This is to certify that the

thesis entitled

An Evaluated Set of Dithered Patterns
For CRT Maps

presented by

Ann Marie Goulette

has been accepted towards fulfillment
of the requirements for

M. A. degree in Geography

Judy M. Olson
Major professor

Date May 13, 1987

AN EVALUATED SET OF DITHERED PATTERNS FOR CRT MAPS

By

Ann Marie Goulette

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF ARTS

Department of Geography

1987

ABSTRACT

AN EVALUATED SET OF DITHERED PATTERNS FOR CRT MAPS

By

Ann Marie Goulette

This research examined a set of patterns created by the dithering technique for use as area symbols on maps displayed on a CRT monitor. Excluding patterns with very coarse texture or disturbing optical effects, a set of twenty-three patterns was initially chosen and subjected to further examination. The evaluation of these patterns focused on value estimation and pattern differentiability. The results indicated that, relative to the percentage of light-colored pixels, subjects underestimated the value of lighter toned patterns and overestimated the value of darker toned patterns. In addition, subjects could easily differentiate twelve patterns from the original twenty-three. The twelve patterns were used as area fill on choropleth maps using five different numbers of classes and seven color combinations. Subjects were asked to match patterns on the map with those in the legend. The maps containing the fewest classes and those with color schemes using dark colors dithered with white had the greatest number of correct matches. Five patterns, two of them solid colors, were correctly matched 95% of the time or better. It was concluded that if a large palette of solid colors is unavailable, dithered patterns can be used effectively for maps requiring a small number of distinguishable patterns.

ACKNOWLEDGEMENTS

I want to thank my advisor, Dr. Judy M. Olson, and Dr. Richard E. Groop for their help throughout my academic career and their guidance on this thesis. In addition, Mr. J. Michael Lipsey had a great influence in my transformation into a cartographer. I am grateful also to the Geography Department of Michigan State University for their efforts to help me think geographically and for their generous grants and student assistantships. I also thank my friends and co-workers for their subtle (and not so subtle) encouragement to complete this thesis. Finally, I thank my parents, Van and Mary Goulette, for their love and care.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Maps have been produced by computers for several decades, but only recently have cartographers begun to display maps on cathode ray tube (CRT) monitors. Recent decreases in price for this technology have made the monitors available to almost every cartographer, but little is known about the limitations of the device for cartographic output. As increasing numbers of maps are made on CRT monitors, solutions must be sought to improve CRT map design.

Perhaps foremost in the cartographic design limitations of inexpensive CRT monitors is their limited color palette. Most common monitors can display only 4, 8, or 16 colors. These color restrictions constrain the cartographer in designing complex or aesthetically-pleasing displays. In particular, the use of cartographic area symbols is severely constrained by narrow color choice because a logical progression of several tones is unavailable. The 4, 8, or 16 colors available on inexpensive CRTs are highly contrasting and very bright when covering large areas on the monitor.

Dithered patterns, commonly used in other computer graphics applications, offer a solution to the limited area symbols available on CRT monitors. The dithering technique uses two or more of the colors available on the CRT to create a pattern. The impression of a greater number of hues is achieved by the viewer's optical mixing of the pattern colors into another hue not in the CRT palette.

There are literally millions of possible dithered patterns, but to use dithered patterns successfully in creating CRT maps, cartographers need sets of patterns that are distinguishable from one another and that form a logical progression from light to dark. The purpose of this thesis is to develop a set of dithered patterns and evaluate their suitability for use as cartographic area symbols.

Historical Context of Cartographic Area Symbols Produced by Computers

The search for suitable cartographic area symbols from computer graphics output devices is not a novel idea. As each new technological advance made its way into the marketplace, cartographers were ready to use the devices for mapping applications. In general, early research on area symbols on a particular device yielded unsatisfactory results; further research focused on improving the output given the constraints of the device.

In the late 1960's computer maps were made with line printers, the only available output device at the time, using mapping packages such as SYMAP. A milestone in computer mapping software, SYMAP was written to produce choropleth, isoline, or proximal maps on the line printer. Area symbols for these maps consisted of repetitive printing of elements of the character set of the printer. The output was coarse and blocky and offended the aesthetic sense of many cartographers (Carter, 1984, p.44).

Refinements to line printer map output are documented in the literature. Smith (1980) has found that SYMAP output can be improved by selecting alternative symbols that enhance the gray tone contrast rather than accepting the default symbols. In some instances where line printers were used for making maps, special modifications were made to line printer characters to produce better cartographic symbols (Brassel, 1974). Many users also improved the image by photographically reducing output, thus making it appear less blocky.

An important advance in computer hardware for mapping was the development of pen plotters. This device enabled the cartographer to plot lines or vectors that resembled hand-drawn lines and offered a choice of pen widths and colors. In many cartographic applications, particularly in the display of base map material, plotter-drawn lines were an aesthetic improvement over line printer symbols.

However, drawing lines did not answer the problem of creating attractive area symbols. Area fill patterns produced by such packages as CALFORM and SAS/GRAPH are limited to those created by drawing stripes or cross-hatching in various orientations. Various densities of patterns are created by varying the spacing of the lines. When few lines are used, the patterns appear coarse; when many lines are specified, plotting time is considerable and so much ink is used that the paper can tear easily.

The invention of the microchip and the proliferation of the microcomputer in the last decade has brought another output device into the hands of most cartographers: the dot-matrix printer. The dot-matrix printer, like the line printer, forms characters by a succession of firings of vertical pins (often nine vertical pins fired six times). The advantage of the dot-matrix printer over the line printer is that software can be written to fire the pins individually. This allows the creation of a wide range of patterns. Recent cartographic research focusing on the use of the dot-matrix printer for creating pattern fills for mapping includes the works of Groop and Smith (1982) and Plumb and Slocum (1986). Both describe improvements in area symbolization for dot-matrix printer maps. Groop and Smith created regularly-spaced pattern fills; Plumb and Slocum produced fill patterns using a random-dot approach.

The Cathode Ray Tube (CRT) Monitor

Like the dot-matrix printer, the cathode ray tube monitor was also made available through the proliferation of the microcomputer. The CRT is available in alphanumeric mode (which is of little use to cartography), graphics mode, or both. The monitors also come with monochrome or color capabilities. Regardless of these differences, however, the CRT display image is created by a scanning electron beam directed at the monitor's screen.

Two factors affect the ability to create area symbols on CRTs: the resolution of the screen and the number of available colors. Resolution refers to the smallest readable character that can be displayed and the minumum spacing (vertical and horizontal) that can be discerned (Machover, 1977). The resolution of CRT monitors is measured in picture elements, or pixels. Expensive monitors often have higher resolution than less expensive models. For example, a Tektronix 4115B monitor has a resolution of 1280 x 1024 pixels; an IBM-PC microcomputer CRT has a resolution of 320 x 200 pixels in the color graphics mode.

Even on the most expensive monitors, individual pixels are evident on CRT images, giving a jagged or stair-step effect. Some sophisticated software for expensive monitors employs a technique called "anti-alaising," which utilizes varying colors or intensities of adjacent pixels to lessen the jagged appearance of lines and highly contrasting colored areas. The inexpensive monitors have neither sufficient resolution nor the color capacity to perform this technique.

CRT hardware devices also vary greatly in the number of colors that can be displayed. Inexpensive monitors available today can display 4, 8, or 16 colors. More expensive monitors can display 256 colors or more, chosen from palettes in the thousands to millions. The variation in the number of colors and the number of colors available simultaneously is not due so much to the hardware, but to the amount of memory allocated for this purpose. Gray-scale (intensity) and color can require from 3 to 12 bits of memory per pixel (Hobbs, 1981). Monitors having high resolution and a large number of available colors require large amounts of memory that are generally not available in inexpensive systems.

