THE END OF THE RAINBOW? AN EXPLORATION OF COLOR IN SCIENTIFIC VISUALIZATION

by

BRENDA GRIGGS

A THESIS

Presented to the Department of Computer and Information Science
at the University of Oregon
in partial fulfillment of the requirements
for the degree of
Bachelor of Science

June 2014

THESIS APPROVAL PAGE

Student: Brenda Griggs

Title: The End of the Rainbow? An Exploration of Color in Scientific Visualization

This thesis has been accepted and approved in partial fulfillment of the requirements for the Bachelor of Science degree in the Department of Computer and Information Science by:

Eugene Luks	Chair
Hank Childs	Advisor

Original approval signatures are on file with the Department of Computer and Information Science at the University of Oregon.

Degree awarded June 2014

THESIS ABSTRACT

Brenda Griggs

Bachelor of Science

Computer and Information Science

June 2014

Title: The End of the Rainbow? An exploration of Color in Scientific Visualization

Approved: ______________________________

Hank Childs

Scientific visualization aims to represent, manipulate, and explore scientific data in a way that provides understanding and insight for both expert and non-expert viewers. As color is a key element in visualization, it is important to keep in mind color map selection as it can significantly influence the viewer's perception and interpretation of the data. Although the rainbow color map is a prevalent choice among the scientific community, research has found it to mislead viewers by obscuring features and introducing artifacts into the visualization. This paper explores the impact of data representation through color using various univariate and redundant color maps. Our study indicates the rainbow color map is not the best choice for interval and ratio data representation, and validates various design guidelines from literature.

TABLE OF CONTENTS

LIST OF FIGURES

Figure

LIST OF TABLES

Table

CHAPTER 1

INTRODUCTION

Scientific visualization allows the study and analysis of large collections of scientific data [1]. One can make discoveries and gain valuable insight into a dataset through the features and patterns that emerge as a result of its treatment [1, 27]. More importantly, as color is a key element in visualization, the manner in which data is mapped — or values assigned a color — has a powerful effect on how it is perceived by a viewer. The color map selection of a visualization plays a significant part in data representation as it can influence a viewer's perception and interpretation of the data.

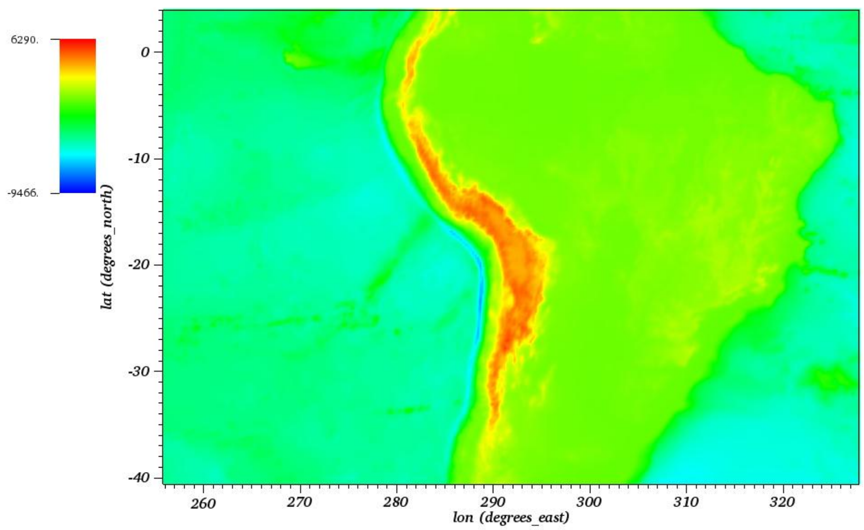


Figure 1. Elevation data of the Himalayas mapped with the rainbow color map.

The rainbow color map, as shown in Figure 1, is a prevalent choice among the scientific visualization community and is used as a default color map in many visualization software packages [4, 23]. With its wide spectral range — with lower values in blue, intermediate values in green, yellow and orange, and higher values in red [22], the rainbow color map may seem to be an optimal choice for data representation. However, evidence is emerging showing the rainbow color map can distort the meaning of underlying data and can lead to incorrect evaluations or conclusions of the data [2, 4, 14, 22].

The three major implications stemming from the ambiguous data representation the rainbow color map can generate are: first, the rainbow color map obscures details due to isoluminance — or lack of lightness and darkness variations — and introduces artifacts due to sharp transitions between hues [2, 4]; second, it artificially divides data into a small number of categories and introduces gradients not related to the data [4]; third, as the rainbow color map has no monotonic perceptual ordering [4], analysis of the data by the viewer may be flawed [2,4].

This research explores the usage of the rainbow color map in scientific visualization and asks the following questions:

- Does the rainbow color map enable accurate data interpretation in visualization tasks?
- How do other color mapping techniques compare to and differ from rainbow color mappings when analyzing and interpreting interval and ratio data?
- How prevalent is the rainbow color map in the 2013 IEEE Visualization Conference publications?

<u>Thesis Statement:</u> The rainbow color map is rarely the best color mapping technique for effective and accurate data visualization.

To answer the thesis questions, we conducted an online survey to assess the accuracy of various univariate and redundant color maps, and to measure the level of ease and level of confidence each participant experienced when performing various visualization tasks for the given color maps. The color maps assessed in our survey included the double-ended, gray, heated-object, linearized optimal, rainbow, and saturation color maps. We collected 133 survey responses, with results confirming what research has shown to be negative side effects of the rainbow color map on data. Our survey results also validate existing color mapping guidelines for effective data representation. The aesthetic evaluation of each color map was also conducted, and through a separate study, the prevalence of the rainbow color map in IEEE Visualization Conference publications from 2013 was also quantified.

CHAPTER II

LITERATURE REVIEW

The selection of color for a visualization can significantly influence the viewer's perception and interpretation of the data. While professional designers and artists are familiar with the rules that guide the design of effective color palettes, the field of visualization has paid less attention to the use of systematic rules embracing color design as they relate to the human visual system and psychophysics [12, 15, 26, 30].

The Human Visual System and Color Perception

Color processing in the human visual system is initiated by the absorption of light by three different spectral classes of cone cells located in the retina of the eye — the short-wavelength sensitive (S), middle-wavelength sensitive (M), and long-wavelength sensitive (L) cones [6, 13, 28]. These three classes of cones are responsive to different frequencies in the light spectrum and have various overlapping spectral sensitivities (Figure 2) which result in the ability to distinguish 10 million colors [6, 13, 28].

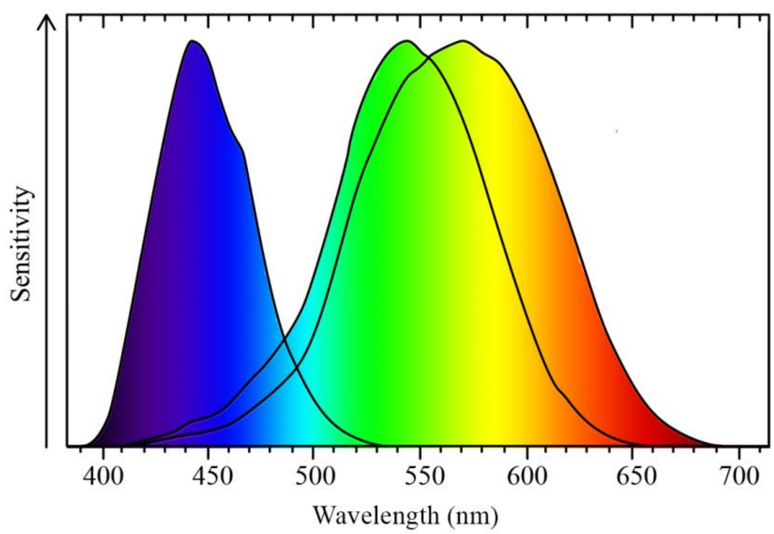


Figure 2. Spectral sensitivity of the S-cone, M-cone and L-cone. The spectral sensitivity of S-cones peak at approximately 440 nm, M-cones peak at 545 nm and L-cones peak at 565 nm [13].

All colors in human color vision can be specified in terms of hue, lightness and saturation, which correspond to the Munsell Color System's dimensions of hue, value, and chroma as shown in Figure 3 [9, 13, 22]. Hue is related to the dominant wavelength and is denoted by a combination of letters and numbers making up a 100 step scale; value corresponds to the lightness or darkness of color and is specified on a numerical scale from 1 (black) to 10 (white) in terms of luminosity (or lightness); chroma corresponds to saturation and is indicated numerically on a scale of 0 to various maxima [9, 13].

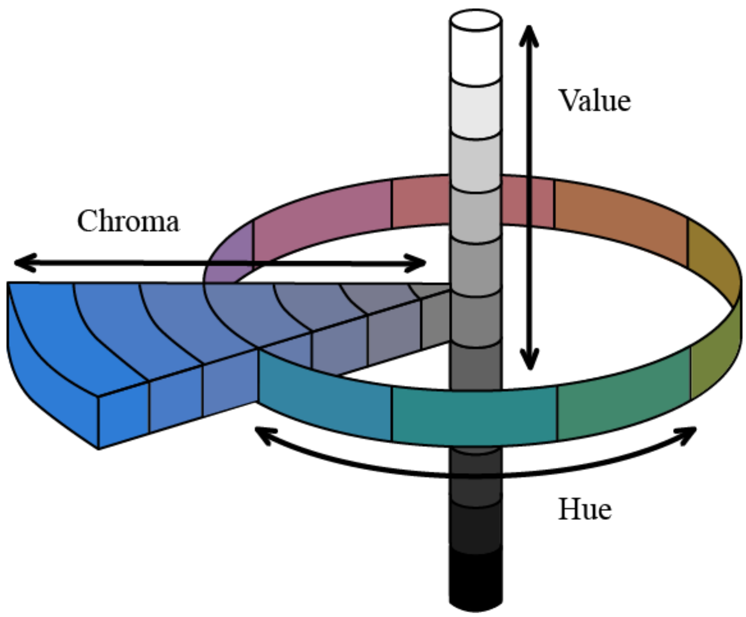


Figure 3. The Munsell Color System illustrating hue, value, and chroma [10, 13]. Adapted from "Munsell Color System" by Jacob Rus, used under CC BY-SA 3.0.

We categorize the colors of the physical spectrum into distinct groupings, but humans do not perceive these distinct color groupings or color changes in a linear manner; instead, our ability to distinguish changes in wavelength varies in a highly nonlinear manner across the spectrum as seen in Figure 4 [10, 29, 31]. Consequently, what we see is not as simple as translating retinal stimuli. Instead, vision is also the result of unconscious inferences based on visual clues and previous experiences stored in memory. With this in mind, by designing visualizations in a visual form that reflects the capabilities of the human visual system, it is possible to design visualizations that accurately reveal underlying relationships and patterns in data [15].

