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A COMPARISON OF USER PERFORMANCE ON
SPECTRAL COLOR AND GRAYSCALE CONTINUOUS-
TONE MAPS

presented by

MICHAEL D. HYSLOP

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of the requirements for the

Master of Arts degree in Geography

Major Professor's Signature

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Date

A COMPARISON OF USER PERFORMANCE ON SPECTRAL COLOR AND GRAYSCALE CONTINUOUS-TONE MAPS

By

Michael D. Hyslop

A THESIS

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in partial fulfillment of the requirements
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ABSTRACT

A COMPARISON OF USER PERFORMANCE ON
SPECTRAL COLOR AND GRAYSCALE
CONTINUOUS-TONE MAPS

By

Michael D. Hyslop

Continuous surfaces such as elevation, precipitation, and temperature are often mapped using isarithms. These representations may be difficult for map readers to understand. Continuous-tone maps are an alternate way of depicting continuous surfaces. Three real surfaces were used to generate continuous-tone maps using spectral color and grayscale color schemes. To assess the effectiveness of these maps, fifty nine subjects were tested. Questions were designed to evaluate how the color scheme affected perception of the surface, and to compare performance on specific map reading tasks. Subjects were shown a grayscale and a spectral color representation of each of the three surfaces. Questions involved the location of surface extremes, elevation estimation, profile identification, landscape position, and interpretation of surface form. Subjects performed significantly better on the spectral color maps than on the grayscale maps.

To my family, for their support and encouragement

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An Introduction to Quantitative Surface Maps

Most maps are two-dimensional representations showing objects relative to a set of x and y coordinates. A typical example would be a standard highway map showing the locations of roads, railroads, cities, lakes, etc. Other examples include maps illustrating land use, forest cover type, soil series, or election results by state or county. Standard symbols may be used to show these features, and they tend to be conceptually straightforward.

In the last 50 years, there has been growth in the production of quantitative maps. Quantitative maps are more complex than simple reference maps or maps showing what is where rather than how much of something is there. Quantitative maps show the location of features measured on ordinal, interval, or ratio scales. Ordinal data provides the map user with information about rank or hierarchy, for example, populated places classified as a city, town or village. Interval and ratio data are continuous and provide more detailed and precise information. They employ a scale of measurement, often revealed in the map legend. Interval data have no natural zero and ratios are meaningless; temperature in degrees Fahrenheit is interval data (2 degrees is not twice as warm as 1 degree). Ratio data have a natural zero point and ratios make sense; rainfall in number of inches per year is ratio data (twenty inches per year is twice as much as ten inches per year). Ordinal, interval, and ratio data as a group are referred to as **quantitative data**, and may be contrasted with **qualitative**, or nominal data (Slocum, 1999). Qualitative data show categories that have no quantitative relationship to one another, such as the cities, roads, and lakes on the road map. Quantitative maps, and the surfaces they represent, require innovation and map reading skills beyond the mere visual recognition of standard symbols. The number of methods developed for mapping quantitative surfaces (discussed below) support this idea.

A common feature shown on a quantitative map is elevation of the earth's surface above or below a datum. Elevation is not the only phenomenon that may be thought of as a "volume" to be mapped, however. *Any* feature that changes quantitatively as it varies across space may be represented by a statistical surface (Jenks, 1963). Depending on how data are enumerated, or on the type of feature being mapped, there may be discontinuities in the data. These gaps may be caused by abrupt changes at the boundaries of the mapping units, or by voids where the mapped feature does not exist. Surfaces such as these are known as *stepped* statistical surfaces (Figure 1, top maps). An example of a stepped surface is population mapped at the county level. *Smooth* statistical surfaces consist of data that vary continuously, not discretely, over geographic space (Figure 1, lower maps). Some examples of smooth statistical surfaces include elevation above sea level, air pressure, ocean temperature, and precipitation. To map statistical surfaces, it is necessary to show both position *and* change in magnitude.

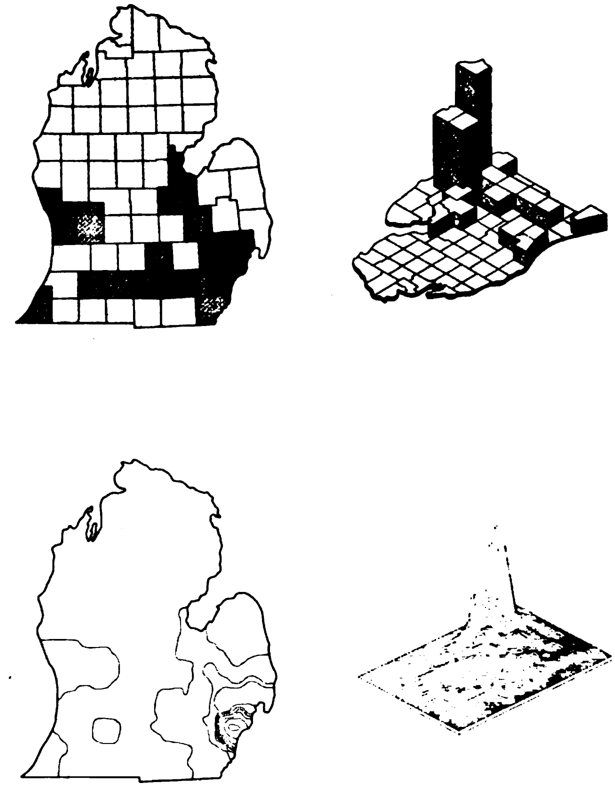


Figure 1. Stepped and smooth statistical surfaces, from Groop and Smith, 1982. Reprinted with permission from *The American Cartographer* 9, October 1982, 123-131.

Cartographers have developed a number of ways to map smooth statistical surfaces. Perhaps the oldest and most often used method of portrayal is the isarithmic, or isoline, map (Figure 2). Though appropriate for many purposes, isarithmic maps can be difficult to read because they are two-dimensional representations of three-dimensional data (Jenks, 1963). Studies have shown that map users may perform well on some tasks when using isarithmic maps, such as estimating the value at a location, but may have difficulty understanding the overall surface (Phillips *et al*, 1975; Griffin and Lock, 1979; Phillips, 1979). The lines are not continuous symbols across the field of the map, so readers must interpolate values between them (Lavin, 1986). Because of these difficulties, cartographers have sought alternate methods for depicting smooth statistical surfaces.

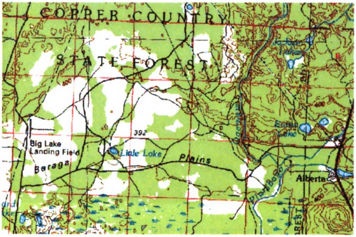


Figure 2. USGS topographic quadrangles include isarithms ("contours" in this case because they represent land elevation). Contours are brown on these maps.

Hill shading is one alternative method for showing continuous surfaces. With hill shading, various tints show the aspect of the statistical surface, with northwest-facing slopes illuminated and southeast-facing slopes in shadow. This combination of illumination and shadow gives a 3-d effect to the surface being mapped. It is difficult to produce quality hill shadings manually, so automated (computer) methods have been developed. Early automated methods could not match the quality of shadings produced manually (Yoeli, 1967; Brassel, 1979), but more recent improvements in computing power and software have made shaded relief maps not only faster and easier to produce, but also of extremely high quality (Thelin and Pike 1992, Lewis 1992). Hill shading gives a general impression of the form of the statistical surface, but as it shows aspect and not the values of the distribution, it is not useful for estimating values on the surface. Hill shading is sometimes combined with tints that represent value (Figure 3).

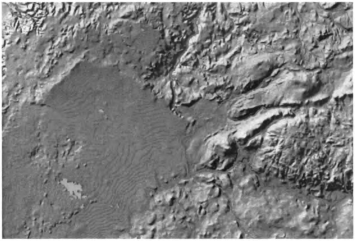


Figure 3. Shaded relief (hill shade) map combined with elevation tints, Baraga County, MI.

Perspective block diagrams, also known as "fishnet" diagrams, perspective traces, or transects, show elevation by placing lines across the statistical surface (Figure 4). Tedious to produce by hand, perspective diagrams can be produced quickly using computers. They do have their limitations, however. Regions of high variability—and thus high relief—can obscure lower areas behind higher zones, requiring rotation about the vertical and horizontal axes to minimize masking. On some block diagrams, obscured areas cannot be eliminated due to the complexity of the distribution. There is no "rule of thumb" for producing the ideal representation, which will vary from surface to surface.

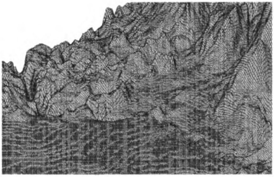


Figure 4. Perspective block diagram, Baraga County, MI.

The Continuous-Tone Method

Another way of portraying smooth statistical surfaces is the continuous-tone map. On continuous-tone maps, gray tones or colors (hues) vary smoothly to illustrate changes in value from high to low. Unlike an isarithmic map, they show value everywhere (Figure 5).

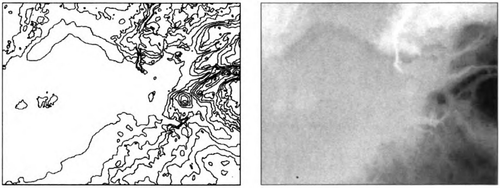


Figure 5. Isoline and continuous-tone grayscale maps of elevation, Baraga County, MI.

Groop and Smith (1982) developed a method that used graduated hexagons for creating virtually continuous-tone maps where hexagon size was plotted proportional to data value. Over a field such as a county, apparent darkness then represented the value (Figure 6). The procedures for this technique were more suited to maps plotted with a pen plotter than current output technologies, and the method used extensive and (then) expensive computer time. The plots had to be photographically reduced to page size.

Figure 6. Groop and Smith hexagon snowfall map. Reprinted with permission from *The American Cartographer* 9, October 1982, 123-131.

Johnson (1984) introduced a procedure that employed a dot matrix printer, driven by a BASIC program, to create continuous shadings (Figure 7). Testing proved the dot matrix maps as effective as isoline maps at conveying information, but test subjects did not like their coarse appearance.

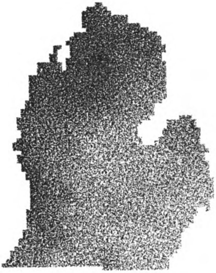


Figure 7. Johnson dot-matrix map.