This lack of a full palette of colors severely limits the complexity of maps that a cartographer can make with inexpensive CRTs. Using an IBM-PC color monitor with a simple color board, for example, one must choose one of two four-color schemes. One color scheme offers black, yellow, red, and green; the other consists of black, white, cyan, and magenta. Using these colors as areal fills, the cartographer can produce only a 3-class choropleth map if the linework and lettering are highlighted in a color of their own. Cartographers frequently make maps requiring considerably greater complexity than this.

In addition to the problem of few colors available, colors such as black, yellow, red, and green in combination are unattractive. On the most common monitors, the colors are of high saturation or chroma, which few cartographers find appealing when used in combination with one another.

The cartographer's options for CRT displays are limited not only by hardware, but also by software and programming languages available for the microcomputer. Both MS-BASIC and TURBO PASCAL support graphics capability on CRT monitors. But neither allows the programmer to draw lines or fill areas (using the convenient line drawing and area fill commands) with anything but solid colors. Clearly, if color CRT monitors are to be more useful for cartography, new solutions for areal symbolization must be found through specialized computer graphics programs.

Dithering as a Proposed Improvement for Cartographic Area Symbols on CRT Monitors

One solution for improved area symbols on CRT displays may be in the computer graphics technique called "dithering" or halftoning. Dithered patterns are created by interspersing pixels of different colors or intensities. Dithering can refer to pixels arranged into repetitive patterns, to arrangements of randomly mixed pixels of different colors, or to pixels arranged to appear to grade from one color into another.

Dithering has been used previously in several computer graphics applications. It has been used typically to display three-dimensional graphics and solid modeling on computer monitors (Ryan, 1983) and in computer art and animation.

Dithered patterns are currently available for use on some microcomputers, such as the Apple Macintosh and the Tektronix 4115B. The Apple Macintosh uses dithering in its MacDraw and MacPaint software applications. Graphics software for the Tektronix 4115B has several dithered and hatched patterns available for use. In addition, both the Macintosh and the

Tektronix 4115B software allow the user to define new patterns.

Despite this availability of dithered patterns, a survey of recent mapping software reveals little use of the patterns. Jensen (1986) notes that MICROPIPS Version 1.0, an image processing package written for the IBM-PC, makes it "difficult to select a group of colors using the standard IBM color palette that will give the impression of a graded progression from low to high brightness values." Jensen views MICROPIPS' inability to display shades of grey and the IBM's limited palette of 16 colors and low resolution as serious disadvantages for digital image processing. These disadvantages restrict the usefulness of the software for its intended purpose.

Several other reviewers note the lack of patterned area symbols in graphics software. Groop (1985) reviewed the Desktop Information Display System (DIDS) Version 2.0 using an IBM-XT with a standard 4-color card. He notes that the "maps displayed were solid-filled areas rather than IBM 'tiling' [dithered] patterns, thereby limiting choropleth symbols to three distinct classes." Similarly, the program PRODESIGN II, a computer-aided design package, does not support line, dot or hatch patterns to fill areas (Gossette, 1986).

At least three software systems employ patterns to fill areas. AutoCAD has several hatch patterns to fill any shape (Morrison and Mendoza, 1986), as does Atlas AMP (Foote, 1985). These hatch patterns, however, are not true dithered patterns. The patterns consist of cross-hatched lines, a throw-back to the pen plotter hatch fills.

The ODYSSEY system, created by the Harvard Laboratory for Computer Graphics and Spatial Analysis, does use a true dither. The POLYPS component of the system allows the user to choose dots, lines, or patterns to fill areas (White, 1980). The patterns consist of regularly spaced light-colored pixels on a background of dark-colored pixels.

Research on CRT Color Displays

Even though CRT images are gaining acceptance and popularity, only a few studies have been conducted on the perceptual aspects of the monitor displays. The work of Haber and Wilkinson (1982) offers practical advise based on color theory in the design of CRT images. They suggest that programmers carefully choose colors, intensities, textures, and shadings to maximize contrast between adjacent features on the display. The study does not produce empirical evidence for their claims of improvement in CRT image design. Indeed, Haber and Wilkinson admit that the lack of research in this area makes design choices "more of an art than a science."

Another descriptive study focuses on the use of pattern on CRT monitors. Truckenbrod (1981), an artist and computer graphics designer, has employed the pointillist theory of the French Impressionist painters in her study of effective use of color on CRT monitors. Using three sets of two-color dithered patterns, she has shown how the technique can effectively change the appearance of hue, value, and chroma. She has varied the percentages of two colors of pixels in inverse proportions to one another from 0% to 100%. She states that the apparent changes in hue, value, and chroma are the result of the viewer's optical mixing of the two colors, perceiving a color different than the two that it comprises.

While Truckenbrod's patterns do effectively vary pixel color densities, they can be described as coarse or "busy." Many of the patterns have definite repetitive shapes within the overall pattern, creating the appearance of rosettes, shells, and leaves. Although textural patterns are often appropriate in general graphic usage, these obvious sub-elements make the patterns unsuitable for mapping.

Murch (1984) describes ways that color can be used effectively on CRT images. He notes that hue information is lost for small areas on the CRT and that not all colors are equally legible or readable. In contrast to his mostly intuitive suggestions, he quantified the amount of luminance (light emitted) for eight colors displayed on a CRT. Luminance values (cd/m^2) range from 0 for black to 10 for white. Examples of intermediate values are 7.6 for yellow, 4.7 for red, and 2.7 for blue. These measures have implications for how CRT colors may be used and perceived when viewed in combination. Small areas of any color will be difficult to perceive. In addition, the contrast of luminance between areas of different colors on the CRT may affect color perception.

Taylor (1983) points out a woeful lack of cartographic research on the CRT. He argues that "as cartographers we must not simply take the approach of modifying our existing maps to display them on [CRTs] -- we must also seek new solutions utilizing the strengths of the new medium." He cautions against the easy misuse of color on the monitors and calls for more cartographic research on color. Basic research on CRT maps, he says, will help the cartographic designer make better maps.

McGranaghan is one of the few cartographers working on CRT map design. In an article written in 1985, he investigated the effect of CRT background color on the map reader's impression of "dark is more" on choropleth maps. He concluded that dark is more when the CRT background is light; conversely, more than 50% of his subjects felt that "light is more" against a dark background (McGranaghan, 1985). He has

also evaluated the applicability of traditional color use guidelines to maps produced on CRT monitors. Based on a reaction-time experiment, he concluded that maps that vary symbols by saturation require more time to evaluate than maps that vary by value only (McGranaghan, 1986). In both studies, McGranaghan used only solidcolor area symbols.

The Problem

The general lack of research on CRT monitors and cartographic use of the device and the unsatisfactory nature of solid-color fill as cartographic area symbols on inexpensive devices have led to the research reported in this thesis. Because so little is known about the device and the patterns the inexpensive but ubiquitous CRT can produce, the goals of this research were to create a reasonable set of dithered patterns on an 8-color monitor and to evaluate them within the context of use on CRT choropleth maps. Two overriding questions were involved: how many patterns would be available (i.e., how many in a light-to-dark progression would be distinguishable), and how effective would they be when used in a map context.

Structure of the Thesis

Chapter 1 has included a brief look at the historical context of the problem, stressing the adjustments that have taken place as computer technology used in mapping has changed. It has also reviewed the literature most closely related to the thesis topic and has stated the thesis problem.