The Rainbow Color Map

Among the scientific community, the rainbow color map is a prevalent choice for mapping data [4]. Due to its encouragement of use by default, its wide spectral range, and aesthetically pleasing colors, the rainbow color map can be considered a good choice for data representation [4, 20]. However, it is rarely the optimal choice when displaying data [4, 14, 17, 19, 20, 22, 23]. As it varies hue to approximate the electromagnetic spectrum of visible wavelengths, the rainbow color map does not conform to the way humans perceive color [4, 17]. In addition, the colors of the rainbow can be ordered by wavelength, in alphabetical order, by a user's aesthetic preference, etc. — ordering varies from individual to individual. As a result, confusion can arise when a color map that is not perceptually ordered is used as the order of colors is ambiguous and not immediately evident [4, 23, 25]. This poses a significant concern to data representation as a good color map should allow the viewer to easily perform the reverse mapping back to the scalar values in order to interpret the data effectively [17]. The rainbow color map also obscures features and introduces artifacts that paint a flawed picture of the data [4, 15, 22, 23], as shown in Figure 5. Due to its wide spectral range, the rainbow color map portrays sharp transitions in the data that are not actually present at its color boundaries [4, 15].

The human visual system is exquisitely adept at seeing and interpreting visual patterns. For this reason, color maps play a critical role in helping to identify meaningful features in complex, scientific data [12, 20].

Color Map Evaluation Methods

Various methodologies exist for assessing the impact of color maps on data representation [2, 11, 21]. From literature [2], a quantitative user study was conducted to determine the efficiency and effectiveness of coronary data representation, specifically data representations using the rainbow and diverging color maps; participants — comprised of higher education medical backgrounds — were given a task (e.g. "identify all low shear stress regions") for each image on a computer. After viewing each image, they were asked to fill out a questionnaire based on the task performed for each image; using the seven-point Likert scale, participants responded to the following statements: "I found it easy to identify low shear stress regions" and "I am confident I found all the low stress regions" [2]. Prior to the study, participants were given an eye test to ensure the integrity of the results. In a similar study [21], color maps with gradual variations of luminance mapped to an image of a face were evaluated using visual judgments; the study aimed at evaluating the degree of luminance that causes data to be misinterpreted. The color maps evaluated included the gray, heated body, isoluminant rainbow, rainbow, decreasing saturation, and isoluminant saturation. Participants were asked to rate each image on the degree to which the image appeared to be a recognizable photograph of a face, and with each session having taken less than five minutes [21].

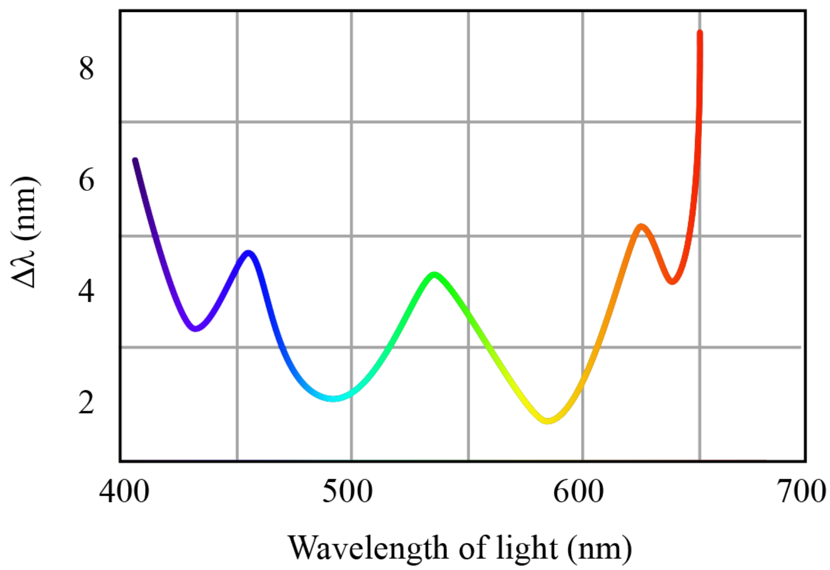


Figure 4. The nonlinear perception of wavelength change [26].

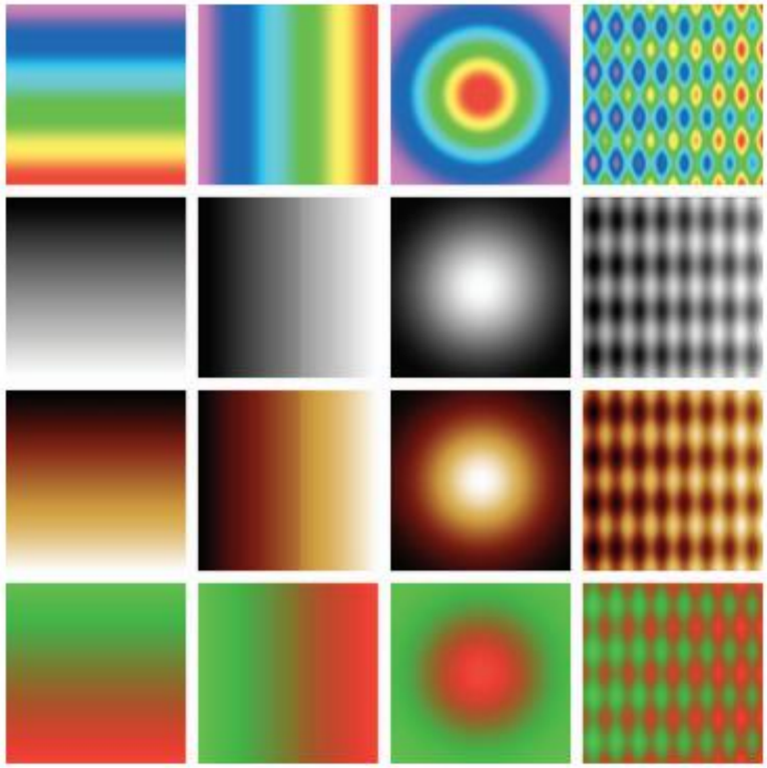


Figure 5. Comparison of color map effectiveness [4]. Reprinted with the permission of David Borland.

CHAPTER III
BACKGROUND

Use of Color in Data Visualization

Color Mapping

Color mapping is a common visualization technique that uses a gradation of colors — or color scale — to represent the scalar values of a dataset in a continuous sequence[1, 29]. Also known as pseudocoloring, color mapping is one of the key techniques used to visualize and interpret data of a phenomena [29]. Color mapping is implemented by indexing into a color lookup table and mapping scalar values into separate intensity values for the red, green, and blue color components [29]. Color maps may enhance important features of a dataset, exaggerate unimportant details, or create visual artifacts due to unforeseen interactions between data, color choice, and human physiology [29].

For this study, we consider six color maps: the double-ended, gray, heated-object, linearized optimal, rainbow, and saturation color maps. As a good visual representation creates a deeper engagement of the human observer in the presentation of data and improves the effectiveness of communication [29], we aim to assess accuracy and aesthetic evaluation of the various color maps.

Univariate Color Maps

The Double-ended Color Map Double-ended maps combine two monotonically increasing scales (such as a map from blue to gray and a map from gray to red), and thus clearly depict the low, high, and middle values of data [18, 26].

The Gray Color Map The gray color map maps the value of the scalar to brightness (luminance) [18, 25, 26, 32]. In general, it maps the lowest value to black and the highest to white; however, as viewers are more acquainted with printed data represented by an increasing amount of ink, lower values can be mapped to white and higher values to black [18, 26].

The Rainbow Color Map The rainbow color map maps scalar values to hue which vary throughout its entire range; saturation and brightness remain constant. As this color map goes from red to violet and makes both extremes visually close, the rainbow map usually does not include the color violet [18, 25, 26, 32].

The Saturation Color Map The saturation map maps the value of a scalar to colors of increasing saturation while maintaining a constant hue [18, 25, 26, 32].

Redundant Color Maps

Redundant color maps vary in both luminance and hue, and employ multiple display parameters to represent data, e.g. brightness, to convey shape, and hue to provide distinguishable display levels [18, 25, 26, 32]. The *heated-object color map* represents a compromise between the grey color map and the rainbow color map, and goes from black to white while passing through orange and yellow [18, 25, 26, 32]. The *linearized-optimal* color map maximizes the number of just noticeable differences while preserving a natural order [18, 25, 26].

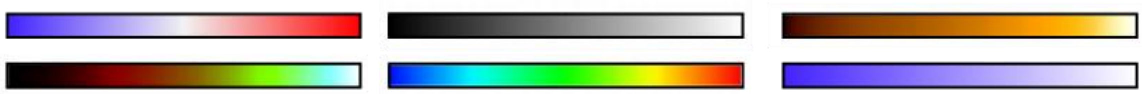


Figure 6. Color maps in study; From left to right, top to bottom: double-ended, gray, heated-object, linearized optimal, rainbow, and saturation [26].

Visualization Characteristics and Color Map Selection

Data Types and Design Guidelines

When designing a visualization and selecting a color map, care must be taken to ensure important features of the image reflect the important features of the data; bright colors, sharp boundaries, or high saturation areas will most likely catch the user’s attention, therefore it is important to consider the data that will be represented and the data type [1, 12, 25, 26].

Interval Data Interval data has numerically equal distances between values which are assumed to be actually equal, such as temperature in degrees Fahrenheit [1, 11, 25, 26]. The visual depiction of interval data should account for the equal steps in the data values and communicate an equally perceived magnitude in the representation [1, 11, 25, 26].

Ratio Data Ratio data has ratios between values which are assumed to be equal with values increasing/decreasing monotonically about a true zero or threshold [1, 11, 26]. An example of ratio data is the Kelvin temperature scale which represents absolute temperature [1, 11, 26]. The visual representation of this data type should take into account equal steps between the ratio values [1, 11, 25, 26].

Spatial Frequency

Spatial frequency refers to the level of detail in a stimulus per degree of visual angle [8, 15, 19]. An image with small details and sharp edges contains more high spatial frequency information than one composed of large coarse stimuli as shown in Figure 7 [1, 11, 19, 8]. The human visual system accurately processes data, which varies rapidly over an area, if that spatial variation is represented as a variation in luminance; luminance channels are responsible for processing high spatial frequency information [1, 3, 11, 16].

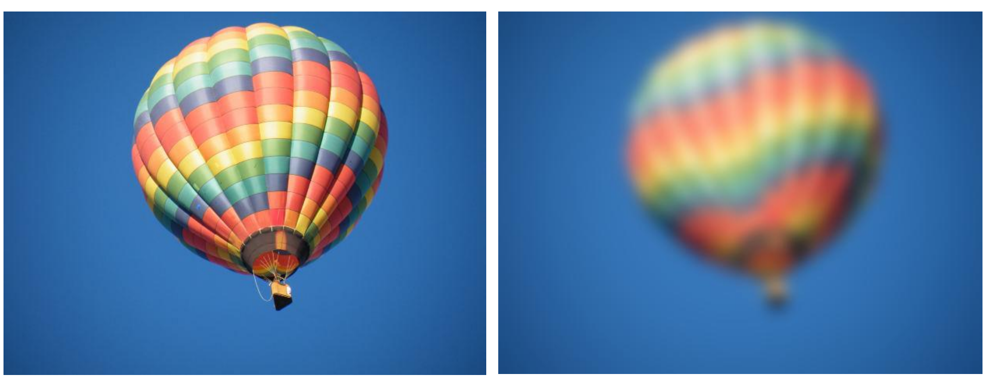


Figure 7. Spatial frequency; From left to right: high spatial frequency, low spatial frequency.[1, 26].