Lavin (1986) developed a technique that used dot-density shading to produce continuous tones. Dots were plotted quasi-randomly in a gridded data matrix to assure non-overlap (Figure 8). Output was produced on a Tektronix™ plotter. Lavin concluded that dot density maps are one alternative method of smooth surface portrayal that can be used to supplement, but not replace, isoline maps.

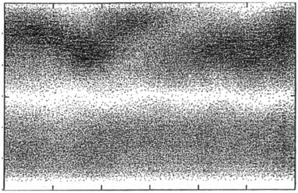


Figure 8. Lavin quasi-random dot map. Reprinted with permission from *The American Cartographer* 13, April 1986, 140-150.

Kumler (1988) created a hybrid method for producing color continuous-tone maps, which used both digital and photographic techniques. He developed a series of BASIC programs that displayed gridded data on a high-resolution color computer monitor in shades of red, green, and blue. He then photographed the monitor, one color at a time, and the color-separated negatives were process-printed to produce test maps. These procedures were chosen to suit the technologies of the time. Kumler's subject testing indicated improved map reading performance on the color continuous-tone maps when compared to standard isoline maps for the questions he asked, which included locating and marking surface lows and highs, estimating the relative elevation of a pair of points, estimating the elevation at a point, and interpreting the slope of a line between map points.

Chapter II
Statement of Problem

On continuous-tone maps, color scheme choice and surface complexity can affect the characteristics of the distributions that map readers perceive. Questions arise about the efficacy of the maps and just what information people are able or likely to gain from them. For example, Rogowitz and Treinish (1994) report that broad surface variations (low spatial frequency data) are more easily visualized when mapped using colors, but local surface variations (high spatial frequency, or fine details) are more evident when mapped using gray tones (Figure 9). Stated differently, the details (high spatial frequency components)

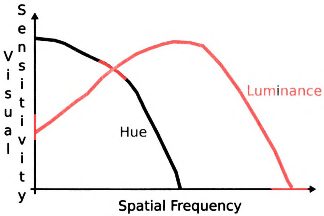


Figure 9. Visual sensitivity and spatial frequency curves, after Rogowitz and Treinish, 1995.

in statistical surfaces tend to stand out when a monochromatic color scheme is used (only luminance varies), whereas broad features (low spatial frequency components) in statistical surfaces stand out more readily when a polychromatic scheme is used (hue varies). These observations appear in visualization literature, but have not been noted in the cartographic journals even though cartographic practice suggests that mapmakers have an intuitive grasp of that principle: black lines are used to put in fine details such as small symbols or fine lines, and hue variations are used for heavy lines and over areas.

In addition to issues of visual processing, advances in computing power have made it possible to produce high-quality, continuous-tone maps relatively simply and quickly, raising the question of whether previous findings apply to more modern images. With powerful image processing and graphics software for microcomputers we can produce maps that are not only of higher quality but accessible to a broader audience, and producible by a wider range of map makers. These same technological advances also enable research on problems that require visual stimuli that was not feasible in the past.

Several previous studies have indicated that continuous-tone maps may be effective for representing smooth statistical surfaces. These studies used several different (then) contemporary output devices, including dot matrix printers and pen plotters. Problems noted in these studies, such as coarseness of output or production complexities, indicate a need for further research into the efficacy of continuous-tone maps, particularly those produced on newer hardware and with current software.

The study presented in the remainder of this paper was designed to test the efficacy of these maps in portraying the statistical surface by comparing the responses of test subjects when gray tone and hue-based continuous-tone maps were presented.

Detailed hypotheses will be given as stimuli are presented in the next chapter, but the general hypotheses were:

- map readers will more easily perceive broad trends when hue-based color schemes are used

- map readers will more easily perceive local details when gray tones are used
- questions about surface values will be more accurately answered when hue-based schemes are used.

Images in this thesis are presented in color.

Chapter III

The Map Test

Three real data sets were used to produce maps for test booklets: growing degree days for the Lower Peninsula of Michigan in 1993 [surface G]; elevation values from a portion of Keweenaw County, Michigan [surface E]; and rainfall data collected by the Southeast Michigan Council of Governments (SEMCOG) in 1993 [surface R] (Figures 10, 11, 12). These three surfaces have very different spatial characteristics. Surface (G) is complex, surface (E) presents intermediate spatial complexity, and surface (R) is relatively simple.

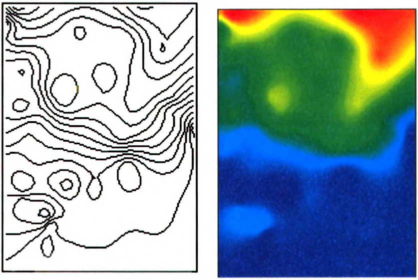


Figure 10. Growing Degree Days for Michigan, 1993. (Surface G).

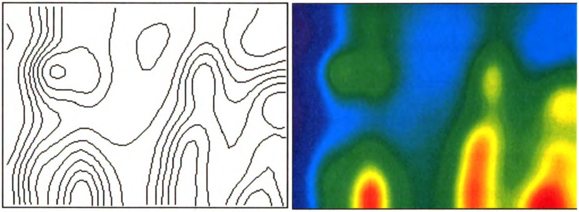


Figure 11. Elevation for a portion of Keweenaw County, Michigan. (Surface E).

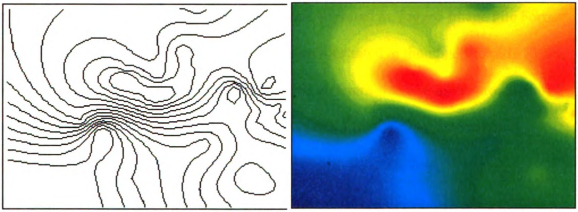


Figure 12. SEMCOG rainfall, 1993. (Surface R).

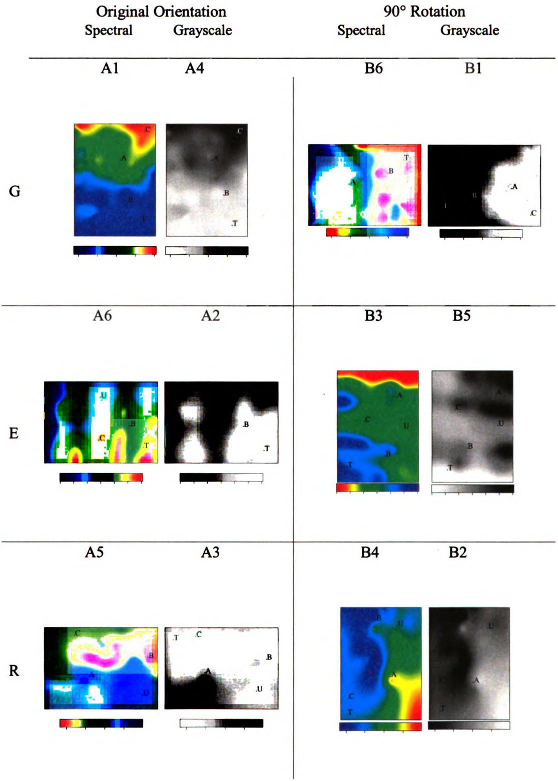
The raw data in each set were collected at irregularly spaced locations. SURFER version 4 (Golden Software, Inc., Golden, Colorado - http://www.goldensoftware.com/) was used to interpolate a regular lattice of points, to create a trend surface and to calculate residuals from the trend surface for each of the three data sets. A 4^{th} order polynomial was used for these trend surfaces after some trial-and-error experimentation. The fourth-order surface was deemed, through a visual check, to capture a reasonable amount of the variation in the actual surface.

Binary grids were output from SURFER™ and imported into Spyglass Transform™ (Spyglass, Inc, Champaign, IL - the Spyglass visualization suite is now being sold under the name Noesys by ITT Visual Information Solutions, Boulder, Colorado - http://www.ittvis.com/), a data visualization package that was used to generate the final continuous-tone maps. In Transform™, four different color lookup tables were applied to each of the three surfaces: a 256-step white-to-black gray-tone scheme; a 256-step black-to-white gray-tone scheme; a 256 spectral color "rainbow" red-to-blue scheme; and a 256 spectral color "rainbow" blue-to-red scheme. The twelve resulting maps (three data sets by four lookup tables) were exported as Tagged Image File Format (TIFF) images. They are listed in Table 1 and are illustrated in thumbnail form in Figure 13. The images were created and exported at two different sizes: small (approximately 2 by 3 inches) for Section I of the test and large (about 3 by 4 inches) for Section II. Additionally, Adobe PhotoShop 4™ (Adobe Systems, Inc., San Jose, CA - http://www.adobe.com/) was used to increase the resolution of the TIFF images from 72 to 300 dots-per-inch (dpi) to improve their appearance when printed.

Table 1. The Twelve Test Illustrations.

Map code	Surface	Color scheme	Triad	Section II Position
I	G	black-white	5	B1
II	G	white-black	11	A4
III	G	red-blue	3	B6
IV	G	blue-red	9	A1
V	E	black-white	10	A2
VI	E	white-black	4	B5
VII	E	red-blue	8	B3
VIII	E	blue-red	1	A6
IX	R	black-white	2	B2
X	R	white-black	12	A3
XI	R	red-blue	7	A5
XII	R	blue-red	6	B4

Figure 13. Orientation and color scheme of test illustrations. G, E, and R indicate the distributions, Growing degree days, Elevation, and Rainfall. The codes A1, B1, etc. indicate their positions in Section II of the test; A1 means test version A, page 1. Larger versions of the maps are in Appendices 3 and 4.



NIH Image, a free image-processing package available from the National Institutes of Health at http://rsb.info.nih.gov/nih-image/, was used to generate surface profiles between selected points on the images. These profiles were exported as raster image files and brought into Freehand™ 7 (Macromedia, Inc., San Francisco, CA - Adobe Systems, Inc. acquired Macromedia in December 2005), converted to vector format, and manipulated by flipping and stretching the correct profile to create a set of six profile choices for each of the surfaces. These profiles can be described as 1) correct with low slope, 2) correct with high slope (stretched on the y axis between 175 and 600% relative to the low slope profile), 3) medium slope (stretched on the y axis between 125 and 300% relative to the low slope) then flipped across the x axis, 4) profile 1 flipped across the y axis (reverse slope), 5) profile 2 flipped across the y axis, and 6) profile 3 flipped across the y axis. The manipulated profiles were saved as TIFF images at 300 dpi for later incorporation into the test booklets.