Chapter 2 covers the several basic steps that had to be taken to create the dithered patterns for this research. Computer software development, initial selection of patterns, and development of a hardcopy procedure for testing the patterns will be discussed.

Chapter 3 presents tests concerned with general perceptual parameters of the dithered patterns. In particular, value estimation, pattern differentiation, and color preference are investigated. Subjects were asked to estimate value percentage of patterns, distinguish differences between two patterns and choose a color scheme preference from seven color schemes. The results of this preliminary testing are intended to further narrow the range of dithered patterns appropriate for mapping.

Chapter 4 presents the test evaluating the patterns in a cartographic context. The patterns are used in combination with one another on classed choropleth maps to investigate which patterns are most easily differentiated and which color schemes are most preferred. Color schemes are also investigated for differences in correct pattern matching responses.

Chapter 5 summarizes the research and presents conclusions. The evaluated set of dithered patterns as cartographic area symbols is discussed, and suggestions are given for potential cartographic applications of the patterns and for possible future research to refine them.

CHAPTER 2

PRELIMINARY STEPS:
DEVELOPING TEST MATERIALS

The nature of this research necessitates that several steps must precede the experimentation. Software must be written to display the dithered patterns. Patterns of potential use for cartographic purposes must be chosen from the numerous ones possible, and the component colors must be selected. Also, an appropriate method to record the CRT images for testing purposes must be defined. This chapter describes the work conducted prior to testing dithered patterns with subjects.

Equipment

Because computer equipment and especially color CRT monitors, differ widely in their capabilities, it is necessary to describe in detail the properties of the equipment used throughout this study. The display of patterns and analysis of data was accomplished on a Texas Instruments Professional Computer (TIPC) with 192K random access memory, a color adapter, and Texas Instruments color monitor. The color monitor features an 8-color palette; all eight colors can be displayed simultaneously on the screen. The resolution of the monitor is 300 pixels vertically by 720 pixels horizontally. The screen measures 13 inches diagonally. The operating system for the computer was MS-DOS, Version 1.10. Software was written using the MS-BASIC, Version 1.10 programming language.

Software

Two original programs were required for this study. One program was written to do basic design work on dithered patterns. The other program was needed to display dithered patterns in a cartographic context.

The program for designing the various dithered patterns is found in Appendix A. In essence, the program will display a square containing a dithered pattern using a triangular lattice arrangement of two colors of pixels from the monitor's palette. Figure 1 contains a black and white simulation of the display's image. The program prompts the user to enter the number of the chosen foreground and background colors and the horizontal and vertical increments for the arrangement of the foreground pixels. The program then fills a square on the screen with the background color and continues by coloring the pixels with the foreground color in the increments specified. Any color combinations and increments (up to the size of the displayed square) can be specified to create a large number of patterns.

The program to fill a base map with dithered patterns is more complex. This program had to fill irregular polygons with the pre-specified patterns. Therefore, a polygon-fill algorithm had to be merged with the dithered pattern algorithm used in the pattern development work. The resultant algorithm was required to fill the polygons pixel by pixel to create the patterns.

The software written to fill polygons with the dithered patterns was based on an algorithm by Pavlidis (1979, 1982). Appendix B contains the programming code to create a 4-class choropleth map. Within a pre-established maximum-minimum x-y pixel window for each polygon, the algorithm checks the color of each pixel inside the window against the

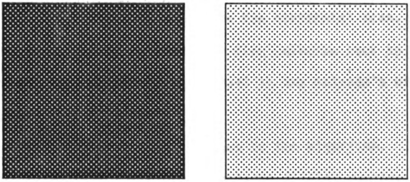


Figure 1. Simulated examples of light-background and dark-background dithered patterns using a triangular lattice arrangement of pixels. This figure was constructed using an Apple Macintosh computer and LaserWriter printer.

color of the polygon's boundary pixels. Moving horizontally across a tier of pixels, a flag is set to "even" until a pixel of the boundary color is encountered. At that point, the flag is set to "odd" and the pixels above and below the pixel are checked to determine if the original pixel is a minimum or maximum point of the polygon. If the pixel is inside the polygon, it is colored appropriately for the selected pattern, as are the other interior pixels in the horizontal scan. When another boundary pixel is encountered, the flag switches back to "even." The procedure continues until every pixel in the polygon's window has been processed.

There are several disadvantages to the algorithm. In his articles, Pavlidis noted that raster-based polygon filling routines are "non-trivial" and often do not work perfectly in practice. Some complex polygons do not fill correctly and require decomposition into simpler shapes. This decomposition creates a greater number of polygons to fill and adds processing time to an already time-consuming algorithm. In addition, the algorithm works best in a recursive language like Pascal or Forth and is therefore complicated to write in Basic. Nevertheless, it fulfilled the needs of the work being performed here and the Basic language was used.

The Patterns

The use of patterns as cartographic symbols is certainly not new. The literature of the past 25 years is replete with studies involving the use of patterns on maps. Because no comparable literature is available to guide the choice of patterns for mapping on CRTs, a brief review of literature on the perception and preferences of subjects for patterns is presented here as background to the choice of patterns in this research.

The perception of several pattern variables has been studied by many researchers. Williams (1958), for example, sought a psychophysical function to describe the differences between the actual percentage of area inked on a pattern versus the subject's estimate of the darkness of the area. Williams found that the relationship was non-linear; subjects overestimated the lighter values and underestimated the darker values.

Castner and Robinson (1969) identified six basic characteristics of dot patterns: 1) the form of the dots; 2) the size of the dots; 3) the linear distance between the dots; 4) the arrangement of dots; 5) the orientation of the arrangement; and 6) the pattern-value of the dot area symbol. The sixth characteristic, pattern-value, refers to the "total impression of gray value which results from the visual integration of the form, size, spacing and arrangement of the dots and from the orientation of the arrangement." The authors stated that the perception of the visual pattern of the dots and the gray value of the pattern is greatly dependent upon the textural characteristics of the pattern. As dot spacing increases, the texture or arrangement of the dots themselves, rather than value, is the first thing a map reader perceives. They added that patterns with fewer than 40 lines per inch will be perceived first as patterns of dots and "only with difficulty can a gray tone be perceived."

Dent (1985, p. 213) discusses whether patterns need to be differentiable on a map. The school of thought that views the map as an areal table carries the idea that each pattern must be visually discernable from its neighboring patterns. The other school concentrates on the overall geographical distribution of data on the map. To them, pattern differentiability is not as important.

Jenks and Knos (1961) found that map users prefer dot patterns to linear or irregular patterns in a graded series. In addition, user preferences tended toward uniform texture among patterns of a series and toward fine, rather than coarse, textures.

Clearly, a broad and evolving literature exists on the use of areal symbols in cartography. How this body of research fits into the design of CRT area symbols is not so clear.

Several problems are immediately apparent in applying this body of knowledge to dithered patterns on CRT monitors. First, the CRT works with emitted light, not reflected light as in the printed products used in the studies mentioned. The resolution of the CRT is fixed (on the TIPC there are approximately 75 pixels per inch horizontally and 43 pixels per inch vertically) while in printing, screens with different numbers of lines per inch are available. In addition, color is very available on the CRT and any number of versions of a map can be displayed virtually without increasing cost; great expense can be incurred when changing colors on printed maps. Also, with the default color of the CRT screen being black (it can be any other available color if the user specifies, however), dark is no longer "more", a tenet of cartographic convention associated with printed maps.