CHAPTER IV

METHODOLOGY

Using the studies from literature as described in Chapter 2 as reference, we designed a similar method for evaluating color maps. Through an online survey, we evaluate whether the rainbow color map is the best choice for accurately representing interval and ratio data, and compare it to the evaluations of the same data mapped with the double-ended, gray, heated-object, linearized optimal, and saturation color maps. In this particular work, we focus on topographic and temperature scalar data — interval and ratio data respectively — of varying spatial frequency. The relationship between aesthetic perception and color map selection is also explored.

The open source visualization and analysis tool VisIt was used to generate the visualizations of our data for the methodology survey. VisIt was selected among other visualization tools due to its wide range of visualization features, compatibility with scalar and vector field data on two- and three-dimensional meshes [5], and ability to recognize over 120 different scientific data formats.

Aesthetic Perception and Color Map Selection

The first question in our survey aimed at exploring whether or not a correlation exists between a color map with a high aesthetically pleasing rating and its selection for best representation of elevation data. Figure 8 demonstrates the images generated using the six colors maps. Participants were asked to assess each of the elevation images on a seven-point Likert scale, with one being "entirely not visually appealing," four being "neither visually appealing nor visually not appealing," and seven being "entirely visually appealing." Additionally, participants were asked to select the color map they believed best represented the elevation data.

Highest Peak Detection

The second question in our survey assessed the accuracy of data evaluation. For this question, the color map to be evaluated by each participant was selected at random. Participants were asked to select the highest peak in the elevation (interval) data of low to medium spatial frequency as shown in Figure 9. In addition, participants were also asked to rate the degree of ease on a seven-point Likert scale; based on the statement "I found it easy to identify the highest peak in the elevation data," with one being "entirely disagree" and seven being "entirely agree," participants rated the degree of ease in identifying the highest peak. Confidence levels were also assessed; participants were asked to rate the visualization task based on the statement "I am confident I correctly identified the highest peak" using a seven-point Likert scale, with one being "entirely disagree" and seven being "entirely agree."

Elevation Detection

For the third question in our survey, participants once again assessed the accuracy of data evaluation, and the color map to be evaluated was selected at random. Participants were asked to select all peaks above 5,775 meters in medium to high spatial frequency interval data as shown in Figure 10. Just as in the previous question, participants were asked to rate the degree of ease and confidence levels, both on a seven-point Likert scale.

Sharp Transition Evaluation

Lastly, participants were asked to evaluate the extent of color transition in temperature (ratio) data with low-medium spatial frequency as shown in Figure 11. Based on the statement, "there appear to be sharp transitions in sea surface temperature," participants were asked to respond on a seven-point Likert scale, with one being "entirely disagree" and seven being "entirely agree."

The Prevalence of the Rainbow Color Map in IEEE Visualization Conference Publications

For the second part of our methodology, we counted the number of times at least one occurrence of the rainbow color map appeared in the IEEE Visualization Conference publications. Publications were separated into categories which include VAST, InfoVis, SciVis, BioVis, LDAV, and Industry.

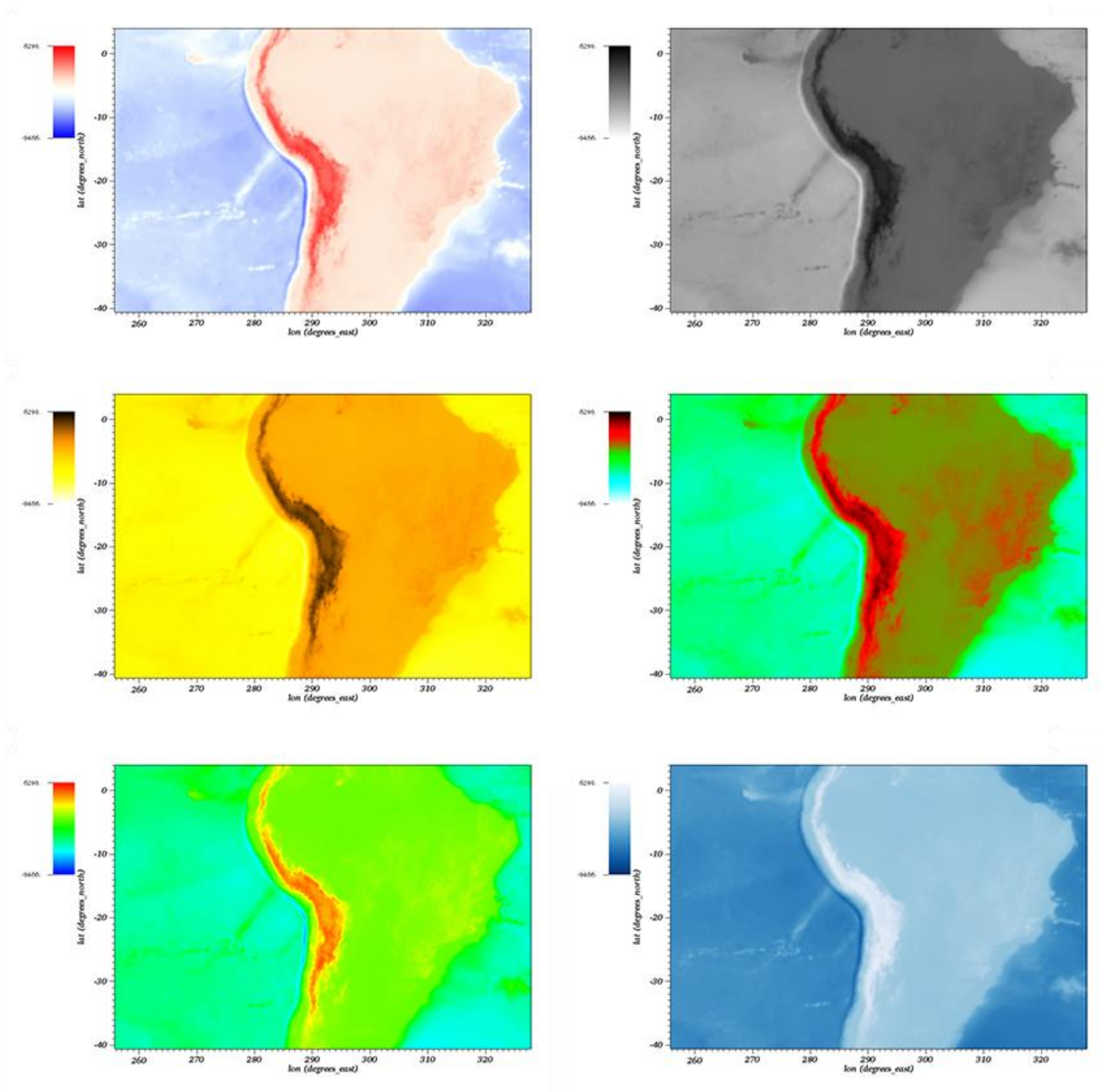


Figure 8. Question 1: Visualizations of Andes Mountains; from left to right, top to bottom: double-ended, gray, heated-object, linearized-optimal, rainbow, and saturation color maps. Survey sample can be found at http://ix.cs.uoregon.edu/~brendag/thesis_survey/survey.php.

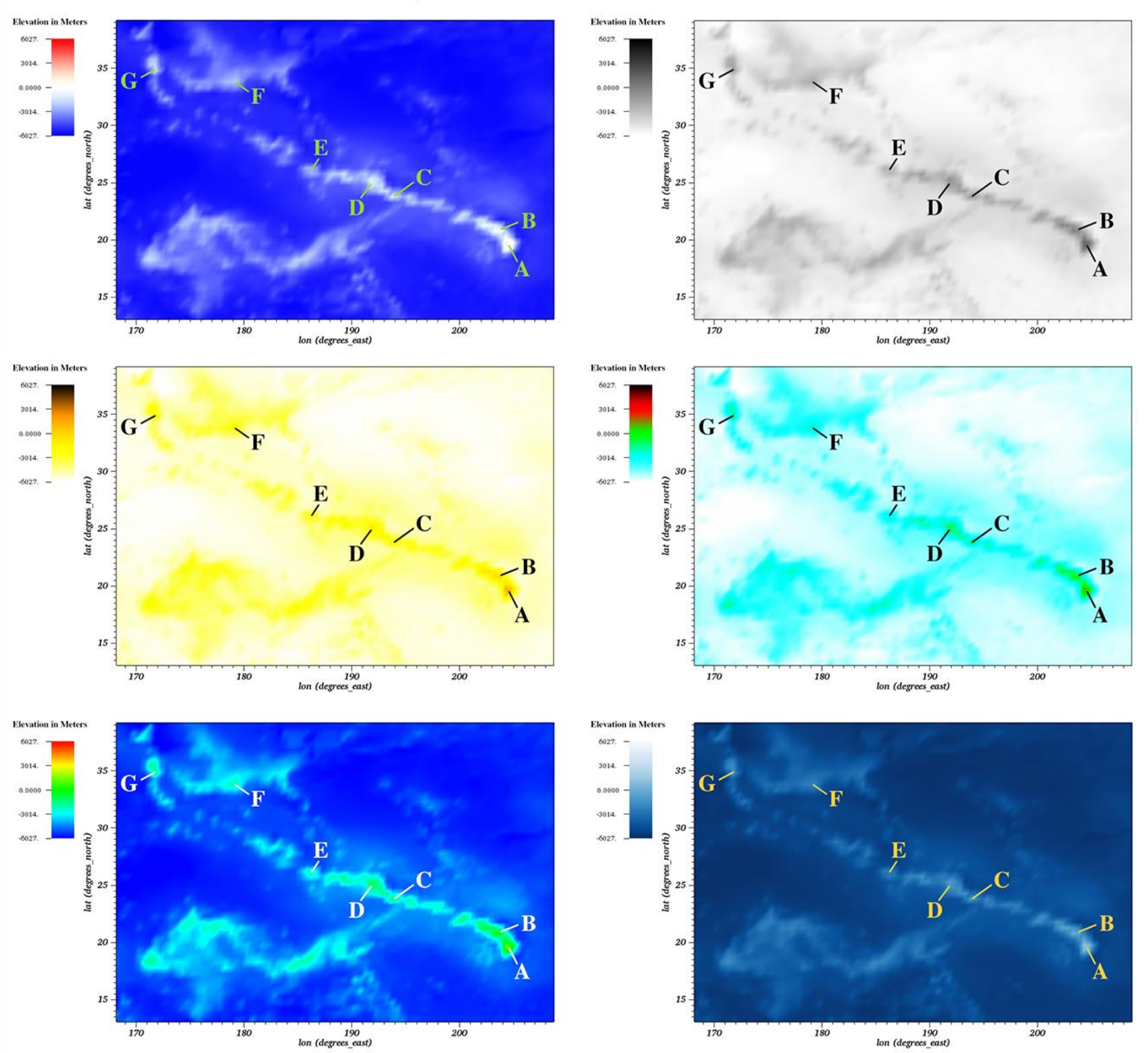


Figure 9. Question 2: Visualizations of island chain; from left to right, top to bottom: double-ended, gray, heated-object, linearized-optimal, rainbow, and saturation color maps. Survey sample can be found at http://ix.cs.uoregon.edu/~brendag/thesis_survey/survey.php.