Adobe FrameMaker™ (Adobe Systems, Inc., San Jose, CA - http://www.adobe.com/) was chosen to assemble the individual maps into test booklets because it could utilize the higher resolution of the images produced. Three files were created, one for Section I of the test, and one each for the two versions of Section II (described below). The booklets were printed on an HP Color LaserJet™ (Hewlett-Packard Co., Palo Alto, CA - http://www.hp.com/) printer on 24-lb laser paper with a brightness rating of 94. The booklets were numbered by hand on the back (inconspicuously) to aid in compiling results. A consent form was distributed at the time of testing; a copy appears in Appendix 1.

Section I of the test booklet was comprised of a series of map triads, with the true surface at the top of each triad and the trend and residual surfaces below. Each of the three surfaces (land elevation, growing degree days, and rainfall) was included in Section I four times, twice as a gray-shaded map (black-to-white and white-to black) and twice as a spectral color map (blue-to-red and red-to-blue), for a total of twelve triads. Because the surfaces were rotated and the maps were in a random order (all the same random order), it was unlikely that subjects recognized the repeated depictions. Also, the order of the trend and residual surfaces was randomly switched on the test pages (all subjects received the same order for a given triad).

In Section I of the test, the subject was instructed to circle the map at the bottom (trend surface or residuals) that looked most like the (actual) surface above. The surfaces and color schemes for Section I are listed in Table 2, and sample color and grayscale map triads are shown in Figure 14. A complete set of map triads may be found in Appendix 2.

Table 2. Order of Triads in Test Booklet Section I

Position	Map code	Surface	Color Scheme	Orientation
1	VIII	E	blue-red	original
2	IX	R	black-white	original
3	III	G	red-blue	original
4	VI	E	white-black	rotated
5	I	G	black-white	rotated
6	XII	R	blue-red	rotated
7	XI	R	red-blue	original
8	VI	E	red-blue	rotated
9	IV	G	blue-red	rotated
10	V	E	black-white	original
11	II	G	white-black	original
12	X	R	white-black	rotated

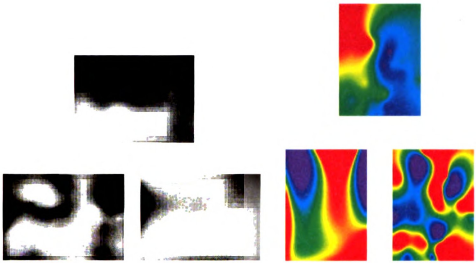


Figure 14. Sample grayscale and color map triads of Surface R from Section I. Original surface is at top, residuals are at outside positions, trend surfaces inside on these examples. Note that the orientation is not the same for the two triads but the map data are identical.

Section II of the test consisted of six maps, three grayscale and three color renditions. Each map had the same eight associated questions, which were designed to gauge the subject's perception of the surface: slope, roughness, high and low points, and elevation. The surfaces used in Section II were larger versions of the surfaces used in Section I of the test. The maps in Section II included the addition of a scale bar below the map, as well as labeled map points used in a number of the questions. Example grayscale and color maps from Section II are shown in Figure 15, and a complete set of maps from Section II may be found in Figure 13, or in Appendices 3 and 4 at larger size.

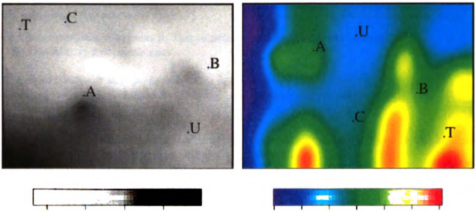


Figure 15. Sample maps—Surfaces R and E—from Section II. Larger versions are available in Appendices 3 and 4.

Section II contained two versions of each of the three surfaces—E, R and G—shown once with a spectral color scheme and once with a grayscale scheme. The surfaces were presented in a random order to help minimize the chance that the duplication would be noticed, and the numbers on the scale bar for three of the six maps were changed to different values to help reduce recognition. In Section II the subject answered questions by drawing on the map, circling the correct answer, or filling in blanks. The questions used in Section II are illustrated in Figure 16.

1) Put an H at the highest point on the map **2)** Put an L at the lowest point on the map

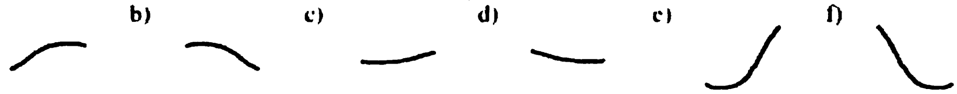
3) Imagine a line from point A to point B. This slope along most of this line is generally
a) uphill b) downhill c) flat (circle one)

4) Point A is ***a) on a ridge or hilltop b) in a valley or depression***
c) on a slope between a ridge or hilltop and a valley or depression (circle one)

5) Estimate the elevation at point C ________

6) Look at the circle to the right of the map and imagine it centered around points T and U. The area around T is
a) flatter b) more irregular than the area around U ***(circle one)***

7) Imagine a line from point C to point B. Circle the profile below that most closely matches its slope
a) b) c) d) e) f)



8) Which quadrant is most irregular? ***(circle one)***

I	II
III	IV

Figure 16. Example test questions from Section II.

Section I of the test was identical for all subjects. However, there were two versions of Section II used in the test. The two versions ("A" and "B") were used to keep the test a reasonable length. The same twelve maps used in Section I were included in Section II, with half in each version. Approximately 50% of subjects had a version "A" booklet (n=29) and 50% a version "B" booklet (n=30). A complete version of Section I of the test booklet is included in Appendix 2, and versions "A" and "B" of Section II of the test booklet are included in Appendices 3 and 4, respectively. A listing of the surfaces and color schemes used in Section II, test versions "A" and "B", may be found in Tables 3 and 4.

Table 3. Order of Maps in Test Section II Version A

Position	Map code	Surface	Color Scheme
A1	IV	G	blue-red
A2	V	E	black-white
A3	X	R	white-black
A4	II	G	white-black
A5	XI	R	red-blue
A6	VIII	E	blue-red

Table 4. Order of Maps in Test Section II Version B

Position	Map code	Surface	Color Scheme
B1	I	G	black-white
B2	IX	R	black-white
B3	VII	E	red-blue
B4	XII	R	blue-red
B5	VI	E	white-black
B6	III	G	red-blue

The specific working hypotheses concerning subject performance on spectral color and grayscale continuous-tone representations of smooth statistical surfaces are:

H_1 On map triads, a majority of subjects will choose the residuals map as appearing more like the actual surface when the three maps are in gray tones.

H_2 On map triads, a majority of subjects will choose the trend map as appearing more like the actual surface when the three maps are in spectral color.

H_3 Subjects will select the profile of correct shape with least vertical exaggeration as correct on grayscale maps.

H_4 Subjects will select the profile of correct shape with higher vertical exaggeration as correct on spectral color maps.

H_5 Subjects will estimate elevation more accurately on spectral color maps.

H_6 Subjects will locate surface extremes more accurately on spectral color maps.

Administration of the test

Students in one undergraduate and one graduate Forestry class at Michigan Technological University were invited to take the test on a voluntary basis. Subjects were allowed approximately 25 minutes to complete it. Both undergraduate and graduate students were included to help ensure a broad range of map reading backgrounds. Additionally, a number of other volunteers took the test. These additional volunteers did not take the test as a group, but were supervised while doing so, with the same time limit as the class subjects.

A short verbal introduction was given in addition to the information on the consent form and sample questions. No names were included on the test booklets to ensure anonymity. In all, fifty-nine subjects took the test. The subject population in the two classes included twelve graduate students and twenty-five undergraduates; the twenty-two additional volunteers were drawn from students, faculty and staff at Michigan Technological University.

Chapter IV
Results and Analysis

Before presenting any analysis, it is useful to look at raw results. For Part I of the test, subjects were asked to circle one of two maps (the "choice maps") that looked most like the one above it (Figure 14). The two choice maps were the trend and the residual surfaces generated from the surface above. Recall that the order of the choice maps—trend on left, residual on right, or residual on left, trend on right—was changed randomly throughout the section. Answers to Section I of the test booklets were recorded for each respondent. The results are summarized in Table 5 below.

Table 5. Summary of responses, Test Section I.
Boxed cells indicate the one map triad where the majority of respondents chose opposite what was predicted

Triad #	1	2	3	4	5	6	7	8	9	10	11	12
Map	VIII	IX	III	VI	I	XII	XI	VI	IV	V	II	X
Surface	E	R	G	E	G	R	R	E	G	E	G	R
Scheme	b-r	k-w	r-b	w-k	k-w	b-r	r-b	r-b	b-r	k-w	w-k	w-k
Trend/ Residual	L/R	R/L	R/L	L/R	R/L	L/R	R/L	R/L	L/R	R/L	L/R	L/R
Trend selected	**47**	13	**52**	4	18	**26**	**30**	**38**	**58**	3	4	6
Residuals selected	12	**46**	6	**54**	**41**	32	29	21	1	**56**	**54**	**53**
Responses	59	59	58	58	59	58	59	59	59	59	58	59
% trend	**79.7**	22.0	**89.7**	6.9	30.5	**44.8**	**50.8**	**64.4**	**98.3**	5.1	6.9	10.2
% resid	20.3	**78.0**	10.3	**93.1**	**69.5**	55.2	49.2	35.6	1.7	**94.9**	**93.1**	**89.8**

In Part II of the test, the answers to questions one and two—which asked subjects to mark the high and low positions on the map—were marked correct if the subject placed their letter within one-quarter inch of the true low or high points on the map. Responses to question three, which dealt with the slope of a line between two points, were compared with a profile generated from the surface and scored accordingly. A block diagram and contour map were used to determine the correct answer to question four, which asked subjects to consider the landscape position of a point. Question five asked subjects to estimate the elevation at a point and was marked correct if the responses were within one-quarter of the interval used on the map legend. This is the same criterion used by Kumler (1988) for his test instrument. To determine the correct answer to question six, which asked readers to estimate the relative surface roughness around two points on the map, a block diagram and contour map were used to assess the landscape position and elevation changes (ups and downs) around the two points. On question seven, subjects were to choose the profile that best fit their interpretation of the slope between two points on the map. There were two possible correct answers—one with greater vertical exaggeration than the other—that were counted as right, but a comparison was made between the spectral color and grayscale maps as to which level of exaggeration was most often chosen. The final question, eight, asked respondents to identify the roughest quarter of the map. Before scoring subject responses, a grid was used to count the number of changes in slope direction within each quadrant of the three surfaces. The quadrant having the most changes from up to down and vice versa was deemed "roughest".