Despite the fact that many accepted conventions and practices can not be directly translated to CRT images, previous research was helpful in designing the dithered patterns tested in this study. As Castner and Robinson (1969, pp. 10-11) suggest, the type of area symbols chosen for basic research "should be the simplest, most fundamental form of mark arranged in the simplest, most uniform manner; only in this way can one eliminate, or reduce as much as possible, any distractions or undesirable associations produced either by the character of the marks or their arrangement." Similarly, Jenks and Knos advocate use of regularly spaced dot patterns with fine texture.

The patterns of this study were limited to dot patterns with the elements arranged in a triangular lattice (as shown in Figure 1). By using different densities of pixel spacing in the lattice, the patterns were also restricted to vary only in value. The dark colors (royal blue, red, and magenta) were dithered with white pixels; the light colors (white, green, yellow, and cyan) were dithered with black pixels. There is no reason that all of the eight colors on the monitor could not be combined in multiples or pairs, but the progression would not go from light to dark (and neutral to saturated or vice versa).

Table 1 shows the horizontal and vertical increments of foreground pixels of patterns first chosen for possible inclusion in this study. These patterns were displayed on the CRT using a program similar to that in Appendix A and were judged (by me only) for suitability for mapping.

Obvious problems with some of these patterns were immediately apparent. As Tufte (1983) forewarns, computer displays often contain "unintentional optical art" in the form of vibrating or moiré patterns. These disturbing effects are one type of graphic noise that Tufte calls "chartjunk." Slocum and McMaster (1986) have noted these effects also and state that "apparent pattern in a symbol implies a qualitative characteristic that (is) inappropriate for quantitative data." Several of the dithered patterns observed on the CRT monitor contained patterns and moirés, some more severe than others. In addition, the regular spacing of the pixels of the patterns eliminated all but one pattern between the values of 25% and 75%.

TABLE 1

Distribution of Foreground and Background Pixels
in Preliminary Dithered Patterns

Light Foreground/Dark Background

Pattern Number	Horizontal Increment	Vertical Increment	Value %
1	(all pixels dark)		0.0 %
2	10	3	3.3 %
3	10	2	5.0 %
4	10	1	10.0 %
5	8	3	4.2 %
6	8	2	6.2 %
7	8	1	12.5 %
8	6	3	5.5 %
9	6	2	8.3 %
10	6	1	16.6 %
11	4	3	8.3 %
12	4	2	12.5 %
13	4	1	25.0 %
14	2	3	16.6 %
15	2	2	25.0 %
16	2	1	50.0 %

Dark Foreground/Light Background

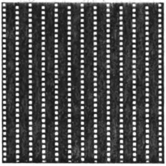
Pattern Number	Horizontal Increment	Vertical Increment	Value %
17	2	2	75.0 %
18	2	3	83.4 %
19	4	1	75.0 %
20	4	2	87.5 %
21	4	3	91.7 %
22	6	1	83.4 %
23	6	2	91.7 %
24	6	3	94.5 %
25	8	1	87.5 %
26	8	2	93.8 %
27	8	3	95.8 %
28	10	1	90.0 %
29	10	2	95.0 %
30	10	3	96.7 %
31	(all pixels light)		100.0 %

Figure 2 shows simulated examples of dithered patterns that required further consideration. The first pattern (4) is representative of a group (Patterns 4, 6, 25, and 28 from Table 1) that contained visible vertical stripes. The second (14) is representative of a group (Patterns 11, 14, 15, 17, 18 and 21) that had horizontal stripes. Patterns 13 and 19 had a diamond-shaped pattern within them. Numbers 15 and 17 had an "op art" look and pattern 16 had elliptical shapes within it. The diamond patterns of 13 and 19 were judged to be acceptable, but the other patterns were dropped from further consideration.

The elimination of the disturbing patterns from the study removed the 50% value pattern and left a gap in the value spectrum. All patterns between 25.0% and 75.0% value had been dropped. This problem was also encountered in the research of Plumb and Slocum (1986) on regularly spaced dot patterns for dot-matrix printers. To fill the gap in values, they designed new patterns. These patterns continued to have regularly spaced elements, but contained much more texture than the original patterns.

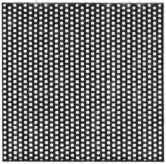
The need for middle-range value patterns led me to design new patterns also. An alternative pattern was designed to replace the 50.0% pattern. New patterns were created to represent 40.0% and 60.0% values. All three of these patterns are simulated in Figure 3. Although these patterns do contain obvious textural differences from the other patterns, the new 50% value pattern seemed less disturbing than the pattern that it replaced. The 40% and 60% value patterns were designed to fill in the gaps in the value spectrum.

Figure 4 shows simulations of the 23 patterns chosen to begin the study. Since the overriding questions were how many patterns would be distinguishable and how successful would they be in a map context, 23 seemed a

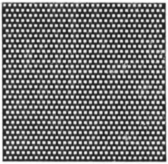


a) Pattern 4

b) Pattern 14



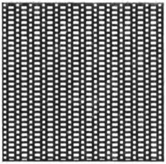
c) Pattern 13



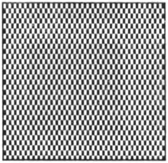
d) Pattern 15

e) Pattern 16

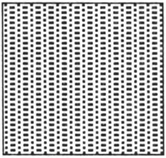
Figure 2. Simulated dithered patterns with disturbing optical effects. a) Vertical stripes; b) Horizontal stripes; c) Diamond shapes; d) Op art; and e) Elliptical shapes. The figure was constructed with an Apple Macintosh computer and LaserWriter printer, which make the patterns look different than on the Texas Instruments Professional Computer monitor. In particular, the optical effects of patterns 13, 15, and 16 were much more pronounced on the monitor.



a) 40% Pattern



b) 50% Pattern



c) 60% Pattern

Figure 3. Redesigned patterns with middle-range values (simulated).

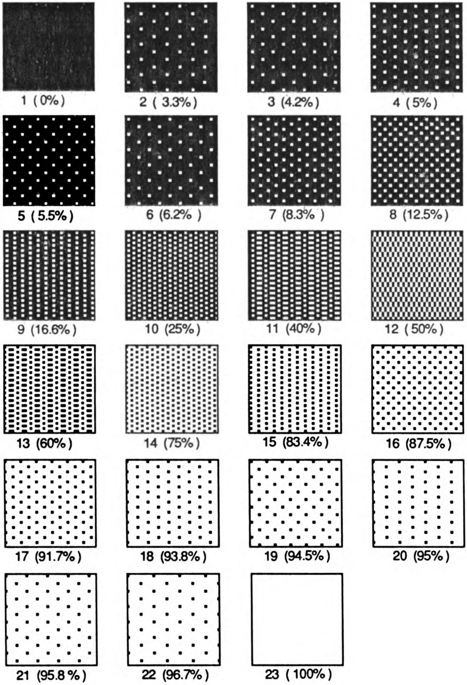


Figure 4. Test patterns for Study 1(simulated). The numbers in parentheses indicate the value percentage of the patterns.

reasonably generous but not overwhelming number with which to work. The patterns range from 0% to 100% with most of the patterns under 25% or over 75%. The pixel arrangements of these patterns is shown in Table 2.

The Slides

Photographic slides were chosen as the medium for presenting the dithered patterns to human subjects. Slides have the advantages of being inexpensive, simple to make, and time-efficient to use for testing. In addition, they are a common medium for displaying the results of CRT mapping to large numbers of viewers.

