed. It is free to use. In Figure 2, the interface layouts of Quickcolor and ColorBrewer are shown.

When the user defines the color coding, setting the colors selected in correspondence with the values of the data, some simple guidelines should be taken into account (Della Ventura, 1993, Lefkowitz, 1992):

- The human eye is only effective in detecting relative values of colored areas in close spatial proximity. If these are far apart, local distortions may somewhat alter the information.
- The edges formed by chromatic differences alone with no lightness difference are poor

Figure 2. Quickcolor (on the left), and ColorBrewer (on the right) interface layouts for nominal color coding



guides to accurate focusing: these edges remain fuzzy.

- Colors that differ only in the amount of blue do not produce a sharp edge.
- The eye can not maintain its focus various on highly-saturated highly-bright objects in spectrally extreme hues (e.g. blue-red, yellow-purple) at the same time (a 3D illusion is produced). Desaturating these colors reduces the need for refocusing.
- The color of a patch affects its perceived area. Saturated colors appear larger than desaturated ones. It has been shown that when highly saturated red and green were used to color a statistical map, the red areas were judged to be larger, even though the regions were actually of the same size. No such consistent distortion occurred when low saturated colors were used.
- Since the smaller the area, the less discriminable the colors, the user should be encouraged to limit the use of highly saturated and bright colors to rendering perceivable thin lines and small shapes in the image.
- Areas of strong color can produce afterimages when the viewer looks away from the screen. Bright, highly saturated colors should not used for prolonged viewing but just to grab attention.

In the framework of nominal color coding, we usually use color for differentiation, that is for indicating that certain elements differ in their properties from the others. However we can also use color for association, that is, for indicating that certain elements in a design have common properties. Nominal color coding is widely employed by the image processing community to represent the output of a classification-segmentation process. In this context a serious problem arises because the chosen colors must be displayed together and assigned to classes composed of regions of different size and morphology. The user must take into account the characteristics of the image (the number of classes, the links between them, and the geometric and topological features that belong to the different classes) so that the association of classes with colors produces a readable, pleasant coded image. Although various systems have been proposed to support the user in color coding, these are mainly based on a trial-and error approach and demand a concerted effort on the part of the user (Campadelli, 1994).

Quantitative Color Coding

When we want to code a quantitative information, we must compromise between the need for correct perception of a single color (so that it can be translated, using the legend, into a numerical value) and the need to convey to the viewer the order intrinsic to the data. In some cases convention determines the choice of a color scale and the assignment of colors to data values, for example geographers have a well-defined scale to display height above sea level. In many instances there is no conventional reason for choosing one color sequence over another, as is the case for a map that illustrates the earth's magnetic field. Trumbo's principles seem important in generating and evaluating an ordinal color scale (Trumbo, 1981):

- **Principle I (Order):** If the data are ordered, then the colors chosen to represent them should be perceived as preserving that order.
- **Principle II (Separation):** Important differences in data values should be represented by colors clearly perceived as different.

To the above principles, Brewers add a third requirement for cartography (http://colorbrewer2.org/): the colors should be perceived as equally important. Grey scale/luminance/brightness and saturation scales have an innate visual order. While, disregard less of its popularity rainbow scales are not particularly useful in conveying a sense of order in the data, since they have no intuitive beginning or end. Heated-object scale represents a compromise between the luminance and the rainbow scale. It goes from black to white, passing through dark red, to orange and to light yellow. This color scale has a perceived natural ordering since it monotonically increases in brightness. Lightness scales, color scales that increase monotonically in lightness and saturation, or color scales that increase monotonically in lightness while cycling through: i.e. range of hues (short sections of the hue circle may be perceived as a "continua" e.g. red, orange and yellow) are more successful in conveying a sense of order. This redundant representation also has the advantage that it can be unambiguously interpreted by someone with a dichromatic color deficiency. It has been empirically demonstrated that when a reference scale (legend) is shown, color scales including hue variations are much to be preferred (in terms of readability) to others. With no legend, luminance encoding is far worse than the other coding.