Scores for individual maps were tallied, with eight being the highest score possible on a given map (if six questions were answered correctly, the subject would score a six for that particular map). Scores on individual maps ranged from a low of one to a high of eight. A composite score was calculated for each subject by counting the number of correct answers out of 48 possible (six maps, each with eight questions).

Preliminary analysis of groups, test Section II

After compiling scores for each subject, preliminary analysis was performed on the results from the three groups—the graduate class, undergraduate class, and volunteers—to see if they were from the same population. As there were two test booklets used, the results for versions "A" and "B" were first analyzed separately to see if there were any significant differences in subject performance between the two booklet versions. No differences were expected, but if they exist, they could confound the testing of the major hypotheses.

A Kruskal-Wallis Rank Sum test was used to determine if subjects in the three test groups were drawn from the same population. This is a nonparametric test that does not rely on normally distributed data and the groups need not have the same number of members. The Kruskal-Wallis test is used in cases where there are three or more groups of data. It is called a "rank sum test" because the scores in all groups are ranked from highest to lowest, the ranks are summed by group, and a mean rank by group is calculated, along with the total sum and overall mean of ranks for all subjects. These factors are used to calculate the H statistic, which can be used to estimate the probability of differences measured in the group scores occurring by chance. The R statistical software version 2.41 (http://www.r-project.org/) was used for analysis. The average score, number of participants by group, H statistic and significance are listed in Table 6.

The H value for both versions of the test, "A" and "B", was well above the rejection value for significance at the $\alpha = 0.05$ level. The differences in scores can be attributed to variation in sampling: the results for the two booklets are not significantly different.

Table 6. Kruskal-Wallis H test for differences between test groups (G: graduate students; U: undergraduate students; O: other volunteers)

H_0: Samples are from populations with identical distributions ($\alpha = 0.05$)

	Group					
Test version	**G**	**U**	**O**	**H statistic**	**Probability**	**Decision**
A (n=29)	63.33 (n=5)	68.91 (n=13)	66.66 (n=11)	1.715	0.424	accept H_0
B (n=30)	68.45 (n=7)	68.75 (n=12)	69.51 (n=11)	0.379	0.827	accept H_0

Map order effects

The order of maps in each of the two versions of Section II of the test was varied, the surfaces were rotated, and the numbers on the legends were altered to minimize the likelihood that subjects would recognize maps and improve as they worked through the test. Even so, it was possible that subjects could better their results as they took the test because of more experience with the maps and familiarity with the questions, or that they might recognize later surfaces as similar to, or the same as, maps they saw earlier, and perform better. To ascertain if such learning bias did take place, the score for each map was tested for dependence on its position in the booklet. If subjects improved their scores as they went along, it is an indication that learning took place, a finding that could confound the testing of the major hypotheses.

A repeated measures analysis was used to determine statistically if learning occurred. Repeated measures is a form of linear regression, where score (the performance on an individual map by each subject), is correlated with time (the position of each map in the booklet), to see if significant improvement occurred. A linear mixed effects (lme) model in R version 2.4 was applied to the aggregated raw scores for each subject using the statement `lme (score~map, random=~1|subj, data=learn)`. This statement translates to "apply an lme analysis to the data set "learn", look at score as a function of map position in the booklet (which equates to time), and treat each subject as a random effect". This approach is suggested in Kutner *et al.* (2005).

The slope of the resulting regression line was very low—0.01, and the p-value, at 0.78, is well above the rejection value for a significance level of 0.05. These results indicate that significant learning did **not** occur by subjects taking the test, i.e., scores did not improve sufficiently to bias further analysis. Table 7 presents the summary output of the linear mixed effects analysis.

Table 7. Linear mixed effects analysis to test for performance improvement, aggregate scores, Part II of test

H_0: Performance did not improve with time
($\alpha = 0.05$)

Fixed effects: score ~ map

	Value	Std. Error	DF	t-value	Probability
(Intercept)	5.4135	0.14963	294	36.179	0.0000
map	**0.010169**	0.03714	294	0.2738	**0.7844**

Decision: Accept H_0

To determine if learning occurred by the subjects who had either booklet version "A" or "B", the results from Section II of the test were looked at separately. A linear mixed effects analysis was performed on the scores stratified by test booklet ("A" and "B") and by subject group (g, u, and o) to see if learning occurred within these groupings. As expected, neither of these analyses, summarized in Table 8, revealed any significant learning effects.

Table 8. Linear mixed effects analysis to test for performance improvement, separate scores, Part II of test

H_0: Performance did not improve with time
($\alpha = 0.05$)

Fixed effects: score ~ map for **booklet version A**

	Value	**Std.Error**	**DF**	**t-value**	**p-value**
map	0.0945	0.05467	144	1.7298	0.0858

Fixed effects: score ~ map for **booklet version B**

	Value	**Std. Error**	**DF**	**t-value**	**p-value**
map	-0.0714	0.0496	149	-1.4374	0.1527

Fixed effects: score ~ map for **group g**

	Value	**Std. Error**	**DF**	**t-value**	**p-value**
map	0.0143	0.07621	59	0.1874	0.8519

Fixed effects: score ~ map for **group u**

	Value	**Std. Error**	**DF**	**t-value**	**p-value**
map	0.0068	0.05775	124	0.1187	0.9057

Fixed effects: score ~ map for **group o**

	Value	**Std. Error**	**DF**	**t-value**	**p-value**
map	0.0117	0.0628	109	0.1859	0.8528

A Linear Mixed Effects analysis was not appropriate to assess the results stratified by color scheme, as no subject had only spectral color or only grayscale maps in their booklet. Instead, the scores were plotted to show map position in the booklet, average score, and color scheme. No obvious pattern was evident in the graphs. The performance on each map for booklets "A", "B", and the combined results, is shown in Figure 17.

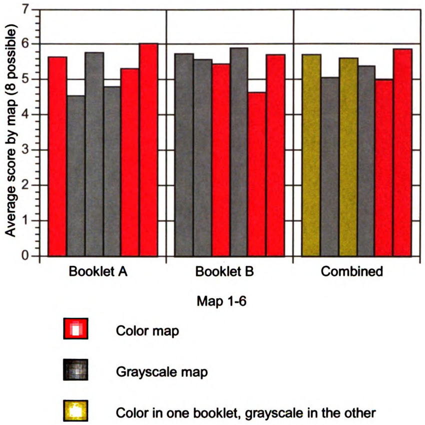


Figure 17. Subject performance on maps from Section II. Scores are out of 8 possible. Map position increases from left to right (map 1 is leftmost bar, map 6 rightmost)

The Kruskal-Wallis analysis indicted that there was no significant difference in the three test subject samples. The repeated measures analysis of all scores from Section II showed that map position did not affect how subjects performed on a given map: i.e., significant learning did not occur during the test. Therefore, the results from Section II were combined for further analysis. Average subject scores from Section II for the twelve test illustrations; the four color schemes (black-to-white, white-to-black, red-to-blue, and blue-to-red); and the two color scheme classes (spectral color and grayscale) are listed in Table 9.

Table 9. Average Scores for Map Types and the Twelve Maps, Section II of test

Map code	Surface	Color scheme	Sample size	Avg Score
I	G	k-w	30	72.1
II	G	w-k	29	60.3
III	G	r-b	30	71.7
IV	G	b-r	29	70.7
V	E	k-w	29	56.9
VI	E	w-k	30	58.3
VII	E	r-b	30	68.3
VIII	E	b-r	29	75.4
IX	R	k-w	30	70.0
X	R	w-k	29	72.4
XI	R	r-b	29	66.8
XII	R	b-r	30	74.2
I V IX	G E R	k-w	89	66.4
II VI X	G E R	w-k	88	63.6
III VII XI	G E R	r-b	89	69.0
IV VIII XII	G E R	b-r	88	73.4
I II V VI IX X	G E R	Grayscale	177	65.0
III IV VII VIII XI XII	G E R	Spectral Color	177	71.2

Subject performance, Test Section I

The main purpose of this research was to test the efficacy of continuous-tone spectral color and grayscale maps in displaying smooth statistical surfaces. The first part of the test was designed to determine if subjects saw a low spatial frequency surface—a fourth-order trend surface—as more like the original surface when it was presented using a spectral color scheme, and a high spatial frequency surface—residuals from the trend surface—as more like the original surface when it was depicted in grays. The first two research hypotheses, H_1 and H_2, are a restatement of the above:

H_1 On map triads, a majority of subjects will choose the residuals map as appearing more like the actual surface when the three maps are in gray tones

H_2 On map triads, a majority of subjects will choose the trend map as appearing more like the actual surface when the three maps are in spectral color

A Chi-square analysis, a non-parametric test of statistical significance for differences in performance on bivariate, or paired, data, was performed on the results from Section I of the test. For triad 1 in Section I of the test, there were 59 subject responses recorded. If there was no difference in response to the question, i.e., subjects did not choose one map preferentially over the other, one would expect that half of the subjects (29.5) would choose the trend map as most like the original surface and half would choose the residual map. The Chi-square analysis tests for significant differences between the **expected** and **observed** responses to the question, using the following formula:

$$\chi^2 = \Sigma\ (\text{Observed-Expected})^2 / \text{Expected}$$

For triad 1, forty seven subjects chose the trend surface and twelve chose the residual surface. Thus, the chi-square value would be calculated as follows:

Observed	Expected	Obs.-Exp.	$(\text{Obs.-Exp.})^2$	$(O-E)^2/E$
47	29.5	17.5	306.25	10.38
12	29.5	-17.5	306.25	10.38

$$\chi^2 = (47-29.5)^2/29.5 + (12-29.5)^2/29.5$$

$$\chi^2 = 10.38 + 10.38$$

$$\chi^2 = 20.76$$

For a pair of observations, the degrees of freedom is one, and the chi-square required for significance at the $\alpha = 0.05$ level is 3.841. A chi-square value of 20.76 is statistically significant beyond the 0.001 level (i.e., the odds of a chance occurrence of these results are less than one in one thousand). The results of the chi-square analysis for the aggregated spectral color and grayscale map scores, as well as for the twelve individual maps in Section I, are presented in Table 10.