The way in which CRT monitors display an image determines how photographs of the screen can be made. The CRT image is produced by an electron beam that quickly scans the surface of the tube. The beam produces only half of the image at a time, however. The beam scans every other line and then returns to scan the remaining lines. The appearance of a static image is created by the rapidity of these beam passes relative to the speed with which the eye-brain system processes the image. The interleaving process (i.e., display of the full image) takes between 1/25 and 1/30 second. If shutter speeds faster than 1/30 second are used to take the photograph, the image may be incomplete on the slide, but if slower speeds are used, at least one complete scan will occur while the shutter is open and a clear and complete image will result.

An article in a photographic magazine (Photo, Vol. 5, Issue 67) makes several suggestions for making successful slides from television screens with equipment most photographers possess. The article suggests darkening the room, eliminating light from windows and lamps to lessen reflections on the screen surface, and providing a black background to

TABLE 2

Distribution of Foreground and Background Pixels
in Dithered Patterns Chosen for Study

Light Foreground/Dark Background

Pattern Number	Horizontal Increment	Vertical Increment	Value %
1	(all pixels dark)		0.0 %
2	10	2	3.3 %
3	8	3	4.2 %
4	10	2	5.0 %
5	6	3	5.5 %
6	8	2	6.2 %
7	6	2	8.3 %
8	4	2	12.5 %
9	6	1	16.6 %
10	4	1	25.0 %
11*			40.0 %
12**			50.0 %
	Dark Foreground/Light Background		
13*			60.0 %
14	4	1	75.0 %
15	6	1	83.4 %
16	4	2	87.5 %
17	6	2	91.7 %
18	8	2	93.8 %
19	6	3	94.5 %
20	10	2	95.0 %
21	8	3	95.8 %
22	10	3	96.7 %
23	(all pixels light)		100.0 %

* Foreground pixels distributed differently over 2 consecutive rows. Row 1 - foreground pixel every fifth pixel; Row 2 - two adjacent pixels of foregound color, followed by three adjacent pixels of background color.

**A four-row repeat checkerboard pattern. Rows 1 and 2 - one pixel of foreground, one pixel of background; Rows 3 and 4 - one pixel of background, one pixel of foreground.

flatten out the rounded shape of the screen. The effect of the shape of the screen can be also lessened by using a telephoto lens. It is necessary to use a tripod because of the slow shutter speed required. The camera back should be aligned parallel to the surface of the screen. With stationary objects, 1/8 second exposures are recommended. Bracketing exposure times using varying f-stop intervals ensures at least one good slide; F/5.6 is offered as a good starting point.

For the test slides, I used Kodak Ektachrome (ASA 64) film, which produced slides with colors very similar to the monitor. This was confirmed by Carter (1984, p. 13), who suggests that "daylight film has the proper balance for raster-scan CRTs." Using a camera with a 50mm lens and tripod, a complete set of slides was photographed at F/5.6 at 1 second for use in the study described in the next chapter.

CHAPTER 3

EVALUATION, PART I:
VALUE ESTIMATION, PATTERN DIFFERENTIATION, PREFERENCE

The selection of dithered patterns for cartographic area symbols in this study, although based on the results of previous cartographic research has been intuitive. Many questions remain regarding the choice of appropriate dithered patterns for cartographic use.

The research discussed in this chapter investigates some perceptual properties of the chosen dithered patterns. In particular, value estimation of a set of monochromatic patterns in several color schemes, differentiability of the patterns from one another, and the subject's preference for particular color schemes used in the patterns will be studied in this chapter.

Method

TEST SLIDES

Three types of slides containing images of dithered patterns displayed on a CRT monitor were shown to subjects to solicit value estimation of the patterns and evaluate pattern differentiation. For convenience, these slide types will be called Type A, B, and C. Samples of the slide types are contained in an envelope on the back inside cover of the thesis.

The Type A slide contained a set of seven royal blue/white dithered patterns ranging in value from 0% blue to 100% blue. Patterns 1 (0%), 2 (3.3%), 7 (8.3%), 12 (50%), 17 (91.7%), 22 (96.7%), and 23 (100%) were displayed. The slide was used to assess subjects' perception of value percentage of the patterns presented. There was only one slide of Type A.

Type B slides contained the same seven royal blue/white patterns as on the Type A slide below another set of identically formed patterns in another color scheme. These slides were used to determine if the value of the patterns was perceived differently using different colors in comparison to the royal blue/white patterns and if the new color scheme yielded more, less, or the same amount of differentiability between patterns. There were six slides of Type B. The color schemes of the other (non-royal blue/white) value scale were: 1) magenta/white; 2) yellow/black; 3) white/black; 4) cyan/black; 5) red/white; and 6) green/black.

Type C slides contained two boxes filled with royal blue/white dithered patterns, which were labelled "A" and "B". Each pattern in the test was paired with itself and with each of the five most adjacent value percentage patterns. Table 3 shows the 123 pattern pairs made into slides. These slides were used to judge differentiability between the patterns chosen for the study.

SUBJECTS

The 64 subjects taking the test were undergraduate students, graduate students, and faculty members of Michigan State University. Most subjects were affiliated with the Geography Department, and of these, many were cartography students. Thirty-six subjects were male; twenty-eight were female.

Because of the large number of Type C slides, the slides were split into two groups for testing to reduce the response burden per subject. One group

TABLE 3

Pattern Pairs Chosen for Study

PATTERN NUMBER

PATTERN NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	x	x	x	x	x	x																	
2		x	x	x	x	x	x																
3			x	x	x	x	x	x															
4				x	x	x	x	x	x														
5					x	x	x	x	x	x													
6						x	x	x	x	x	x												
7							x	x	x	x	x	x											
8								x	x	x	x	x	x										
9									x	x	x	x	x	x									
10										x	x	x	x	x	x								
11											x	x	x	x	x	x							
12												x	x	x	x	x	x						
13													x	x	x	x	x	x					
14														x	x	x	x	x	x				
15															x	x	x	x	x	x			
16																x	x	x	x	x	x		
17																	x	x	x	x	x	x	
18																		x	x	x	x	x	x
19																			x	x	x	x	x
20																				x	x	x	x
21																					x	x	x
22																						x	x
23																							x

of subjects was tested using the Type A slide, the six Type B slides, and 60 Type C slides. The other group was tested using the Type A slide, and 63 Type C slides.

TESTING ENVIRONMENT

Testing was conducted in the late afternoon in a small room darkened for viewing the slides. The slide projector was positioned approximately 8 feet away from the screen, which in combination with the focal length of the projector lens created an image approximately 24 by 16 inches on the screen. Subjects sat between 8 and 16 feet away from the screen. They were tested in small groups; no group contained more than 6 subjects. Testing lasted approximately 25 minutes.

PROCEDURE

After all subjects for a session were seated in the testing room, the door was closed and a brief explanation of the study was given. The subjects were told that this was an experiment about the use of patterns on CRT monitors and that they would look at slides of the patterns and answer some simple questions about them. Each subject was given a consent form to sign (See Appendix C), a test booklet (See Appendix D), and a pencil. They were told that they could ask questions at any time during the session.

The room was darkened and the slide projector turned on. The subjects were asked if they felt that they could read the text on the test booklet and yet view the slides easily.

Subjects were also told to write in the margins of the test booklet any comments they had on the testing itself, any vision problems they had (especially color deficiencies), and any preferences they had for particular patterns or color schemes as they looked at the slides.

The subjects were then instructed to read the first set of directions on the test booklet, and the first slide (Type A) was presented. Using this slide, subjects were to estimate the value percentages of the five patterns between solid color and solid white.