Ware (1988) classified the information extracted from color coded maps into metric and form. Metric information conveys quantitative information at each point; form information conveys the shape or structure of the data. The human eye has different Contrast Sensitivity Functions (CSF) for luminance and chromatic channels. These differences imply that luminance is more suitable for carrying high spatial frequency information and plays and depict image structure and surface shape, while saturation and hue suitable for convey low spatial frequency information in the coded data. Color scales which monotonically increase in luminance are good candidates for representing data with a high spatial frequency. A color scale without luminance variation will not be able to convey fine spatial information, while a color scale which only varies in luminance may effectively code large-scale structural composition and variation but may not be able to depict information about low frequency, gradual changes. A color scale that varies in both luminance and hue can be used to accurately represent both metric and surface properties.

The use of RGB color spaces is not appropriate for quantitative color coding since its metrics does not represent color differences in a uniform scale and the color are not organized in an intuitive manner for human observers. Color is described more meaningfully in terms of the perceptual dimensions of lightness, hue, and colorfulness than in terms of device signals. Transformations have been developed to map the RGB color space into more intuitive ones such as HSV, HIS, HLS. However, the perceptual dimensions defined within these color spaces are only a rough approximation of the psychological dimensions. For interval and ratio color coding, equal steps in data values should correspond to equally perceived magnitude in the representation. A perceptually uniform color space can be used to help choosing the appropriate colors.

Bivariate color scales provide a method for encoding two data sets into one producing a visual representation that allows the observer to interpret these two sources of information simultaneously. The simplest bivariate schemes use planes or surface which are constant along a perceptual variable (hue, chroma, or lightness). A number of bivariate color palettes using various combinations of hue and lightness color scales have been proposed and investigated (Ware, 1988). Some bivariate and trivariate color scales can be hard to understand for an untrained user (Pham, 1990).

As examples of different color scales, we here consider the built-in colormaps supported by MATLAB (www.mathworks.com). The built-in colormaps (in the case of 128 colors) are shown in Figure 3 and described below.

- **Colorcube:** Contains as many regularly spaced colors in RGB color space as possible, while

Figure 3. The MATLAB built-in colormaps

attempting to provide more steps of gray, pure red, pure green, and pure blue

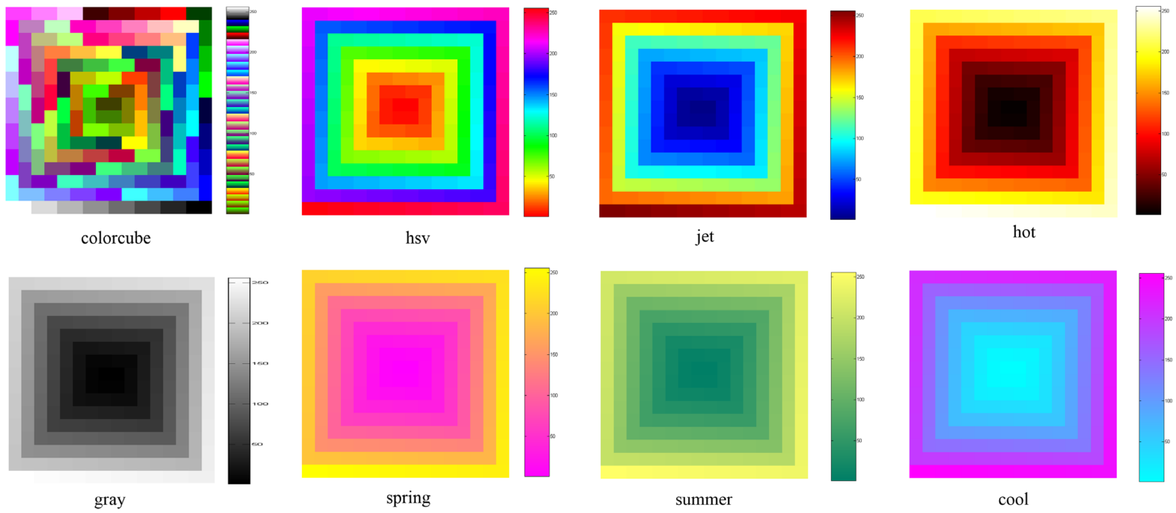
- **Hsv**: Varies the hue component of the hue-saturation-value color model. The colors begin with red, pass through yellow, green, cyan, blue, magenta, and return to red. This colormap is particularly appropriate for displaying periodic functions.
- **Jet**: Ranges from blue to red, and passes through the colors cyan, yellow, and orange. It is a variation of the hsv colormap. It corresponds to the rainbow colormap.
- **Hot:** Varies smoothly from black through shades of red, orange, and yellow, to white.
- **Cool**: Consists of colors that are shades of cyan and magenta. It varies smoothly from cyan to magenta.
- **Spring**: Consists of colors that are shades of magenta and yellow.
- **Summer**: Consists of colors that are shades of green and yellow.
- **Autumn:** Varies smoothly from red, through orange, to yellow.
- **Winter**: Consists of colors that are shades of blue and green.
- **Gray**: Returns a linear grayscale colormap.
- **Bone:** Is a grayscale colormap with a higher value for the blue component.
- **Copper**: Varies smoothly from black to bright copper.
- **Pink**: Contains pastel shades of pink. The pink colormap provides sepia tone colorization of grayscale photographs.
- **Flag:** Consists of the colors red, white, blue, and black. This colormap completely changes color with each index increment.
- **Prism**: Repeats the six colors red, orange, yellow, green, blue, and violet.