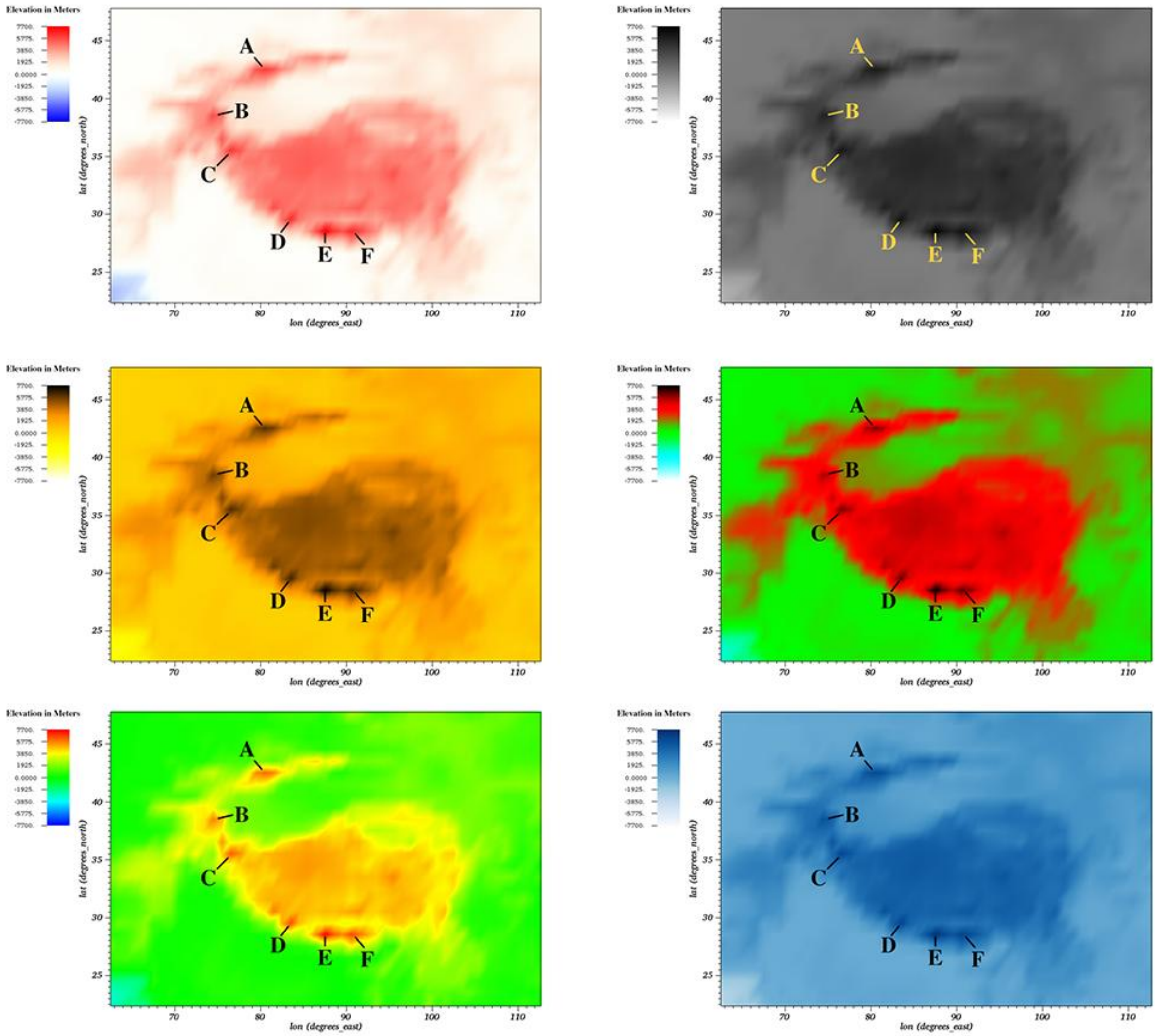


Figure 10. Question 3: Visualizations of the Himalayas; from left to right, top to bottom: double-ended, gray, heated-object, linearized-optimal, rainbow, and saturation color maps. Survey sample can be found at http://ix.cs.uoregon.edu/~brendag/thesis_survey/survey.php.

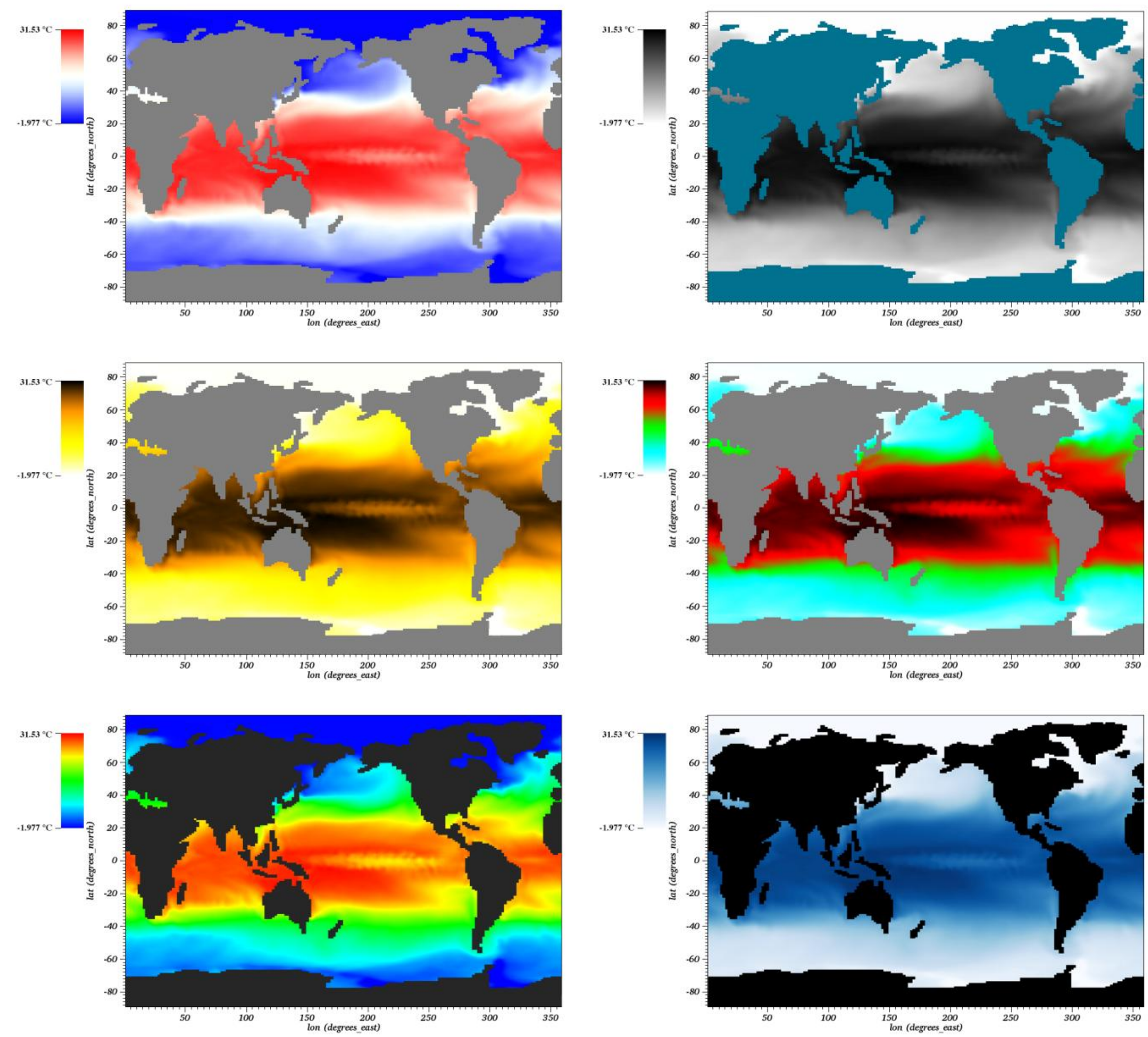


Figure 11. Question 4: Visualizations of the world sea temperature; from left to right, top to bottom: double-ended, gray, heated-object, linearized-optimal, rainbow, and saturation color maps. Survey sample can be found at http://ix.cs.uoregon.edu/~brendag/thesis_survey/survey.php.

CHAPTER V

DATA COLLECTION AND DATA CORPUS

Data Collection

For our survey, we mapped geographic interval data with both univariate and redundant color maps of varying spatial frequency. Participants consisted of individuals with some higher education or a higher education degree, including visualization and geography experts. In addition, participants who identified themselves as being colorblind were omitted from the results. Our survey was structured so it could be completed in five minutes or less, and was made available online via desktop, laptop, mobile device, and tablet computer. A total of 133 participant responses were recorded.

Data Corpus

Survey Results

Our survey explored whether a correlation exists between aesthetic perception and color map selection, as well as the accuracy of visualization tasks for the visualizations mapped with univariate and redundant color maps: double-ended, gray, heated-object, linearized-optimal, rainbow, and saturation. Data was gathered using an online database. Out of 136 participants who took part in our survey, three identified themselves as being colorblind. As a result, a total of 133 responses were examined. Additionally, all survey responses of participants with some higher education or a higher education degree make up our data corpus.

The results of our survey answer the following thesis questions:

- Does the rainbow color map enable accurate data interpretation in visualization tasks?
- How do other color mapping techniques compare to and differ from rainbow color mappings when analyzing and interpreting interval and ratio data?

For the first question in our survey, we collected 133 aesthetic ratings and best representation responses for the double-ended, gray, heated object, linearized optimal, rainbow, and saturation color maps. Survey responses for question one can be found in Figure 12 and Figure 13.