Table 10: Chi-square analysis of Test Booklet Section I

H_0: Performance differences are evenly distributed

($\alpha = 0.05$)

Map	χ^2	DF	Scheme	Probability	Decision
All color	63.92	1	color	1.295e-15	Reject H_0
All gray	186.18	1	gray	<2.2e-16	Reject H_0
1	20.76	1	color	5.199e-06	Reject H_0
2	18.46	1	gray	1.73e-05	Reject H_0
3	36.48	1	color	1.54e-09	Reject H_0
4	43.10	1	gray	5.19e-11	Reject H_0
5	8.97	1	gray	.002750	Reject H_0
6	0.62	1	color	0.4308	Accept H_0
7	0.02	1	color	0.896	Accept H_0
8	4.89	1	color	0.027	Reject H_0
9	55.07	1	color	1.164e-13	Reject H_0
10	47.61	1	gray	5.2e-12	Reject H_0
11	43.10	1	gray	5.192e-11	Reject H_0
12	37.44	1	gray	9.42e-10	Reject H_0

For the scores aggregated by color scheme (spectral color and grayscale), subjects much more often chose the residuals map as appearing more like the original map when portrayed in grayscale, i.e., they preferentially chose the high spatial frequency surface. Of three hundred and fifty two responses, only forty eight chose the trend surface (14% of respondents), while three hundred and four chose the residual surface (86% of respondents), which yielded a chi-square value of 186. Subjects also overwhelmingly chose the trend maps as more like the original surface when shown with a spectral color scheme, i.e., they preferentially chose the low spatial frequency surface. The tendency was not as strong with the color surfaces, however, as two hundred and fifty one respondents chose the trend surface (71%) vs. 101 respondents who chose the residual map (29%). This produced a chi-square value of 63.92. Both research hypotheses one and two were accepted.

When analyzed separately (no corrections for multiple tests), ten of the twelve triads had chi-square values significant enough to reject the null hypothesis: respondents did preferentially choose one representation over the other. However, maps six and seven had chi-square values of 0.62 and 0.02, respectively, which were well below the value of 3.84 required to reject the null hypothesis. Triads six and seven were both spectral color surfaces, and triad six was the only one of the twelve triads where a (small) majority of subjects chose the surface opposite of what was predicted – thirty two subjects chose the residual map as appearing more like the original surface, and twenty six chose the trend surface. On map seven, an even slimmer majority—thirty—chose the trend surface as most like the original, while twenty nine chose the residual surface. Triads six and seven were the two color versions of the rainfall surface (R), and the trend maps included in the test accidentally had their color order reversed with respect to the original map to which they were being compared; the colors ran from red to blue and blue to red instead of the opposite order for these two trend maps. This inadvertent color sequence reversal reveals an interesting point: even though the opposite color sequence was used on the trend map, the residual map (with correct color order) was not chosen over the trend map. Rather, the choice seemed to have become a random one, with close to equal numbers choosing the trend and residual surfaces. Given the problem with these two maps, it makes the results even more overwhelmingly in favor of the research hypothesis.

Subject Performance, Test Section II

Section II of the test was designed to assess how well subjects could interpret the three surfaces when shown in spectral colors *vs*. graytones, and to compare differences in their performance when answering questions about spectral color and grayscale maps. A chi-square analysis was performed on the aggregated scores for all spectral color and grayscale maps in Section II. The results of this analysis are presented in Table 11.

When scores from Section II of the test were analyzed as a whole, a significant chi-square value, 12.25, was the result. Overall, subjects performed significantly better on the spectral color maps than on the grayscale maps. However, when looking separately at the six pairs of maps from the two versions of the test ("A" and "B"), only three pairs, A1/A4, A6/A2, and B3/B5, had chi-square values large enough to reject the null hypothesis. In each case, performance was significantly better on the spectral color map. In the other pairing from test version "A", and for two pairings from version "B", there was no significant difference in subject performance on the color surfaces *vs*. the grayscale representations. Maps A1 and A6 used spectral schemes that ran from blue to red; B3 used a red-to-blue spectral scheme. The paired maps, A4, A2, and B5, used white-to-black, black-to-white, and black-to-white grayscale schemes, respectively, so the color tables of the pairs are not consistent. However, this result may indicate that the blue-to-red color scheme is the most effective of those color schemes used. This observation is supported by the information in Table 9, which lists the average map score by scheme. Subjects performed best on maps shown with the blue-to-red color scheme, with an average score of 73.4% correct. This is four percent higher than the next closest color scheme, and six to ten percent better than the two grayscale schemes.

In the three non-significant pairings, performance was slightly better on the grayscale maps in two instances (A5/A3 and B1/B6) and slightly better on the spectral color maps in the third (B4/B2). The chi-square values for A1/A4, A6/A2, and B3/B5, were high enough, at 16.2, 12.5, and 7.54, to produce the overall significant chi-square value of 12.25, and override the non-significant chi-square values of the other three pairings.

Table 11: Chi Square Tests of differences between spectral color and grayscale maps

H_0: Performance differences are evenly distributed
($\alpha = 0.05$)

*The difference between **pairs** and **total** in the table below is where performance was the same, e.g., for all maps, there were fifty-nine pairings (one for each subject). Eight subjects performed equally well on the color and grayscale maps. Thirty-eight scored higher on the color maps and thirteen on the grayscale, yielding a total of fifty-one.*

All maps, color vs. grayscale

Scheme	**Maps**	**Pairs**	**Higher scores**	χ^2	**Probability**	**Decision**
Color	A1 A5 A6 B3 B4 B6	59	38	12.2549	0.000464	Reject H_0
Grayscale	A2 A3 A4 B1 B2 B5		13			
Total			**51**			

Booklet "A"

Scheme	**Maps**	**Surface**	**Pairs**	**Higher scores**	χ^2	**Probability**	**Decision**
Color	A1	G	29	19	16.2	5.70e-05	Reject H_0
Grayscale	A4			1			
Total				**20**			
Color	A6	E	29	22	12.4615	0.0004154	Reject H_0
Grayscale	A2			4			
Total				**26**			
Color	A5	R	29	10	0.6667	0.4142	Accept H_0
Grayscale	A3			14			
Total				**24**			

Booklet "B"

Scheme	**Maps**	**Surface**	**Pairs**	**Higher scores**	χ^2	**Probability**	**Decision**
Color	B6	G	30	9	0.2	0.6547	Accept H_0
Grayscale	B1			11			
Total				**20**			
Color	B3	E	30	20	7.5385	0.00604	Reject H_0
Grayscale	B5			6			
Total				**26**			
Color	B4	R	30	12	0.8	0.3711	Accept H_0
Grayscale	B2			8			
Total				**20**			

To obtain a second measure of performance differences shown by subjects between the spectral color and grayscale maps in Section II of the test, a Wilcoxon Signed Rank Test was performed on the aggregated results of all maps from booklet versions “A” and “B”. The Wilcoxon Signed Rank Test is used for two-sample data involving matched pairs, repeated measures, or “before” and “after” measures when the populations are not normally distributed. In this case, the “pairs” are the differing performance of each subject on the color maps *vs*. the grayscale maps. The absolute difference of each pair is determined, $|X_a - X_b|$, then observations where performance is tied are dropped ($|X_a - X_b| = 0$). The remaining absolute differences are ranked from smallest to largest, and ranked values are given signs: "+" when $X_a-X_b > 0$ and "-" when $X_a-X_b < 0$. The signed ranks are then summed and used to calculate W. R version 2.41 was used for this calculation, and the resulting W statistic was 1066, with a p-value of 0.00014. This result, like the chi-square test, indicates there were significant performance differences between the color maps *vs*. the grayscale maps: subject performance was significantly better on the spectral color maps. The result of the Wilcoxon Signed Rank Test is listed in Table 12.

Table 12: Wilcoxon Signed Rank Test comparing color and grayscale map performance

H_0: Performance differences are evenly distributed
($\alpha = 0.05$)

W value	**Probablility**	**Decision**
1066	0.0001382	Reject H_0

Testing the Other Research Hypotheses, Test Section II

Section II of the test was designed to assess how well subjects could interpret the three surfaces when shown in spectral colors *vs*. gray tones. Research hypotheses three through six addressed specific map reading tasks from Section II of the test:

H_3 Subjects will select the profile of correct shape with least vertical exaggeration as correct on grayscale maps.

H_4 Subjects will select the profile of correct shape with higher vertical exaggeration as correct on spectral color maps.

H_5 Subjects will estimate elevation more accurately on spectral color maps.

H_6 Subjects will locate surface extremes more accurately on spectral color maps.

A chi-square analysis was performed on the results from Section II of the test on a question-by-question basis to compare the performance differences between spectral color and grayscale maps. The results of this analysis are listed in Table 13.

Table 13: Chi-Square Test Comparing Spectral Color and Grayscale Map Performance

H_0: No difference in performance with color *vs*. grayscale maps
($\alpha = 0.05$)

Aggregate Scores

Question	Number correct Color	Number correct Gray	χ^2	Probability	Decision
1	171	170	0.0029	0.9568	Accept H_0
2	165	160	0.0769	0.7815	Accept H_0
3	117	132	0.9036	0.3418	Accept H_0
4	110	77	**5.8235**	0.0158	**Reject H_0**
5	99	80	2.0168	0.1556	Accept H_0
6	131	142	0.4432	0.5056	Accept H_0
7	130	95	**5.4444**	0.0196	**Reject H_0**
8	72	75	0.0612	0.8046	Accept H_0

Significant chi-square values are in **bold**

A brief assessment of the results of this chi-square analysis would suggest that subjects performed equally well on the spectral color and grayscale maps on six of the eight associated questions. Only questions four and seven produced chi-square values that were significant. These two questions (four and seven) dealt with the landscape position of a point and the form of a slope between two points. Subjects performed significantly better on the spectral color surfaces on questions four and seven.

To assess research hypotheses three and four, which suggested that higher magnitude profiles would be chosen on spectral color maps and lower magnitude profiles on grayscale maps, the compiled answers to question seven were scrutinized. There were 130 correct answers selected on color maps: 59 of these were the profile of lesser magnitude, and 71 were higher magnitude. On the grayscale maps, 95 correct answers were recorded: 50 were the lesser-magnitude profile and 45 the higher magnitude. At first glance, these results support the research hypotheses, as a majority of subjects preferred the higher-magnitude profile on color surfaces and the lesser-magnitude profiles on grayscale surfaces. To test these observations for significance, the correct answers—which included both the low and high magnitude profiles—were subjected to chi-square analysis. Both the color and grayscale profile results did not have chi-square values large enough to be significant. Research hypotheses three and four were rejected and the null hypotheses of no difference was accepted. The results of the chi-square analysis comparing actual and high-magnitude profile selection are presented in Table 14.