In Figures 4, 5, 6, and 7 some example images with different contents are visualized using different color scales. The reader may note how the data forms and values are differently coded and thus perceivable. It could also be noted how different color scales make more or less visible high frequency contents.

FUTURE RESEARCH DIRECTIONS

The relationship between color combinations that have harmony, which is defined as a set of colors that are aesthetically pleasing together to the human perceptual system, and visualization effectiveness is as topic that are gathering attention in the in the visualization com-

Figure 4. Different MATLAB colormaps applied to a synthetic image



munity in and reserves further research (Einakian & Newman 2010).

Concepts can invoke colors, and vice versa. In Lin et al. (2013) the authors investigate concept-color associations to design effective categorical color assignments for visualization. Such mappings may allow people to use more automated pathways to process value-color associations, require less conscious thought. Practically, concept-color associations improved recognition of category values may reduce the need to consult the data legend. Given a set of categorical values and a target color palette, the proposed algorithm matches each data value with a unique color. Values are mapped to colors by collecting representative images, analyzing image color distributions to determine value-color affinity scores, and choosing an optimal assignment.

Annotation of an image with text is a commonly encountered task. Garg et al. present a prototype system that helps users by suggesting appropriate colors for inserting text and symbols into an image. The color distribution in the image regions surrounding the annotation area determines the colors that make a good choice – i.e. capture a viewer's attention, while remaining legible. Future work includes incorporating aesthetics giving scores to colors based on color har-

Figure 5. Different MATLAB colormaps applied to a portrait image having regions of different spatial frequency