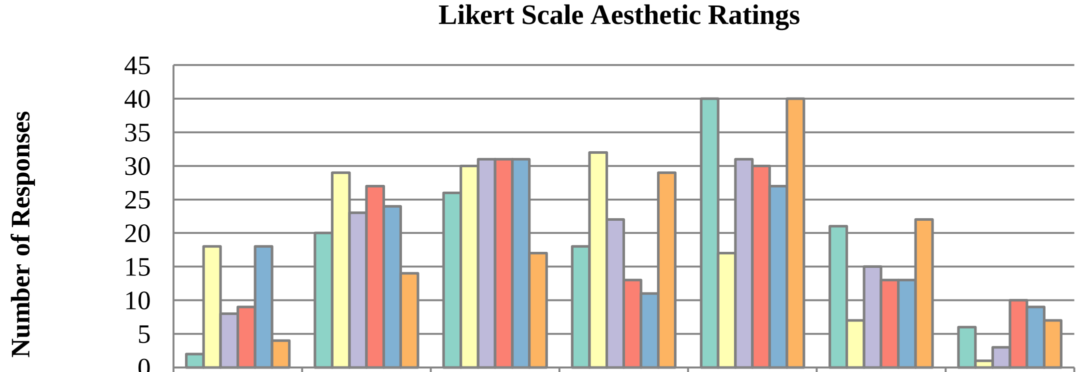
For the second question in our survey, responses varied as color maps for the elevation data were randomized. We collected twenty-six responses for the double-ended color map, fourteen for the gray color map, twenty for the heated-object color map, twenty-two for the linearized optimal color map, twenty-one for the rainbow color map, and thirty for the saturation color map. As shown in Figure 14, the highest peak in the elevation data was peak A. Results for the highest peak identification, level of ease, and level of confidence can be found in Figure 15, Figure 16, and Figure 17.

For the third question in our survey, color maps for the elevation data varied due to color map randomization. We collected twenty-one responses for the double-ended color map, twenty-one responses for the gray color map, nineteen responses for the heated-object color map, fifteen responses for the linearized optimal color map, thirty responses for the rainbow color map, and twenty-seven responses for the saturation color map. As shown in Figure 18, peaks above 5,775 meters were peak A, peak C, peak D, peak E, and peak F. Results for highest peak identification, level of ease, and level of confidence can be found in Figure 19, Figure 20, and Figure 21.

For the last question in our survey, color maps for the temperature data varied as well as color maps were randomized. We collected twenty-four responses for the double-ended color map, thirty-three for the gray color map, fifteen for the heated-object color map, twenty-nine for the linearized optimal color map, sixteen for the rainbow color map, and sixteen for the saturation color map. Likert scale results for the statement "there appear to be sharp transitions in the sea surface temperature" can be found in Figure 22.

Results for the Prevalence of the Rainbow Color Map in 2013 IEEE Scientific Publications

The second part of our methodology addressed the prevalence of the rainbow color map in IEEE scientific publications from 2013. Total occurrences of the usage of the rainbow color map can be found in Table 1.



	(1): Entirely not visually appealing	(2): Mostly not visually appealing	(3): Somewhat not visually appealing	(4): Neither visually appealing nor visually unappealing	(5): Somewhat visually appealing	(6): Mostly visually appealing	(7): Entirely visually appealing
Double-ended	2	20	26	18	40	21	6
Gray	18	29	30	32	17	7	1
Heated-object	8	23	31	22	31	15	3
Linearized Optimal	9	27	31	13	30	13	10
Rainbow	18	24	31	11	27	13	9
Saturation	4	14	17	29	40	22	7

Figure 12. Question 1: Aesthetic ratings.

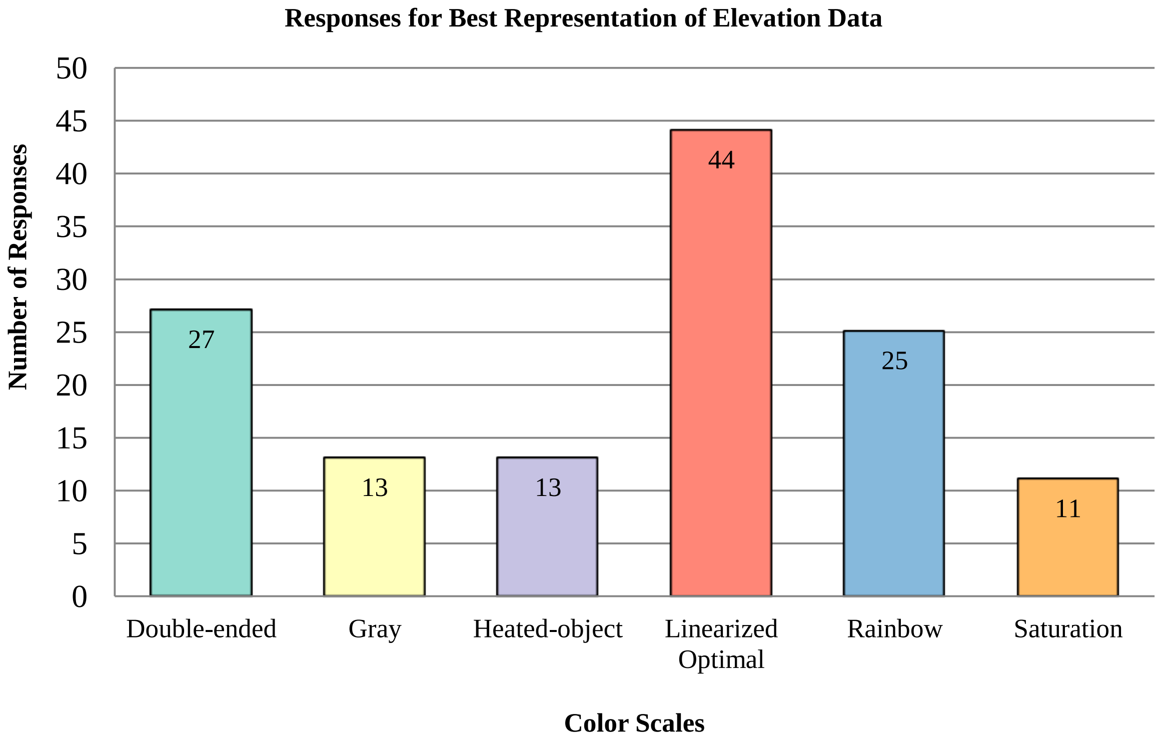


Figure 13. Question 1: Best representation results.

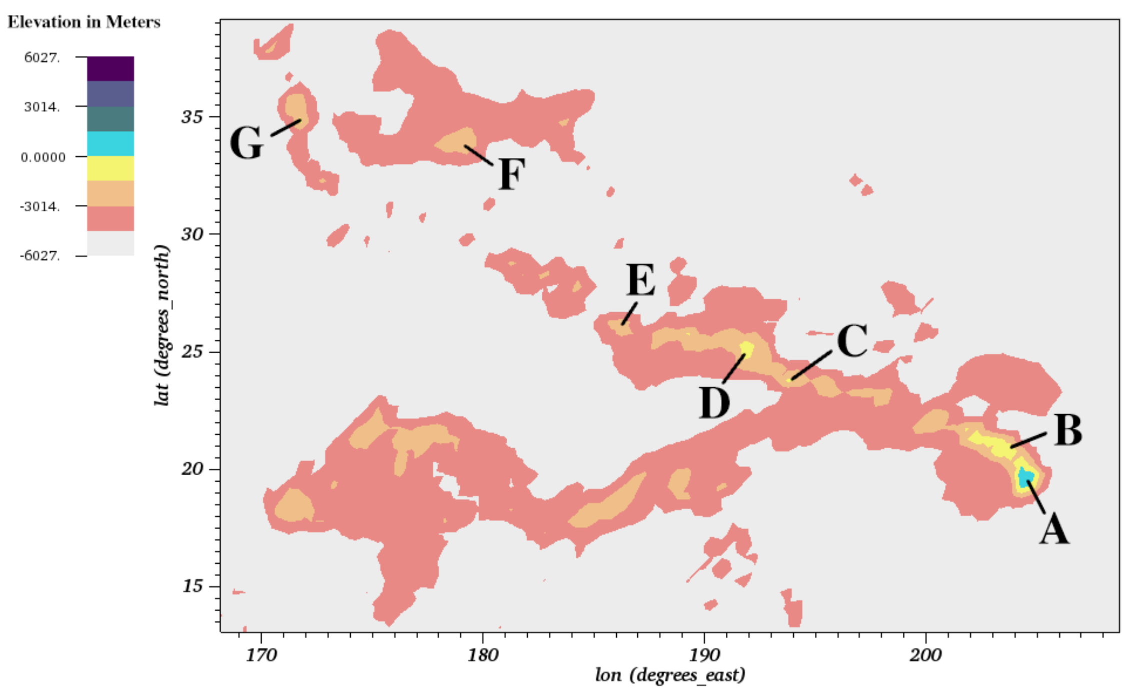
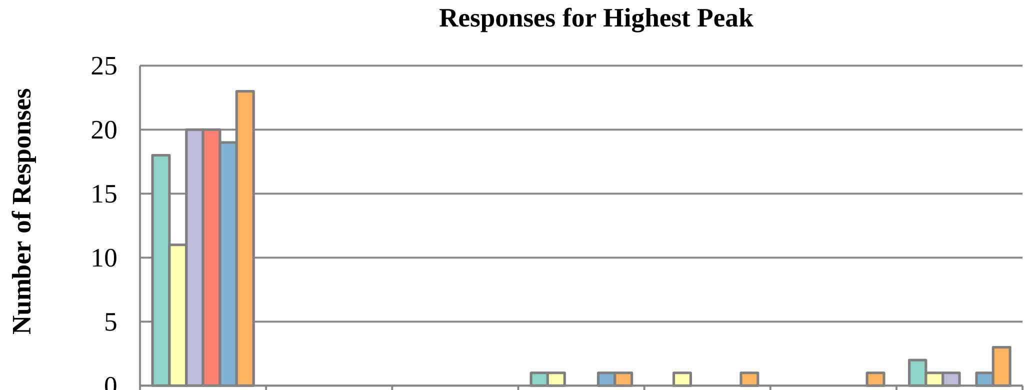
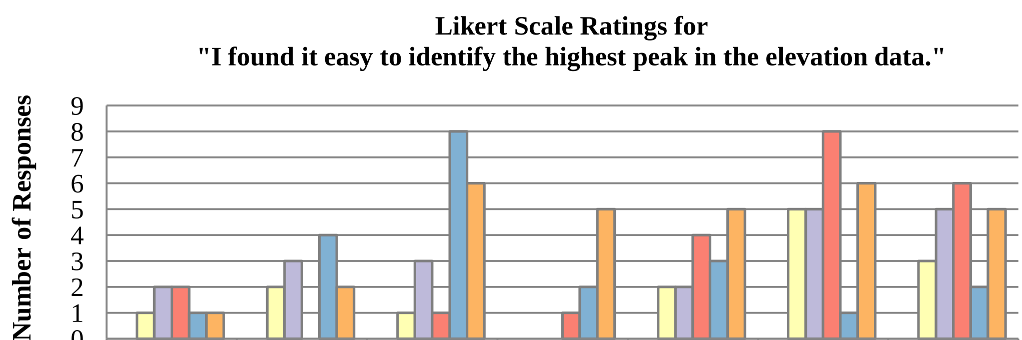


Figure 14. Question 2: Segmented color map for highest peak.