Table 14: Chi-Square Test Comparing Profile Magnitude Selections, Spectral Color and Grayscale Maps

H_0: Performance differences are evenly distributed ($\alpha = 0.05$)

Scheme type	**Number correct Actual**	**Number correct Higher Magnitude**	χ^2	**Probability**	**Decision**
Color	59	71	1.1077	0.2926	Accept H_0
Grayscale	50	45	0.2632	0.6080	Accept H_0

Research hypothesis five predicted that subjects would be able to estimate elevation at a point more accurately on spectral color maps. Though performance was better on the color maps when compared with the grayscale maps, with 99 and 80 correct responses respectively, the difference in performance was not statistically significant. The resulting chi-square value was 2.01, below the necessary significance threshold of 3.84. Research hypothesis five was, therefore, rejected and the null hypothesis of no difference was accepted.

Research hypothesis six proposed that test subjects would be better able to locate surface extremes—the high and low points—on spectral color maps than on grayscale maps. Test questions one and two dealt with marking the surface extremes on each map. With 171 (color) and 170 (gray) correct answers for question one, and 165 and 160 correct answers for question two, performance was again (marginally) better on the color maps when compared with the gray surfaces. The resulting chi-square values—0.0029 and 0.0769 for questions one and two—were far from significant enough to accept the hypothesis. Research hypothesis six was also rejected and the null hypothesis accepted.

Summary of Results

The test instrument discussed above was designed with two goals in mind. The first was to see if gray tones better represent high spatial frequency data, and spectral colors (hue) better represent low spatial frequency data. The second was to compare map reading performance on spectral color *vs*. grayscale representations of the same statistical surfaces.

The first part of the test was designed to help assess how subjects saw spatial frequency. Research hypotheses one and two predicted that a majority of subjects would choose a residual map as most like an original surface when shown in grays, and a trend surface as most like the original surface when mapped in spectral colors. A chi-square analysis of the results from Section I showed significant differences in the selections made by test subjects. As a result, both research hypotheses one and two were accepted.

In Section II of the test, subjects were asked to answer a series of eight questions on each of six maps – three surfaces shown in two color schemes: once in grayscale and once in spectral color. Differences in performance on these map reading tasks were tested for significance, to assess whether the color scheme type—spectral color or grayscale—affected performance. Subjects scored higher overall on the color surfaces when compared with the grayscale surfaces—about six percent better on average. A chi-square analysis of the subject performance showed that subjects performed significantly better on the spectral color maps than on the grayscale maps. When performance on selected individual questions were subjected to the chi-square test, however, research hypotheses three through six, which dealt with profile selection, elevation estimation, and location of surface extrema, were rejected, as significant differences between the grayscale and spectral color surfaces were not evident in the subject response data.

Discussion

Some oversights in test design and production occurred while carrying out this research. In addition to the inverted color schemes used in triads six and seven, one other error was present in the test booklets. In Section II of test "B", map five was rotated to help reduce the chance that it would be recognized as the same surface as map three, but the corresponding map points were not moved accordingly. Answers were adjusted so they were correct relative to the points as actually shown, but the comparability of the two maps was not as well controlled as in the other pairs. Maps B3 and B5 are shown in Figure 18.

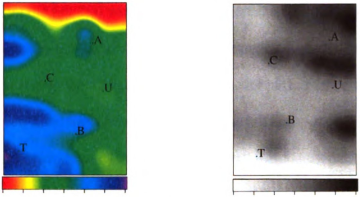


Figure 18. Maps B3 (left) and B5 (right, map points unrotated).

This omission reduced the effectiveness of directly comparing B5 with its paired map, B3. Like three of the other six map pairs, however, there was no significant difference in subject performance on map pair B3/B5, so the oversight may not have effected a significant change in answers.

Conversations with some of the subjects after testing revealed an interest in the study and questions about how the maps might be used. One subject mentioned that he felt the maps were easy to use, but found the color maps easier than the grayscale, which were "too dark". This may be only a preference due to the appearance of the bright spectral color scheme used, but it also suggests that the overall darkness of the grayscale maps may have been part of the reason for inferior performance with them. On the other hand, the values ran virtually the full gamut from white to black and any changes to lighten the maps would have meant less differentiation in the lighter end of the scale. The increased visual differentiation afforded by the spectral scheme is much more likely responsible for the better performance.

It is interesting that all the research hypotheses involving specific questions were rejected (i.e., the null hypotheses were accepted). Since the one involving question 7 (selection of profile) did not deal with correct *vs.* incorrect answers, but whether subjects answering correctly selected the less exaggerated or more exaggerated profile, its rejection is not contrary to the overall hypothesis of better performance with color maps. The others, however, involving Questions 1, 2, 3, 5, and 6, each showed no difference in performance with the two maps. The significant overall difference, then, was attributable to other questions, and Table 13 indicates these are 4 and 7.

Perhaps a different criterion for assessing questions 1 and 2 would have yielded different results, e.g., a smaller radius in which answers were marked correct. However, it is likely that marking the "blackest" or "whitest" regions on a grayscale map is no more difficult than marking the "reddest" or "bluest" locations on a spectral color map, and the non-significant results are, therefore, not surprising. It may be that the non-linear nature of the spectral color schemes used in the test affected the results for question 3, as performance was marginally, but not significantly, better on the grayscale maps.

Question 5 dealt with estimating elevation at a point on the map, which had better, but not significantly so, results on the spectral color maps. Again, a different criterion, such as a smaller margin for correct answers, might have given a different outcome. Questions 6 and 8 were both about roughness of the surfaces, and non-significant differences were found again. Performance was slightly better on the grayscale maps, so "roughness" may be a characteristic better communicated by the luminance changes of a grayscale presentation.

Questions 4 and 7 were the two with significant chi-square values, and these questions addressed landscape position and slope profile selection. It may be that the non-linear appearance of the spectral color scheme aided in assessing the location of point A on question 4, e.g., the rapid change between red and green (through yellow) or between blue and green (through cyan) gave better clues to the form of the landscape than the steady progression of grays in the grayscale maps. Perhaps the same clues in the color table assisted the subjects in selecting profiles for question 7.

What does all this mean for mapmaking? It seems clear that spectral color allows better performance on at least some of the questions, but not on all. It is particularly interesting that it was form of the distribution on which subjects performed better with the spectral scheme because it has been the non-sequential nature of spectral colors that has long made cartographers reluctant to use them for representing quantitative data.

One potential area for additional research would be to test monochromatic color schemes against grayscale, and even more important, a spectral scheme with a progression of value (say, light yellow through medium-value greens through dark blues and even darker reds), since progressive schemes resulted in good performance in Mersey's (1990) study and Brewer (1997) recommends them for diverging data. Would we, for example, see the shift of visual emphasis from broad patterns to local features if we compared a light-to-dark spectral scheme to the light-to-dark grayscale? And for the questions posed in Section II of the test, would we continue to see superior performance (perhaps even more superior performance) with a light-to-dark spectral scheme? For the questions they asked, Brewer et al. (1997) had good results with a diverging spectral scheme (yellow for the middle category, with light oranges to highly saturated red in one direction and light greens to highly saturated blue in the other), and even better results for more conventional bi-color diverging schemes. The spectral scheme used in this thesis research does not have continuous-appearing values and is not arranged as a diverging scheme. This means certain hues—such as yellows and cyans that occupy a narrow portion of the color spectrum compared to greens or blues—can give the impression of greater importance (because of greater contrast) than is warranted to the areas mapped in those colors. This phenomenon can be especially pronounced on some data distributions, where the combination of data values, surface form and color scheme can cause representations that are not true to the surface due to visual artifacts.

Another area for further research is the perception of broad patterns on spectral maps and local variation on grayscale ones. The fourth-order surfaces showed strong differences in choices between trend and residual maps depending on whether the maps were in color or grayscale. But was it just because of the trial and error selection of the fourth-order that was based on our visual inspection? Is there something inherent in that level of trend surface? Rogowitz *et al* (1995) do not use trend surfaces to determine the appropriate color scheme to use for a given data set. Instead, their software uses what is, in effect, a low-pass filter to derive new data from the original. It then subtracts the original data values from the filtered. The standard deviation of difference values is computed, then divided by the original data values. The resulting "normalized standard deviation" is used to assess the complexity of the surface. An image with a normalized standard deviation (NSD) of less than 0.1 is deemed "low frequency" and can use a spectral color map, whereas an image with a NSD of greater than 0.1 is flagged as "high frequency" and only monochromatic color maps are available.

Is the Rogowitz method the best way to choose a color map? Not necessarily: they state that the method was chosen for its speed and simplicity, and it may not stand up to rigorous scrutiny. It might not be the best for a data set that has both high and low frequency areas.

This thesis research has added to favorable results with spectral color maps. It has also provided food for thought.

Chapter V
Summary and Conclusions

Mapping quantitative surfaces has been somewhat problematic for cartographers. A number of techniques have been developed to portray statistical surfaces, with varying degrees of success. Research has shown that many map readers have difficulty in perceiving quantitative surfaces when depicted with isolines, and numerous alternate techniques have drawbacks as well, both with reader perception and production by map makers. The purpose of this research was twofold: to develop a new technique for producing continuous-tone maps using both free and commercial software, and to test the effectiveness of these maps at representing quantitative surfaces by testing map readers.

Moore's Law, observed in 1965 by Gordon Moore of Intel, the CPU manufacturer, roughly states that computing power doubles every two years. This phenomenon has had several effects: computers that were once too large or too expensive for the average user have become ubiquitous over the last twenty years, and tasks that were once relegated to mainframes or minicomputers can now be easily accomplished with widely available software on desktop computers. Continuous improvement has also occurred in output devices, and currently, high-resolution color laser printers can be purchased for under $500. The map production technique outlined in this study was performed on desktop computers with software available commercially and for free, and the test illustrations were produced on a Hewlett-Packard color laser printer that is relatively standard equipment in modern computer labs and offices.