After all subjects had completed their answers on the first slide, they were asked to read the second set of directions. (Note: The second group of subjects was not tested on this section.) As before, the subjects were to estimate the value percentages of five patterns. However, they were also asked to determine if the patterns in the new color scheme were more or less differentiable than the royal blue/white patterns, or about the same. Six slides were presented.

Both testing groups were asked to read the next set of directions on the testing booklet. Subjects viewed slides with two dithered patterns to determine if the patterns contained the same value percentage of blue. If the patterns were considered to contain different percentages, subjects were to determine which of the patterns contained the higher percentage of blue. Subjects were verbally instructed to make a "first impression" type of answer, and that each slide would be presented for only 10 seconds. Sixty Type C slides were shown to the first group of subjects; sixty-three to the second group.

Results

The results of the value estimation experiment of the royal blue/white patterns are shown in Table 4. Using a two-tailed t-test with 60 degrees of freedom, all of the estimated means of value percentage were determined to be significantly different from the actual value at the

TABLE 4

Estimates of Value Percentages of Royal Blue/White Patterns
(N = 63)

	Pattern 2 (3.3%)	Pattern 7 (8.3%)	Pattern 12 (50.0%)	Pattern 17 (91.7%)	Pattern 22 (96.7%)
$\overline{X}$	17.10	30.59	55.35	81.75	89.57
s	9.65	10.56	9.74	10.84	5.46
t	-11.28*	-16.75*	-4.36*	7.29*	10.37*

* $p \leq .025$

TABLE 5

Estimates of Value Percentage for Different Colored Patterns
(N = 34)

Pattern Colors	Statistic	Pat. 2 (3.3%)	Pat. 7 (8.3%)	Pat. 12 (50.0%)	Pat. 17 (91.7%)	Pat 22 (96.7%)
Magenta/ white	$\overline{X}$	17.88	28.97	58.82	84.82	90.21
	s	10.62	13.70	14.83	9.97	6.03
	t	-8.01*	-8.80*	-3.47*	4.02*	6.28*
Yellow/ black	$\overline{X}$	15.88	30.29	58.53	82.22	89.00
	s	10.48	14.92	16.07	12.56	7.16
	t	-7.00*	-8.59*	-3.09*	4.40*	6.27*
White/ black	$\overline{X}$	15.97	32.26	57.18	83.26	89.53
	s	11.06	18.01	15.40	12.24	6.68
	t	-6.68*	-7.76*	-2.72*	3.85*	6.26*
Cyan/ black	$\overline{X}$	15.09	28.12	54.71	81.74	89.00
	s	11.91	14.53	11.07	13.34	7.44
	t	-5.77*	-7.95*	-2.48*	4.35*	6.03*
Red/ white	$\overline{X}$	14.97	28.38	55.35	83.15	89.68
	s	10.11	13.18	13.90	11.57	5.99
	t	-6.73*	-8.88*	-2.24*	5.32*	6.83*
Green/ black	$\overline{X}$	12.12	24.47	53.53	82.94	88.91
	s	10.22	13.79	15.50	12.89	7.65
	t	-5.03*	-6.84*	-1.33	3.96*	5.94*

* $p \leq .025$

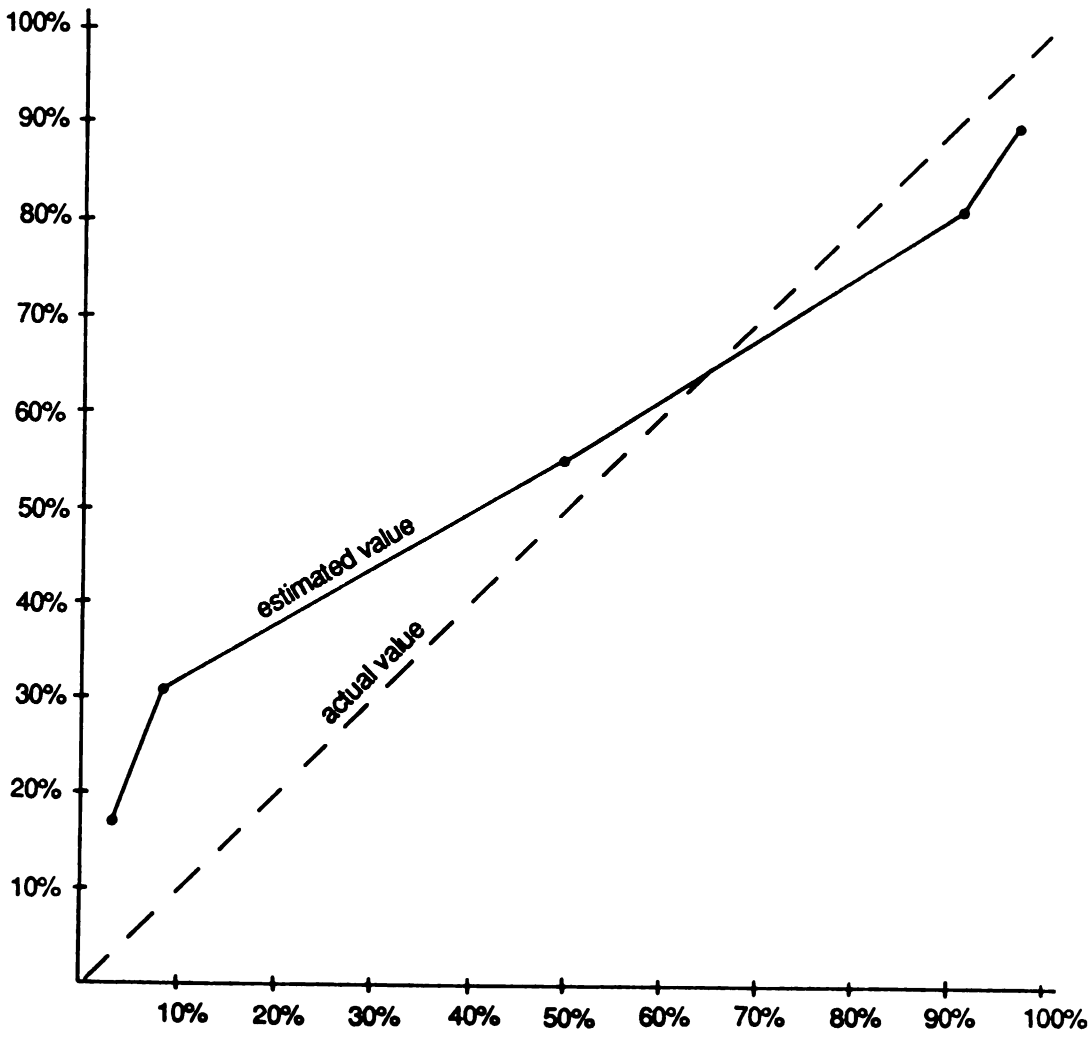


Figure 5. Relationship between estimated and actual value percentage of royal blue/white patterns.

.025 level of significance. The graph in Figure 5 shows the relationship between the estimated and actual values of the patterns.

Similar results were found for value estimation of identical patterns using different color schemes. The results are shown in Table 5. Only one estimated mean was not statistically different from its actual value percentage at the .025 level with 30 degrees of freedom. This was the 50% pattern on the green/black slide. All other estimations were significantly different from the actual value.

The normal approximation to the binomial distribution was used to test whether different color schemes were more, less, or about the same in differentiability compared to the royal blue/white patterns. The following formula was used:

$$Z = (X - NP)/\sqrt{NP\ (1-P)}$$

where X = the number of correct responses;

N = the number of subjects;

and P = the probability of a correct response occuring by chance.