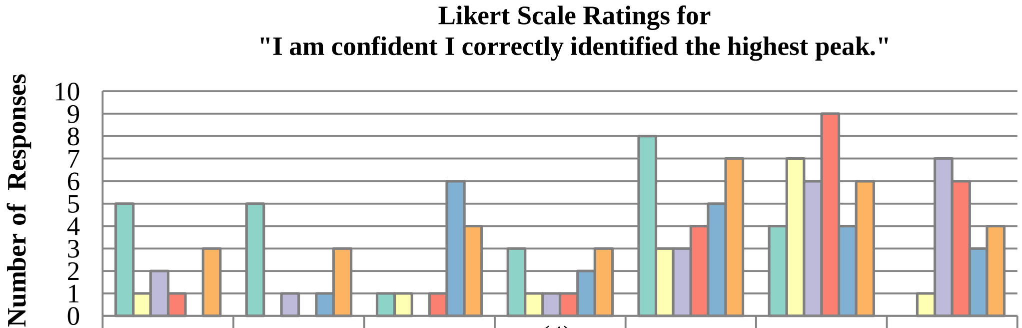
	A*	B	C	D	E	F	G
Double-ended	18	0	0	1	0	0	2
Gray	11	0	0	1	1	0	1
Heated-object	20	0	0	0	0	0	1
Linearized Optimal	20	0	0	0	0	0	0
Rainbow	19	0	0	1	0	0	1
Saturation	23	0	0	1	1	1	3

Figure 15. Question 2: Highest peak results. Asterisk designates correct answer.



	(1): Entirely Disagree	(2): Mostly Disagree	(3): Somewhat Disagree	(4): Neither Agree nor Disagree	(5): Somewhat Agree	(6): Mostly Agree	(7): Entirely Agree
Double-ended							
Gray	1	2	1	0	2	5	3
Heated-object	2	3	3	0	2	5	5
Linearized Optimal	2	0	1	1	4	8	6
Rainbow	1	4	8	2	3	1	2
Saturation	1	2	6	5	5	6	5

Figure 16. Question 2: Likert scale results based on statement "I found it easy to identify the highest peak in the elevation data."



	(1): Entirely Disagree	(2): Mostly Disagree	(3): Somewhat Disagree	(4): Neither Agree nor Disagree	(5): Somewhat Agree	(6): Mostly Agree	(7): Entirely Agree
Double-ended	5	5	1	3	8	4	0
Heated-object	1	0	1	1	3	7	1
Gray	2	1	0	1	3	6	7
Linearized-optimal	1	0	1	1	4	9	6
Rainbow	0	1	6	2	5	4	3
Saturation	3	3	4	3	7	6	4

Figure 17. Question 2: Likert scale results based on statement "I am confident I correctly identified the highest peak."

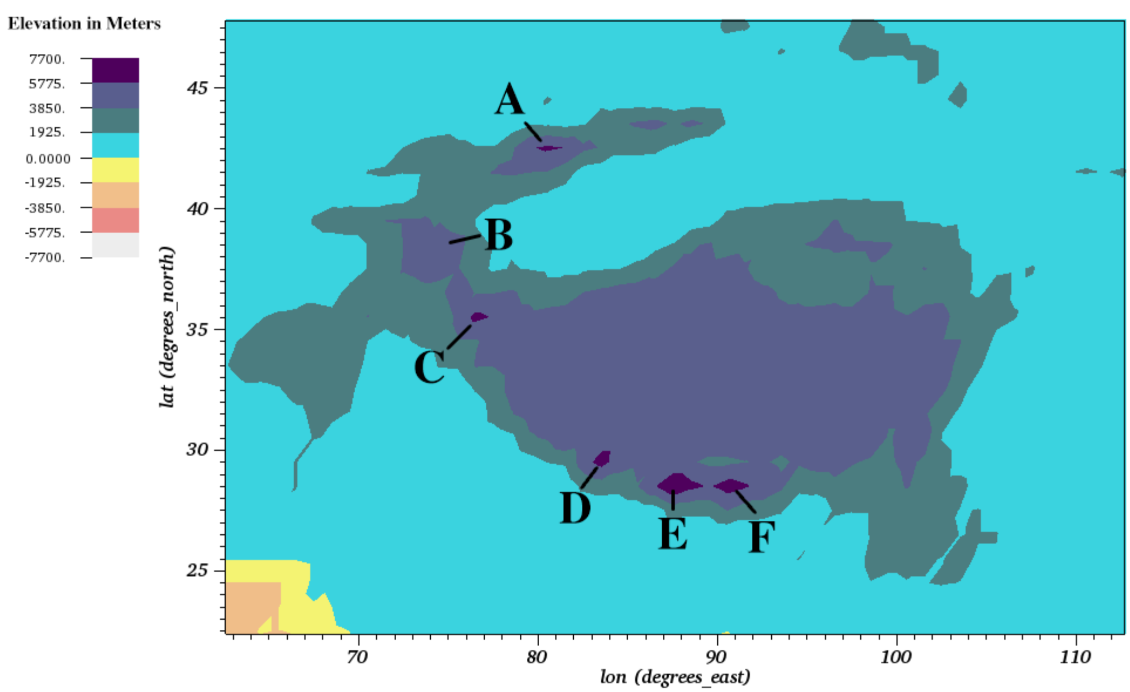
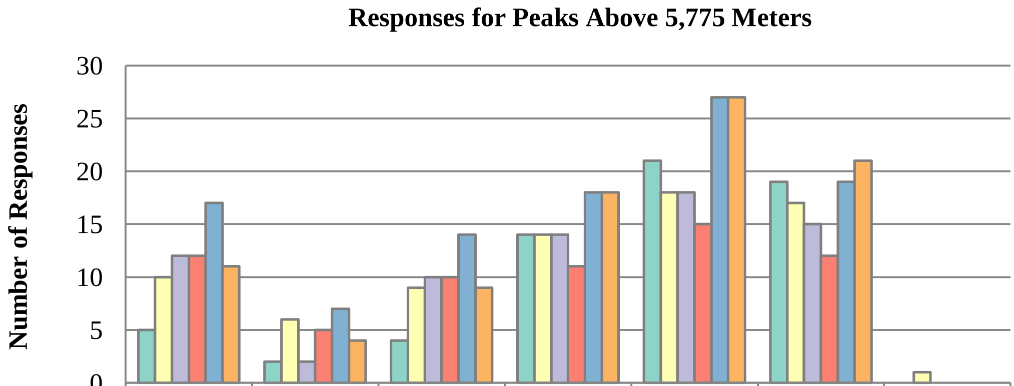
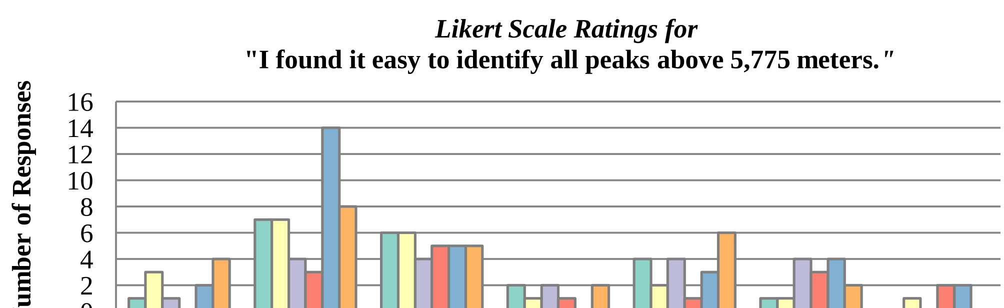


Figure 18. Question 3: Segmented color map for peaks above 5,775 meters.



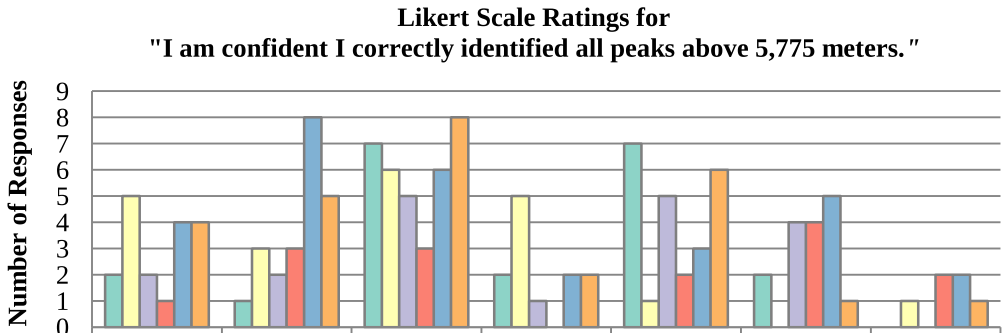
	A*	B	C*	D*	E*	F*	None
Double-ended	5	2	4	14	21	19	0
Gray	10	6	9	14	18	17	1
Heated-object	12	2	10	14	18	15	0
Linearized Optimal	12	5	10	11	15	12	0
Rainbow	17	7	14	18	27	19	0
Saturation	11	4	9	18	27	21	0

Figure 19. Question 3: Highest peak results. Asterisks designate correct answers.



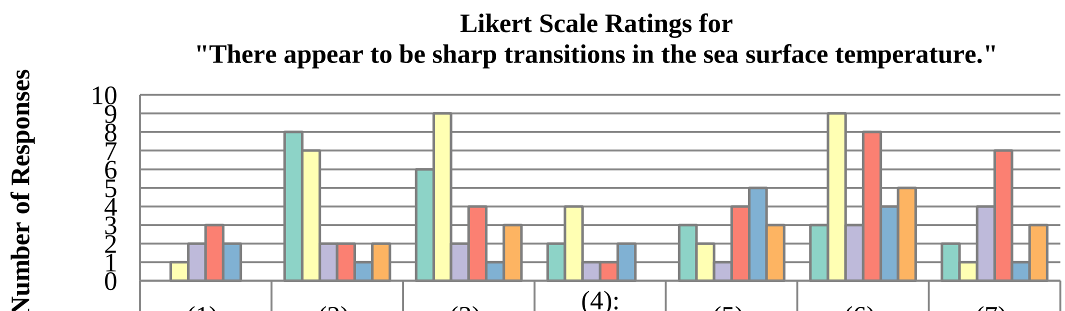
	(1): Entirely Disagree	(2): Mostly Disagree	(3): Somewhat Disagree	(4): Neither Agree nor Disagree	(5): Somewhat Agree	(6): Mostly Agree	(7): Entirely Agree
Double-ended	1	7	6	2	4	1	0
Gray	3	7	6	1	2	1	1
Heated-object	1	4	4	2	4	4	0
Linearized Optimal	0	3	5	1	1	3	2
Rainbow	2	14	5	0	3	4	2
Saturation	4	8	5	2	6	2	0

Figure 20. Question 3: Likert scale results based on statement "I found it easy to identify all peaks above 5,775 meters."