The test instrument was designed to assess two things: first, whether high-spatial frequency data is best represented with grayscale color schemes and lower spatial frequency data with spectral colors, and second, to compare subject map reading performance on spectral color and grayscale depictions of the same three quantitative surfaces. Three real surfaces from Michigan were used: elevation, rainfall, and growing degree days.

To answer the color scheme *vs*. spatial frequency question, readers were shown a small version of each surface, along with two additional representations: a fourth-order polynomial trend surface derived from the original, and the residuals from the trend surface. These map triads were shown once in each of the four color schemes, for a total of twelve triads. A significant number of subjects chose the trend map as most like the original surface when shown in spectral colors, and the residuals map when shown in grays. These results indicate that a significant number of subjects perceive high spatial frequency features when surfaces are shown in grayscale, and they perceive broad trends when surfaces are shown in spectral colors.

To compare map reading performance on spectral color and grayscale maps, readers answered questions about high and low spots on each map, the landscape position of points, the slope between map points, and surface roughness. Subjects saw each of the three surfaces twice, once in colors and once in grays. The maps were rotated to help reduce possible recognition of duplication, but map points were, with one inadvertent exception, in the same locations so direct comparisons from map to map could be made. Overall, the subjects performed significantly better on the color maps than on the grayscale representations. The highest average score was on maps shown in the blue-to-red spectral color scheme, and the worst performance was observed on the white-to-black grayscale maps. Only two of the eight individual questions, however, showed significantly higher performance on the color maps.

Mapping quantitative surfaces as outlined above is practicable. No unusual hardware or expensive software is necessary to produce the maps, and high-quality output may be obtained on an inexpensive color laser printer with ordinary paper.

Continuous-tone maps are planimetric, and, unlike isopleth maps, present the map reader with a continuous-appearing symbology for interpretation. They represent the quantitative surface as faithfully as other maps produced from the same data. Previous studies have shown them to be more effective at conveying information about the mapped surface than isoline maps. The results from the fifty-nine subjects tested during the course of this research showed that spectral color, continuous-tone maps are easier for subjects to interpret than continuous-tone, grayscale maps. However, caution should be used when applying a spectral color scheme to a surface with potentially important components that are high in spatial frequency, as they could be masked. In these circumstances, regional components may look more important than is warranted, due to the non-linear nature of the spectral color scheme.

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Appendix 1

Consent Form

Map Study

1. You are being asked to participate in a map perception study. The study is being conducted by Michael Hyslop as part of a master's program in geography, under the direction of Drs. Richard Groop and Judy Olson of the Geography Department at Michigan State University.
2. You will be asked to answer questions on maps provided in a test booklet.
3. The length of time for participation is approximately 25 minutes.
4. There are no foreseeable risks to you if you participate in this study. Your participation will not affect your grade in any course, and you are free to discontinue participation at any time without penalty.
5. You are assured that you will remain anonymous in any reports of the research. Within these restrictions you may receive a copy of results upon request.
6. You may receive further information about the study at the end of this session if you request.
8. For further information about the research, you may contact:

Michael Hyslop MTU School of Forestry 101 UJ Noblet Forestry and Wood Products Bldg 1400 Townsend Drive Houghton, MI 49931-1295	voice: fax:	906-487-2308 906-487-2915
or		
Dr. Richard Groop or Dr. Judy Olson Department of Geography Natural Science Building Michigan State University East Lansing MI 48824	voice: fax:	517/355-4649 517/432-1671

9. For information about your rights as a subject in a research project, you may contact:

David Wright Univ. Comm. for Research Involving Human Subjects 246 Hannah Administration Bldg. Michigan State University East Lansing, MI 48824	voice: fax:	355-2180 517/432-1171

I understand the above statements and freely consent to participate in this study.

____

Signed

____

Date

Appendix 2 – Test Booklet Part I

Test Booklet

PLEASE DO NOT OPEN UNTIL INSTRUCTED.

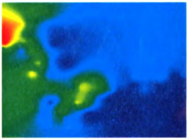
Section I

In this part of the test you will be shown maps in sets of three. Circle one of the two lower maps -- the one that looks the most like the top map.

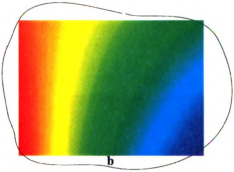
Example:

Which map, b or c, looks more like map a?

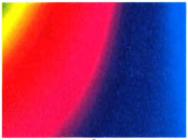
(circle your choice)



a

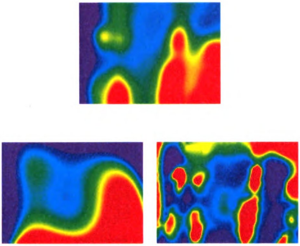


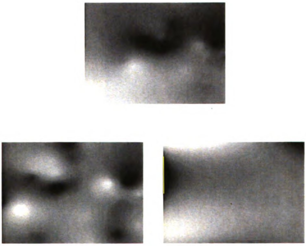
b

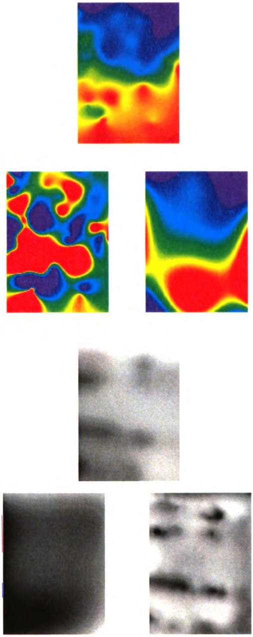


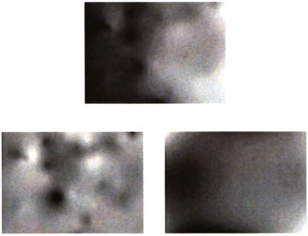
c

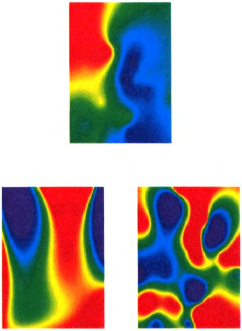
Go ahead and complete this section of the test

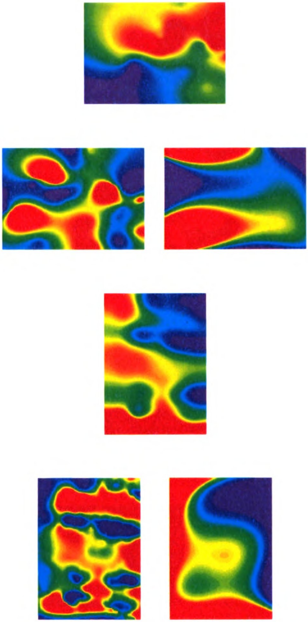


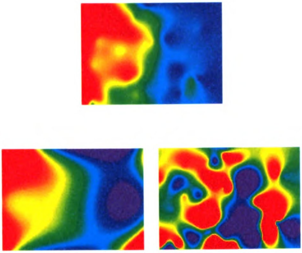


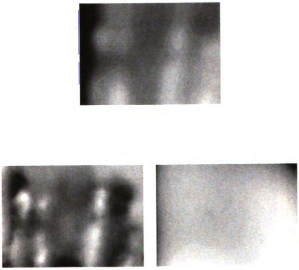


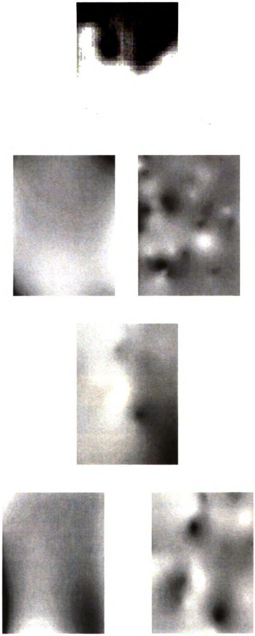










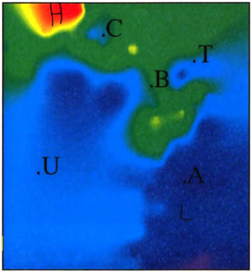


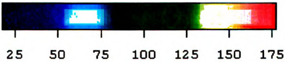
Appendix 3 – Test Booklet Part II Version A

Section II

In this part of the test you will be shown individual maps and asked a series of questions. Circle the correct answer, fill in the blank, or draw on the map as asked.

Example:





1) Put an H at the highest point on the map

2) Put an L at the lowest point on the map

3) Imagine a line from point A to point B. This slope along most of this line is generally
a) *uphill* ***b)*** *downhill* ***c)*** *flat* ***(circle one)***

4) Point A is ***a)*** *on a ridge or hilltop* ***b)*** *in a valley or depression*
c) *on a slope between a ridge or hilltop and a valley or depression* ***(circle one)***

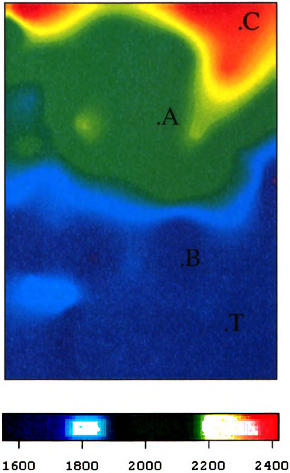
5) Estimate the elevation at point C 70

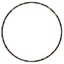
6) Look at the circle to the right of the map and imagine it centered around points T and U.
The area around T is ***a)*** *flatter* ***b)*** *more irregular* than the area around U ***(circle one)***

7) Imagine a line from point C to point B. Circle the profile below that most closely matches its slope

a) b) c) d) e) f)

8) Which quadrant is most irregular? ***(circle one)***





1) Put an H at the highest point on the map **2)** Put an L at the lowest point on the map

3) Imagine a line from point A to point B. This slope along most of this line is generally
a) *uphill* ***b)*** *downhill* ***c)*** *flat* ***(circle one)***

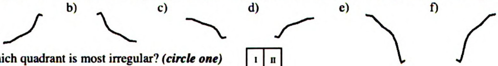
4) Point A is ***a)*** *on a ridge or hilltop* ***b)*** *in a valley or depression*
c) *on a slope between a ridge or hilltop and a valley or depression* ***(circle one)***

5) Estimate the elevation at point C ________

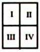
6) Look at the circle to the right of the map and imagine it centered around points T and C. The area around T is ***a)*** *flatter* ***b)*** *more irregular* than the area around C ***(circle one)***