The probability of any answer (more, less, or same amount) is .33. Given an N of 34, at least 16 responses ($Z = 1.75$ [which is the first value exceeding 1.65], $p < .05$) are required for statistical significance. The results are summarized in Table 6.

As Table 6 shows, the patterns using the magenta/white, cyan/black, and green/black color schemes were found to be more differentiable than the royal blue/white scheme. The green/black scheme was perceived as being the most differentiable. The yellow/black and red/white color schemes appeared less differentiable than the royal blue/white scheme.

TABLE 6

Perceived Amount of Differentiability Between Royal Blue/White Patterns and Those of Different Color Schemes

Pattern Colors	More Differentiable	Less Differentiable	Same Amount
Magenta/ White	19*	0	15
Yellow/ Black	13	19*	2
White/ Black	10	11	13
Cyan/ Black	20*	8	6
Red/ White	4	17*	13
Green/ Black	25*	5	4

* $P \leq .05$

N = 34

The normal approximation to the binomial distribution was also used to evaluate the 123 pattern pairs selected for investigation of pattern differentiability. However, the probability of determining whether a pattern is the same or different from another is .50. Given an N of 34 (the first group of subjects), at least 23 ($Z = 2.05$) correct responses are needed for statistical significance at the .05 level. Given an N of 30 (the second group of subjects), at least 23 ($Z = 2.19$) correct responses are needed for the same conclusion. Table 7 presents the number of correct responses for the 123 slides. Table 8 shows which pattern pairs were determined to be the same or different.

Of the patterns determined to be different from one another, all ordinal rankings of the value percentages of the pair were in the correct direction. That is, the pattern with the lowest value percentage of blue was perceived to be "bluer."

Discussion

The results of the value percentage estimates for the patterns show that subjects do not judge value of the royal blue/white patterns chosen for this study as a linear relationship. Similar to the results of Williams (1958), the values of patterns that were predominantly blue were overestimated; the values of predominantly white patterns were underestimated. (Note that the measurement of the pattern itself was percent colored pixels, not a physical measurement of the amount of light.)

Similar results were found for the patterns using other colors. Comparing all seven color schemes, the closest to actual value estimates were made on the green/black colored patterns. However, the presence of the original royal blue/white value scale on the Type B slides probably

TABLE 7

Number of Correct Responses to Pattern Pairs

PATTERN NUMBER

PATTERN NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	18**	34**	30*	34**	29**	32**																	
2		32**	8*	16**	23*	28*	30*																
3			28**	14*	27**	25*	33**	30*															
4				29*	19**	12**	27*	30*	30*														
5					27*	6*	34**	30*	34**	34**													
6						25**	20*	33**	30*	33**	34**												
7							24**	34**	30*	29*	33**	26*											
8								30*	32**	34**	29*	31**	34**										
9									28*	28*	30*	32**	30*	34**									
10										28*	34**	28*	30*	32**	30*								
11											27*	34**	32**	30*	33**	30*							
12												28*	30*	34**	30*	33**	29*						
13													26*	18*	32**	34**	28*	33**					
14														24*	31**	32**	30**	28*	31**				
15															27*	11*	21*	22*	21*	28**			
16																20**	11*	18**	22**	17*	13*		
17																	19*	12*	18**	10*	21**	21*	
18																		26*	17**	7*	20†	17**	22*
19																			20**	18**	17**	18**	29**
20																				26*	10*	11*	16*
21																					22*	10**	22*
22																						31**	15*
23																							26**

* N = 30
** N = 34
† N = 33 (One subject did not respond to this slide.)

TABLE 8

Pattern Pairs Judged to Be "Same" or "Different"

PATTERN NUMBER

PATTERN NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	S	D	D	D	D	D																	
2		S	S	S	D	D	D																
3			S	S	D	D	D	D															
4				S	S	S	D	D	D														
5					S	S	D	D	D	D													
6						S	S	D	D	D	D												
7							S	D	D	D	D	D											
8								S	D	D	D	D	D										
9									S	D	D	D	D	D									
10										S	D	D	D	D	D								
11											S	D	D	D	D	D							
12												S	D	D	D	D	D						
13													S	S	D	D	D	D					
14														S	D	D	D	D	D				
15															S	S	S	D	S	D			
16																S	S	S	S	S	S		
17																	S	S	S	S	S	D	
18																		S	S	S	S	S	D
19																			S	S	S	S	D
20																				S	S	S	S
21																					S	S	D
22																						S	S
23																							S

S = Same
D = Different ($p \leq .05$)

confounded this finding.

Subjects who noted color preferences most often liked the dark colors dithered with white and disliked the light colors dithered with black. In particular, the royal blue/white, and red/white patterns were most preferred; the cyan/black patterns were the least preferred.

Color preferences bore anything but a perfect relationship to perceived amount of pattern differentiability. Although the red/white color scheme was one of the most preferred, it was one of the least differentiable. The cyan/black combination was the most disliked, but it was quite differentiable. The green/black patterns were the most differentiable and were the most accurately estimated for value percentage, despite being one of the most disliked color combinations.

Subjects seemed to have considerable difficulty judging value percentage for the patterns. This may be due to the relatively coarse resolution of the CRT screen. As Castner and Robinson (1969) noted, coarse patterns are often first perceived as patterns of dots, not as a gray tone. Many subjects noted that they needed to squint to blur the dots to make the value estimation. In addition, many subjects divided their five value estimates evenly between 0% and 100%, and often gave the same value estimates to each color scheme. For these reasons, I find the results of the estimations only roughly indicative of relative values associated with the patterns.

The results of the pattern differentiability experiment (using the Type C slides) were more substantive. After the testing, patterns 2, 3, 5, 19, 21, and 22 were re-evaluated and found to be too coarse for cartographic use. They were removed from consideration. Twelve of the eighteen remaining patterns were determined to be different from one another. Derived from Table 8, these patterns are: 1, 4, 7, 8, 9, 10, 11, 12, 13, 15, 20, and 23. The patterns are simulated in Figure 6.

Comparing the value percentages of these patterns, it appears that subjects are better able to discriminate patterns at the dark end of the value scale. Of the twelve differentiable patterns, eight patterns contained 50% value or less. Four patterns contained more than 50% and of these, one contained no dark pixels at all.

Perhaps the cause of this value imbalance in pattern discrimination is the different amounts of light (luminance) emitted from the CRT for each of the two colors (royal blue and white) that make up the patterns. As described in Murch (1984), blue has very low luminance (black has no luminance); white has the highest luminance. The white pixels may overwhelm the blue, causing the overestimations of value on the dark patterns. Predominantly white patterns may appear so bright that no (or fewer) blue pixels can be perceived. As a result, fewer of the high value patterns were distinguishable from one another.

That twelve patterns out of eighteen appeared distinguishable to subjects was a positive outcome in that it indicated that a wide range of potentially useful area symbols was possible. It was also disconcerting. Previous literature indicated that this exceeds the number of patterns usually recommended for mapping (Jenks and Knos, 1961; Dent, 1985). The appropriateness of these twelve patterns for a mapping context will be investigated in the next chapter.