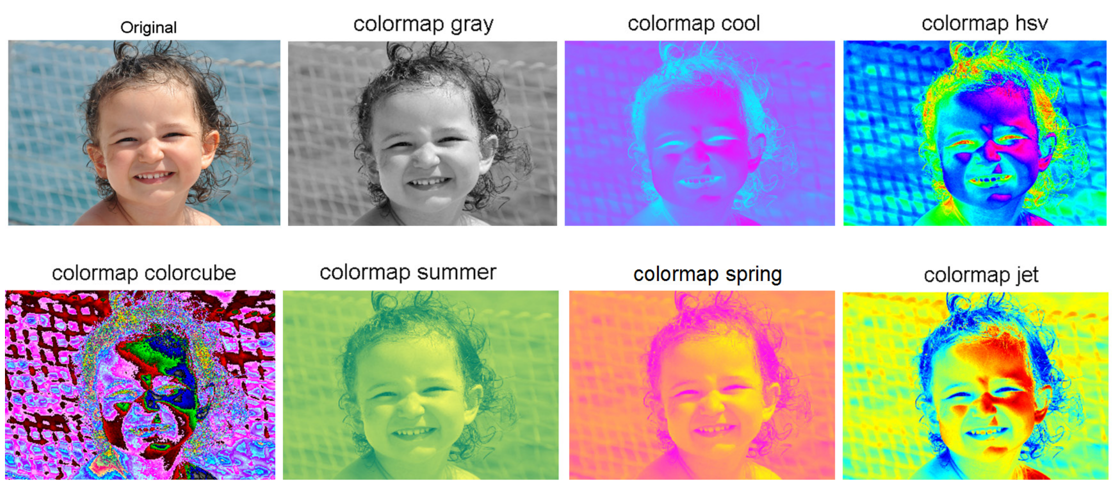
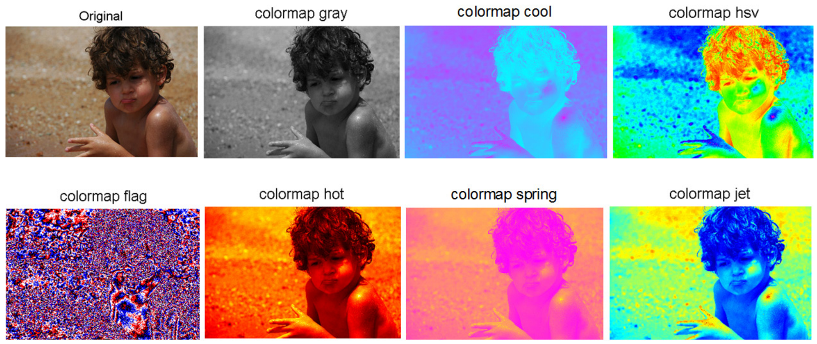


Figure 6. Different MATLAB colormaps applied to a sample image



mony and extending the system to highlight elements volume datasets.

CONCLUSION

Color is a basic visual feature, which, together with shape, size, and texture and a few other features, characterizes an image. Color is pre-attentively observed, this characteristic makes it particularly effective in conveying qualitative and quantitative information in images, maps, graphics illustrations, and diagrams. The goal of this paper has been to critically discuss how a color scale should be designed to effectively represent both qualitative and quantitative information. We have discussed color coding requirements with regard to the task at hand, the characteristics of the media, and the characteristics of data to be coded. We have shown that the choice of the proper color representation scheme to use with a particular data and communication task is not just an esthetic matter. Nonetheless, taking into account the fundamental principles of human vision and the characteristics of the output device, an effective color coding is possible providing representations which communicate aspects of both the data values and the structure effectively.

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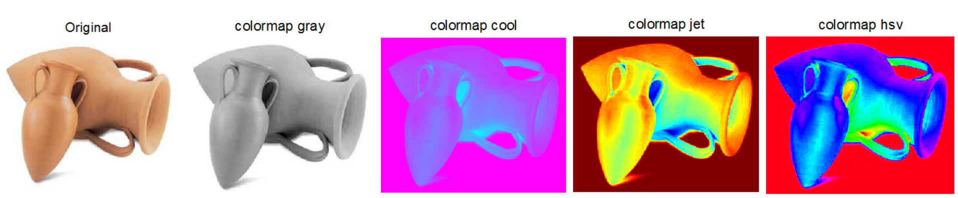
Figure 7. Different MATLAB colormaps applied to render the shapes of 3D objects



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KEY TERMS AND DEFINITIONS

D

Color Space: Mathematical model describing the way colors can be represented as tuples of numbers.

CMS: Color Management Systems.

HVS: Human Visual System.

Qualitative Color Coding: Process of associating a set of colors with a set of items to express their significance.

Quantitative Color Coding: Process of associating a color scale to represent information about ordered data set.

Visualization: Process of mapping data onto visual dimensions to create a pictorial representation.