7) Imagine a line from point C to point B. Circle the profile below that most closely matches its slope

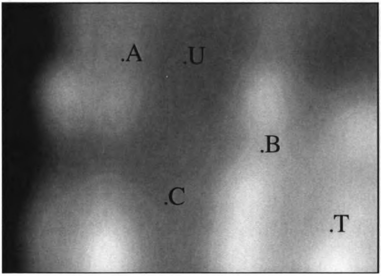
a) b) c) d) e) f)

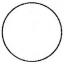


8) Which quadrant is most irregular? ***(circle one)***



9





1) Put an H at the highest point on the map

2) Put an L at the lowest point on the map

3) Imagine a line from point A to point B. This slope along most of this line is generally
a) *uphill* ***b)*** *downhill* ***c)*** *flat* ***(circle one)***

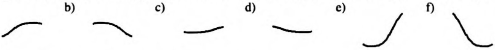
4) Point A is ***a)*** *on a ridge or hilltop* ***b)*** *in a valley or depression*
c) *on a slope between a ridge or hilltop and a valley or depression* ***(circle one)***

5) Estimate the elevation at point C ________

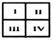
6) Look at the circle to the right of the map and imagine it centered around points T and U. The area around T is
a) *flatter* ***b)*** *more irregular* than the area around U ***(circle one)***

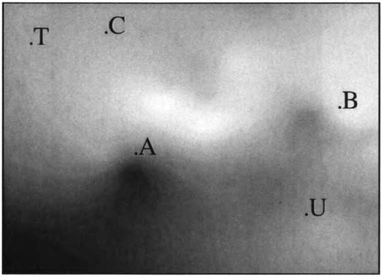
7) Imagine a line from point C to point B. Circle the profile below that most closely matches its slope

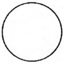
a) b) c) d) e) f)

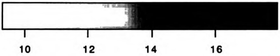


8) Which quadrant is most irregular? ***(circle one)***









1) Put an H at the highest point on the map

2) Put an L at the lowest point on the map

3) Imagine a line from point A to point B. This slope along most of this line is generally
a)** uphill* ***b)** downhill* ***c)** flat* ***(circle one)

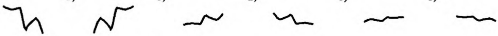
4) Point A is ***a)*** *on a ridge or hilltop* ***b)*** *in a valley or depression*
c) *on a slope between a ridge or hilltop and a valley or depression* ***(circle one)***

5) Estimate the elevation at point C ________

6) Look at the circle to the right of the map and imagine it centered around points T and U. The area around T is
a) *flatter* ***b)*** *more irregular* than the area around U ***(circle one)***

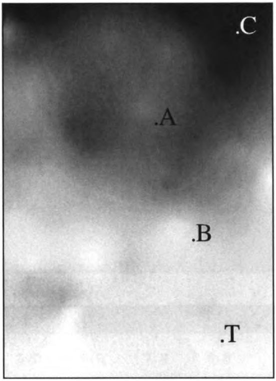
7) Imagine a line from point C to point B. Circle the profile below that most closely matches its slope

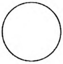
a) b) c) d) e) f)

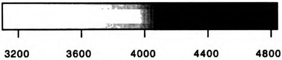


8) Which quadrant is most irregular? ***(circle one)***

I	II
III	IV







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2) Put an L at the lowest point on the map

3) Imagine a line from point A to point B. This slope along most of this line is generally
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4) Point A is ***a)*** *on a ridge or hilltop* ***b)*** *in a valley or depression*
c) *on a slope between a ridge or hilltop and a valley or depression* ***(circle one)***

5) Estimate the elevation at point C ________

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7) Imagine a line from point C to point B. Circle the profile below that most closely matches its slope

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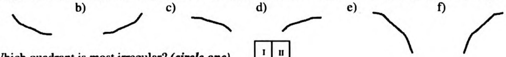
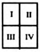
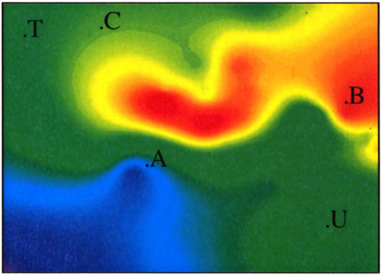
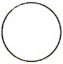
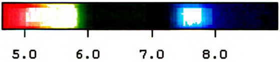


8) Which quadrant is most irregular? ***(circle one)***









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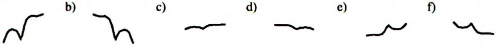
5) Estimate the elevation at point C ________

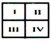
6) Look at the circle to the right of the map and imagine it centered around points T and U. The area around T is ***a)*** *flatter* ***b)*** *more irregular* than the area around U ***(circle one)***

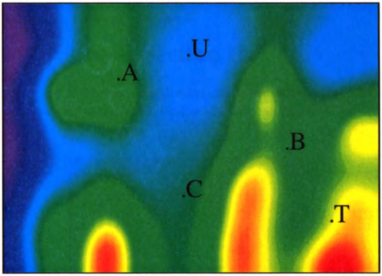
7) Imagine a line from point C to point B. Circle the profile below that most closely matches its slope

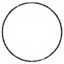
a) b) c) d) e) f)

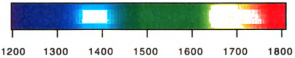


8) Which quadrant is most irregular? ***(circle one)***









1) Put an H at the highest point on the map

2) Put an L at the lowest point on the map

3) Imagine a line from point A to point B. This slope along most of this line is generally
a)** uphill* ***b)** downhill* ***c)** flat* ***(circle one)

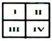
4) Point A is ***a)** on a ridge or hilltop* ***b)** in a valley or depression*
c)** on a slope between a ridge or hilltop and a valley or depression* ***(circle one)

5) Estimate the elevation at point C ________

6) Look at the circle to the right of the map and imagine it centered around points T and U. The area around T is
a)** flatter* ***b)** more irregular* than the area around U ***(circle one)

7) Imagine a line from point C to point B. Circle the profile below that most closely matches its slope
a) b) c) d) e) f)

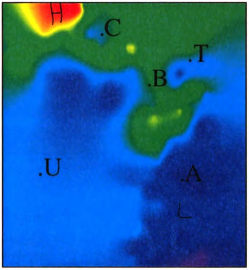
8) Which quadrant is most irregular? ***(circle one)***

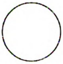


Section II

In this part of the test you will be shown individual maps and asked a series of questions. Circle the correct answer, fill in the blank, or draw on the map as asked.

Example:





1) Put an H at the highest point on the map

2) Put an L at the lowest point on the map

3) Imagine a line from point A to point B. This slope along most of this line is generally
a) uphill b) downhill c) flat (circle one)

4) Point A is ***a) on a ridge or hilltop b) in a valley or depression***
c) on a slope between a ridge or hilltop and a valley or depression (circle one)

5) Estimate the elevation at point C 70

6) Look at the circle to the right of the map and imagine it centered around points T and U. The area around T is ***a) flatter b) more irregular*** than the area around U ***(circle one)***

7) Imagine a line from point C to point B. Circle the profile below that most closely matches its slope

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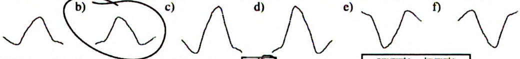
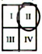
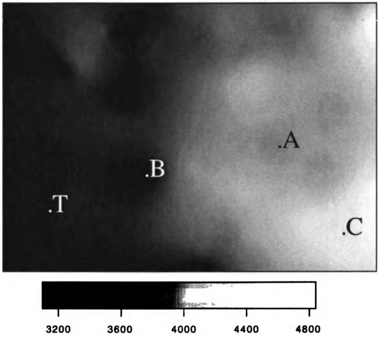
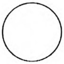


8) Which quadrant is most irregular? ***(circle one)***







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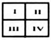

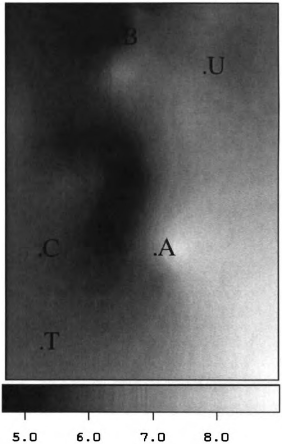

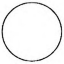

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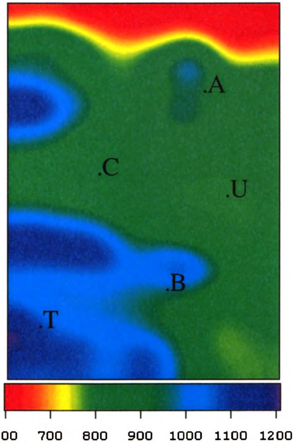

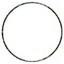

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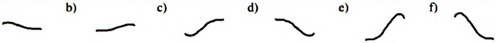

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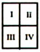

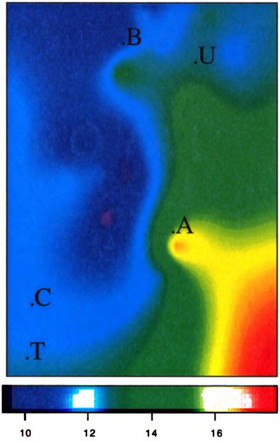

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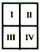

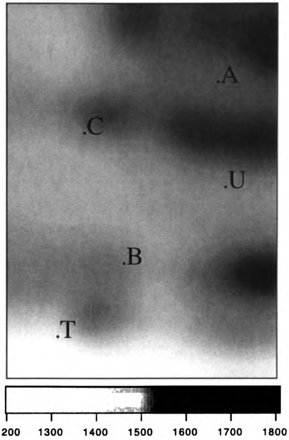

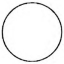

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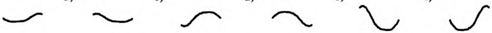

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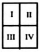

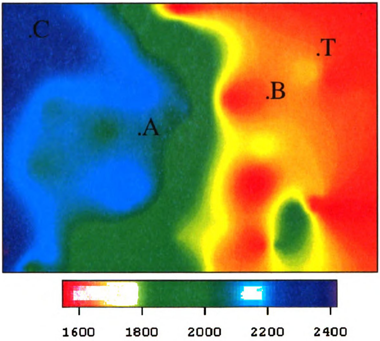

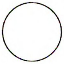

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