	(1): Entirely Disagree	(2): Mostly Disagree	(3): Somewhat Disagree	(4): Neither Agree nor Disagree	(5): Somewhat Agree	(6): Mostly Agree	(7): Entirely Agree
Double-ended	2	1	7	2	7	2	0
Gray	5	3	6	5	1	0	1
Heated-object	2	2	5	1	5	4	0
Linearized Optimal	1	3	3	0	2	4	2
Rainbow	4	8	6	2	3	5	2
Saturation	4	5	8	2	6	1	1

Figure 21. Question 3: Likert scale results based on statement "I am confident I correctly identified all peaks above 5,775 meters."



	(1): Entirely Disagree	(2): Mostly Disagree	(3): Somewhat Disagree	(4): Neither Agree nor Disagree	(5): Somewhat Agree	(6): Mostly Agree	(7): Entirely Agree
Double-ended	0	8	6	2	3	3	2
Gray	1	7	9	4	2	9	1
Heated-object	2	2	2	1	1	3	4
Linearized Optimal	3	2	4	1	4	8	7
Rainbow	2	1	1	2	5	4	1
Saturation	0	2	3	0	3	5	3

Figure 22. Question 4: Likert scale results based on statement "there appear to be sharp transitions in the sea surface temperature."

Paper Type	Number of Publications with at Least One Occurrence of the Rainbow Color Map	Total Publications
VAST	8	32
InfoVis	8	38
SciVis	13	31
BioVis	6	14
LDAV	6	13
Industry	2	11

Table 1. The prevalence of the rainbow color map in 2013 IEEE Visualization Conference publications.

CHAPTER VI

ANALYSIS

Aesthetics and Best Representation Selection

We found a high correlation between the rainbow color map's aesthetic rating and its selection as the best color map to represent the elevation data. Seventeen out of the twenty-five participants who evaluated the rainbow color map reported a positive aesthetic rating and its selection as the best representation of the data. Overall, color maps with the highest, positive aesthetic ratings include the saturation and double-ended color maps. The linearized optimal color map received the highest rating as the best representation of the elevation data. Conversely, the gray color map received the highest, negative aesthetic ratings, and the saturation color map received the lowest scores for best representation of the elevation data.

Highest Peak Identification

The rainbow color map rated the lowest in terms of accuracy of data interpretation for the second question in our survey. In terms of level of ease and level of confidence, approximately 28% of participants who assessed the rainbow color map rated the task of highest peak identification as somewhat, mostly, or entirely easy with a 58% level of confidence in successfully identifying the highest peak. The gray color map scored the lowest in accuracy, which validates the design guideline of luminance alone being a poor choice for making absolute value judgments [3,11,16]. Overall, visualizations mapped with the double-ended and heated-object color maps received the highest accuracy ratings; however, the double-ended color map received the lowest ratings in terms of level of ease and level of confidence. Percentage-wise, the highest peak identification task mapped with the linearized optimal color map was perceived as the easiest, and with participants reporting the highest level of confidence for this color map. As the linearized optimal color map varies both hue and luminance, our results validate the notion of redundant color scales providing a better distinction between values as they reinforce visual differences [25, 26]; the linearized optimal color map scored third-highest in accuracy. Accuracy, level of ease, and level of confidence analysis can be found in Tables 2-4.

Elevation Identification

Overall and percentage-wise, the rainbow color map ranked fourth-lowest in accuracy, with the third-largest percentage of participants reporting the task of elevation identification as somewhat, mostly, or entirely difficult; the rainbow color map also ranked as third-lowest in confidence levels for the visualization task. The linearized optimal color map rated highest in terms of accuracy, while the gray color map received the lowest accuracy ratings. In terms of level of ease, the majority of participants reported the visualization task as somewhat, mostly, or entirely difficult for all color maps. The gray color map received the highest percentage of low confidence levels for the visualization task. There exist no significant results for high levels of confidence for the visualization task. Accuracy, level of ease, and level of confidence analysis can be found in Table 5, Table 6, and Table 7 respectively.

Sharp Transition Evaluation

Approximately 62% of participants who assessed the rainbow color map of the sea surface temperature data agreed sharp transitions were present in the visualization. Significant results also include findings for the double-ended, linearized optimal, and saturation color scales, in which approximately 58% of participants somewhat, mostly, or entirely disagreed, approximately 66% of participants somewhat, mostly, or entirely agreed, and 69% of participants somewhat, mostly, or entirely agreed sharp transitions were present in the visualization respectively. Other findings were not of significance — with 15% or less margin of deviation.

The Prevalence of the Rainbow Color Map in 2013 IEEE Scientific Publications

The most significant prevalence findings of the rainbow color map were found in the BioVis, SciVis, and LDAV (Large-scale Data Analysis and Visualization) scientific publications. We found approximately 42%, 43%, and 46% of the BioVis, SciVIs, and LDAV publications respectively had at least one occurrence of the rainbow color map. Our findings are consistent with findings from literature; 40-50% of scientific publications from the 2001-2005 IEEE Visualization Conference proceedings implemented the rainbow color map for data representation [4].

Color Map	Correct	Incorrect	Total	Accuracy
Double-ended	21	1	22	95.45%
Gray	17	4	21	80.95%
Heated-object	19	1	20	95.00%
Linearized Optimal	12	2	14	85.71%
Rainbow	24	6	30	80.00%
Saturation	23	3	26	88.46%

Table 2. Question 2: Accuracy results for highest peak.

	Double-ended		**Gray**		**Heated-object**	
	Responses	Total	Responses	Total	Responses	Total
(1): Entirely Disagree	4	57.69%	1	28.57%	2	40.00%
(2): Mostly Disagree	7		2		3	
(3): Somewhat Disagree	4		1		3	
(4): Neither Agree nor Disagree	2	7.69%	0	0.00%	0	0.00%
(5): Somewhat Agree	5	34.62%	2	71.43%	2	60.00%
(6): Mostly Agree	4		5		5	
(7): Entirely Agree	0		3		5	
Total	26		14		20	

	Linearized Optimal		**Rainbow**		**Saturation**	
	Responses	Total	Responses	Total	Responses	Total
(1): Entirely Disagree	2	13.64%	1	61.90%	1	30.00%
(2): Mostly Disagree	0		4		2	
(3): Somewhat Disagree	1		8		6	
(4): Neither Agree nor Disagree	1	4.55%	2	9.52%	5	16.67%
(5): Somewhat Agree	4	81.82%	3	28.57%	5	53.33%
(6): Mostly Agree	8		1		6	
(7): Entirely Agree	6		2		5	
Total	22		21		30	

Table 3. Question 2: Overall Likert scale results for statement "I found it easy to identify the highest peak."

	Double-ended		Gray		Heated-object	
	Responses	Total	Responses	Total	Responses	Total
(1): Entirely Disagree	5	42.31%	1	14.29%	2	15.00%
(2): Mostly Disagree	5		0		1	
(3): Somewhat Disagree	1		1		0	
(4): Neither Agree nor Disagree	3	11.54%	1	7.14%	1	5.00%
(5): Somewhat Agree	8	46.15%	3	78.57%	3	80.00%
(6): Mostly Agree	4		7		6	
(7): Entirely Agree	0		1		7	
Total	26		14		20	

	Linearized Optimal		**Rainbow**		**Saturation**	
	Responses	Total	Responses	Total	Responses	Total
(1): Entirely Disagree	1	9.09%	0	33.33%	3	33.33%
(2): Mostly Disagree	0		1		3	
(3): Somewhat Disagree	1		6		4	
(4): Neither Agree nor Disagree	1	4.55%	2	9.52%	3	10.00%
(5): Somewhat Agree	4	86.36%	5	57.14%	7	56.67%
(6): Mostly Agree	9		4		6	
(7): Entirely Agree	6		3		4	
Total	22		21		30	

Table 4. Question 2: Overall Likert scale results for statement "I am confident I correctly identified the highest peak."

	Double-ended		Gray		Heated-object	
Area	Number of Responses	Correctness	Number of Responses	Correctness	Number of Responses	Correctness
A*	5	23.81%	10	47.62%	12	63.16%
B	2	9.52%	6	28.57%	2	10.53%
C*	4	19.05%	9	42.86%	10	52.63%
D*	14	66.67%	14	66.67%	14	73.68%
E*	21	100.00%	18	85.71%	18	94.74%
F*	19	90.48%	17	80.95%	15	78.95%
None	0	100.00%	1	0.00%	0	100.00%
AVG	51.59%		50.34%		67.67%	
Total Responses	21		21		19	

	Linearized Optimal		Rainbow		Saturation	
Area	Number of Responses	Correctness	Number of Responses	Correctness	Number of Responses	Correctness
A*	12	80.00%	17	56.67%	11	40.74%
B	5	33.33%	7	23.33%	4	14.81%
C*	10	66.67%	14	46.67%	9	33.33%
D*	11	73.33%	18	60.00%	18	66.67%
E*	15	100.00%	27	90.00%	27	100.00%
F*	12	80.00%	19	63.33%	21	77.78%
None	0	100.00%	0	100.00%	0	100.00%
AVG	76.19%		62.86%		61.90%	
Total Responses	15		30		27	

Table 5. Question 3: Accuracy results for highest peak. Asterisks designate correct answers.

	Double-ended		Gray		Heated-object	
	Responses	Total	Responses	Total	Responses	Total
(1): Entirely Disagree	1	66.67%	3	76.10%	1	47.37%
(2): Mostly Disagree	7		7		4	
(3): Somewhat Disagree	6		6		4	
(4): Neither Agree nor Disagree	2	9.52%	1	4.76%	2	10.53%
(5): Somewhat Agree	4	23.81%	2	19.05%	4	42.11%
(6): Mostly Agree	1		1		4	
(7): Entirely Agree	0		1		0	
Total	21		21		19	

	Linearized Optimal		Rainbow		Saturation	
	Responses	Total	Responses	Total	Responses	Total
(1): Entirely Disagree	0	53.33%	2	70.00%	4	62.96%
(2): Mostly Disagree	3		14		8	
(3): Somewhat Disagree	5		5		5	
(4): Neither Agree nor Disagree	1	6.67%	0	0.00%	2	7.41%
(5): Somewhat Agree	1	40.00%	3	30.00%	6	29.63%
(6): Mostly Agree	3		4		2	
(7): Entirely Agree	2		2		0	
Total	15		30		27	

Table 6. Question 3: Overall Likert scale results for statement "I found it easy to identify all peaks above 5,775 meters."

	Double-ended		Gray		Heated-object	
	Responses	Total	Responses	Total	Responses	Total
(1): Entirely Disagree	2	47.62%	5	66.67%	2	47.37%
(2): Mostly Disagree	1		3		2	
(3): Somewhat Disagree	7		6		5	
(4): Neither Agree nor Disagree	2	9.52%	5	23.81%	1	5.26%
(5): Somewhat Agree	7	42.86%	1	9.52%	5	47.37%
(6): Mostly Agree	2		0		4	
(7): Entirely Agree	0		1		0	
Total	21		21		19	

	Linearized Optimal		Rainbow		Saturation	
	Responses	Total	Responses	Total	Responses	Total
(1): Entirely Disagree	1	46.67%	4	60.00%	4	62.96%
(2): Mostly Disagree	3		8		5	
(3): Somewhat Disagree	3		6		8	
(4): Neither Agree nor Disagree	0	0.00%	2	6.67%	2	7.41%
(5): Somewhat Agree	2	53.33%	3	33.33%	6	29.63%
(6): Mostly Agree	4		5		1	
(7): Entirely Agree	2		2		1	
Total	15		30		27	

Table 7. Question 3: Overall Likert scale results for statement "I am confident I correctly identified all peaks above 5,775 meters."

CHAPTER VII

LIMITATIONS AND FUTURE WORK

Participation

As survey participation was of concern, we chose to make our survey available to the general population in a convenient manner to ensure participation in our survey. As a result, there was a diverse makeup of device types as shown in Figure 23. The color in our visualizations may have varied from participant to participant due to color output as this varies from device to device. In future work, we would like to capture results on a the same, calibrated machine to collect all participants responses.

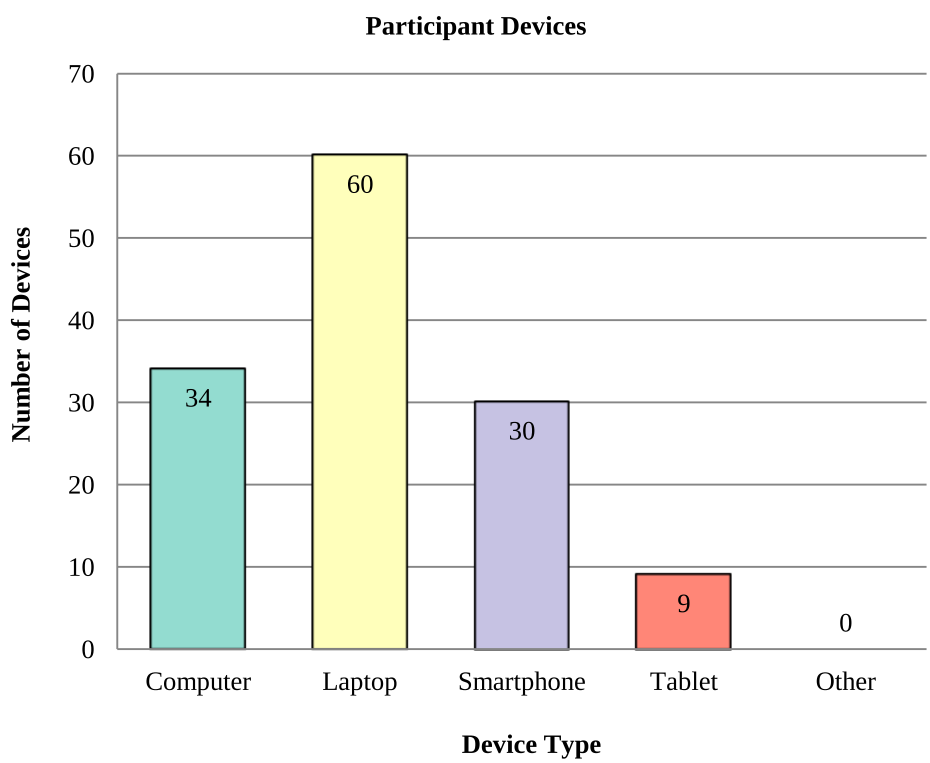


Figure 23. Devices used to complete the visualization survey.

Effectiveness Evaluation

While our survey aimed to measure the effectiveness of visualization tasks using visualizations mapped with various color maps, we depend on user responses to weigh the ease of the task and confidence level of accurate feature identification. Alternative approaches such as recording the time a participant took to respond each visualization task question could have ensured a more accurate evaluation of the effectiveness of the various color maps. This is something we would like to implement in future work.

CHAPTER VIII

CONCLUSION

The rainbow color map continues to be a popular choice among the scientific community. Through our visualization survey and prevalence study, we show the rainbow color map is rarely the best choice for interval and ratio data representation, and note its continued use in IEEE Visualization Conference proceedings. In addition, we validate various color mapping guidelines from literature. However, a limitation in this analysis is a small sample size. Only a total of 133 responses were analyzed; a larger sample size would have yielded more conclusive results. Nevertheless, as color is a key element in visualization, it is important to keep in mind color map selection as it can significantly influence the viewer's perception and interpretation of the data.

REFERENCES CITED

[1] Bergman, L. D., Rogowitz, B. E., & Treinish, L. A. (1995, October). A rule-based tool for assisting color map selection. In Proceedings of the 6th conference on Visualization'95 (p. 118). IEEE Computer Society.

[2] Borkin, M., Gajos, K., Peters, A., Mitsouras, D., Melchionna, S., Rybicki, F., ... & Pfister, H. (2011). Evaluation of artery visualizations for heart disease diagnosis. Visualization and Computer Graphics, IEEE Transactions on,17(12), 2479-2488.

[3] Borland, D., & Huber, A. (2011). Collaboration-Specific Color-Map Design. Computer Graphics and Applications, IEEE, 31(4), 7-11.

[4] Borland, D., & Taylor, I. I. I. R. M. (March 01, 2007). Rainbow Color Map (Still) Considered Harmful. IEEE Computer Graphics & Applications, 27, 2.)

[5] Childs, H., Brugger, E., Whitlock, B., Meredith, J. S., Ahern, S., Bonnell, K., ... & Vivodtzev, F. (2011). *VisIt: An End-User Tool for Visualizing and Analyzing Very Large Data*. Oak Ridge National Laboratory (ORNL).

[6] Froner, B., Purves, S. J., Lowell, J., & Henderson, J. (2013). Perception of visual information: the role of colour in seismic interpretation. first break, 31(4).

[7] Harrower, M., & Brewer, C. A. (2003). Colorbrewer. org: An online tool for selecting colour schemes for maps. The Cartographic Journal, 40(1), 27-37.

[8] Hauser, L. (n.d.). Spatial Frequency. *Home*. Retrieved June 4, 2014, from http://ucalgary.ca/pip369/mod4/spatial/frequency1

[9] Healey, C. G. (1996, October). Choosing effective colours for data visualization. In Visualization'96. Proceedings. (pp. 263-270). IEEE.

[10] Hibbard, B., Johnson, C., Chen, C., Eick, S., & Moderator-Rhyne, T. M. (2004, October). Panel 1: Can we determine the top unresolved problems of visualization?. In Proceedings of the conference on Visualization'04 (pp. 563-566). IEEE Computer Society.

[11] Kalvin, A. D., Rogowitz, B. E., Pelah, A., & Cohen, A. (2000, June). Building perceptual color maps for visualizing interval data. In Electronic Imaging (pp. 323-335). International Society for Optics and Photonics.

[12] Kelleher, C., & Wagener, T. (2011). Ten guidelines for effective data visualization in scientific publications. Environmental Modeling & Software, 26(6), 822-827.

[13] Kolb, H., Fernandez, E., & Nelson, R. (1995). *Webvision*. Retrieved April 4, 2014 from http://www.ncbi.nlm.nih.gov/books/NBK11538/

[14] Light, A., & Bartlein, P. J. (January 01, 2004). The end of the rainbow? Color schemes for improved data graphics. Eos, Transactions American Geophysical Union, 85, 40, 385.

[15] Marchak, F. M., Cleveland, W. S., Rogowitz, B. E., & Wickens, C. D. (1993, October). The psychology of visualization. In Proceedings of the 4th conference on Visualization'93 (pp. 351-354). IEEE Computer Society.

[16] McNames, J. (2006). An effective color scale for simultaneous color and gray-scale publications. Signal Processing Magazine, IEEE, 23(1), 82-96.

[17] Moreland, K. (2009). Diverging color maps for scientific visualization. InAdvances in Visual Computing (pp. 92-103). Springer Berlin Heidelberg.

[18] Rheingans, P. L. (2000, May). Task-based color scale design. In 28th AIPR Workshop: 3D Visualization for Data Exploration and Decision Making (pp. 35-43). International Society for Optics and Photonics.

[19] Rogowitz, B. E. (2013, March). Perceptual approaches to finding features in data. In IS&T/SPIE Electronic Imaging (pp. 86510B-86510B). International Society for Optics and Photonics.

[20] Rogowitz, B. E., & Goodman, A. (2012, February). Integrating human-and computer-based approaches to feature extraction and analysis. In IS&T/SPIE Electronic Imaging (pp. 82910W-82910W). International Society for Optics and Photonics.

[21] Rogowitz, B. E., & Kalvin, A. D. (2001, October). The "Which Blair Project": a quick visual method for evaluating perceptual color maps. In *Visualization, 2001. VIS'01. Proceedings* (pp. 183-556). IEEE.

[22] Rogowitz, B. E., & Treinish, L. A. (1998). Data visualization: the end of the rainbow. Spectrum, IEEE, 35(12), 52-59.

[23] Rogowitz, B. E., & Treinish, L. A. (January 01, 1996). Practical Visualization: How Not to Lie with Visualization. Computers in Physics, 10, 3, 268.

[24] Schroeder, W., Martin, K., & Kitware, I. (2006). Fundamental Algorithms. The visualization toolkit: an object-oriented approach to 3D graphics (4th ed.,). Clifton Park, N.Y.: Kitware.

[25] Silva, S., Madeira, J., & Santos, B. S. (2007, July). There is more to color scales than meets the eye: a review on the use of color in visualization. InInformation Visualization, 2007. IV'07. 11th International Conference (pp. 943-950). IEEE.

[26] Silva, S., Sousa Santos, B., & Madeira, J. (2011). Using color in visualization: A survey. Computers & Graphics, 35(2), 320-333.

[27] Stone, M. (2009). Challenge for the Humanities. Working together or apart: Promoting the next generation of digital scholarship, 43.

[28] Stone, M. C. (2005). Representing colors as three numbers [color graphics].Computer Graphics and Applications, IEEE, 25(4), 78-85.

[29] Tory, M., & Moller, T. (2004). Human factors in visualization research. Visualization and Computer Graphics, IEEE Transactions on, 10(1), 72-84.

[30] Wang, L., Giesen, J., McDonnell, K. T., Zolliker, P., & Mueller, K. (2008). Color design for illustrative visualization. Visualization and Computer Graphics, IEEE Transactions on, 14(6), 1739-1754.

[31] Welland, M., Donnelly, N., & Menneer, T. (2006). Are we properly using our brains in seismic interpretation?. The Leading Edge, 25(2), 142-144.

[32] Wijffelaars, M., & Wijk, J. (2008). Synthesis of Color Palettes (Doctoral dissertation, Master’s thesis. Supervisors Wijk, J. van, and Vliegen).