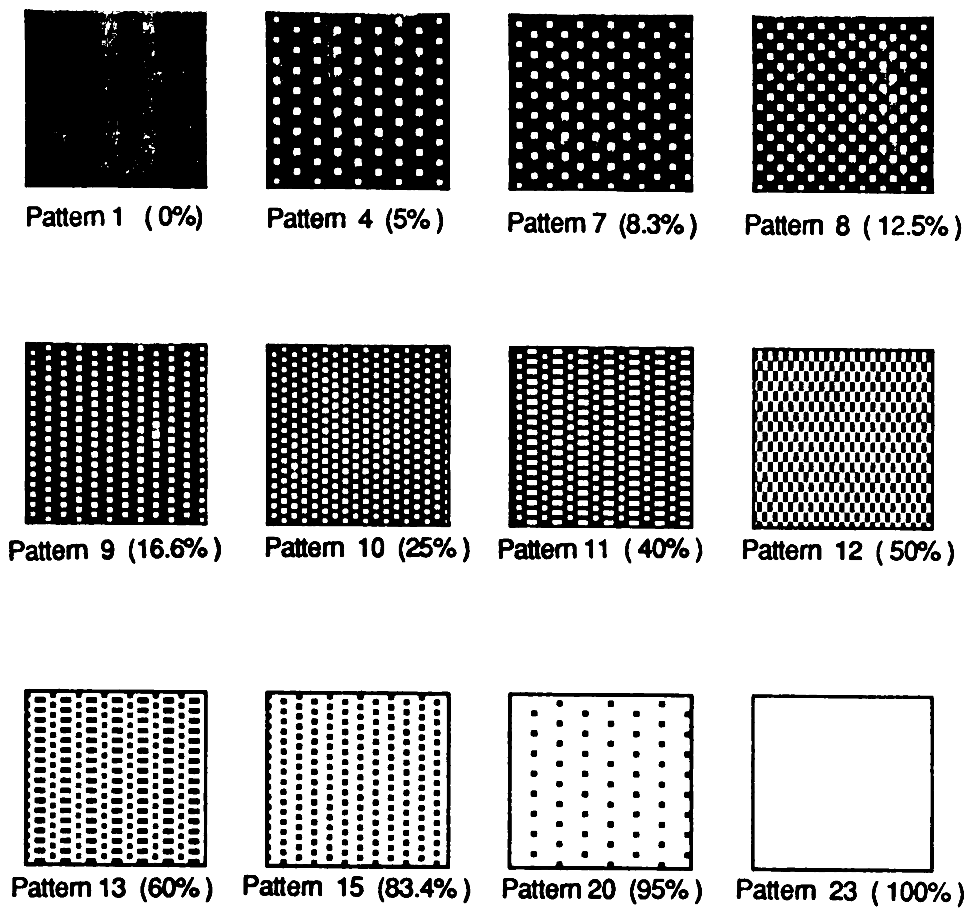


Figure 6. Simulated examples of patterns judged to be differentiable in Study 1. The numbers in parentheses indicate the value percentages of the patterns.

CHAPTER 4

EVALUATION, PART II:

DITHERED PATTERNS IN MAP CONTEXT

The maps used in the experiment described in this chapter employed the twelve dithered patterns from the previous chapter as cartographic area symbols. The twelve patterns were relabelled 1 to 12 from dark to light and were displayed on classed choropleth maps. Subjects were asked to match selected patterns on the map with the corresponding pattern on the map legend. The accuracy with which subjects match patterns in a mapping context will provide further information about the appropriateness of the dithered patterns as cartographic area symbols.

Seven different color schemes were chosen for investigation: royal blue/white, red/white, magenta/white, white/black, green/black, cyan/black, and yellow/black. Each of the five choropleth maps was displayed using the seven color schemes. The effect of color scheme on matching accuracy was investigated. Subjects were also asked to note color scheme preferences.

Method

TEST SLIDES

All slides (Slide Type D) contained a choropleth map of the counties of the State of Michigan and a legend. Slides were made using 4, 6, 8, 10, and 12 class maps. The legend boxes were labelled with class numbers. A Type D slide is in the envelope on the inside back cover of the thesis.

Thirty-five Type D slides were made. Five slides (one each for the 4, 6, 8, 10, and 12 class maps) were produced for each of the seven color schemes.

Data for the maps were derived from the Michigan Statistical Abstract (1981). Percentage change in unemployment from 1970 to 1980 was used. The data were classed using a Michigan State University Geography Department computer program based on the Jenks method (as described in Dent, 1985, pp. 205-206). Appendix E lists the raw data and the classes into which each Michigan county falls when different numbers of intervals are used.

The following patterns were used on the choropleth maps: 4-class map (Patterns 1, 5, 9, and 12); 6-class map (Patterns 1, 3, 6, 8, 10, and 12); 8-class map (Patterns 1, 3, 5, 6, 7, 8, 10, and 12); 10-class map (Patterns 1, 2, 4, 5, 6, 7, 8, 9, 11, and 12); and 12-class map (all twelve patterns). The pattern displayed for each county is also listed in Appendix E.

Counties were selected for testing so that patterns near one another in value percentage would be matched on the same map to determine their differentiability in a mapping context. The 12-class map slides evaluated pattern pairs 2-3, 3-4, 9-10, and 10-11. The 10-class map slides tested pairs 1-2, 4-5, 8-9, and 11-12. Pattern pairs 5-6, 6-7, and 7-8 were tested on the 8-class map slides. Non-adjacent pattern pairs 3-6, 6-8, and 8-10 were investigated on the 6-class map slides; pair 5-9 was evaluated using the 4-class map slides. To eliminate differences in a pattern's areal extent, only counties of approximately the same size were selected for testing.

SUBJECTS

Thirty-four subjects participated in the testing. The subjects were all employees of the Geography Division of the U. S. Bureau of the Census. It was no longer feasible for me to use Michigan State University students as subjects because I relocated between studies. Many of the subjects were cartographers; all subjects used maps frequently in their work. Because most of the subjects had training in geography, there was little reason to believe they would yield highly different results than the original subjects. Twenty-two subjects were male; twelve were female.

TESTING ENVIRONMENT

Testing was conducted in a large room darkened for viewing the slides. The slide projector was positioned approximately 8 feet away from the screen, which in combination with the focal length of the projector lens created an image approximately 24 by 16 inches on the screen. Subjects sat between 10 and 20 feet away from the screen. They were tested in small groups; no group contained more than 8 subjects. Testing lasted approximately 30 minutes.

PROCEDURE

As in the first study, subjects were given a brief explanation of the purpose of the study. They were told that the experiment was about the use of patterns for maps on CRT monitors. They were informed that they would look at slides of choropleth maps displayed on a CRT screen and would match patterns with the map legend. Each subject was given a consent form to sign (Appendix C), and a test booklet (Appendix D), and a pencil. They were told that they could ask questions at any time during the test session.

The subjects were also instructed to write in the margins of the test booklet any comments they had on the testing itself, any vision problems they had (in particular, deficient color vision), and any preferences they had for particular color schemes.

The subjects were asked to read the instructions on the test booklet and the first slide was presented. Using a pointer, a county was selected on the screen and subjects were asked to match the pattern of the county to the corresponding pattern in the legend. Figure 7 shows the counties used to test patterns on each map. Although the patterns were the same for a map with a given number of classes, the order of presentation of the counties on each map was randomly determined for each slide. The order of presentation is listed in Appendix F.

Subjects were given as much time as they needed to complete their answers. When all subjects had completed a response, the pointer was moved to the next county or the next slide was presented. Each subject completed 168 pattern matchings.

Results

The responses of Study 2 were tested for significance using the normal approximation to the binomial distribution as described in Chapter 3. Under normal conditions for this statistic, the assumption is made that all responses are equally likely. However, in this experiment, a case can be made that all responses are not equally likely. When a subject is asked to match a 90% value pattern, he or she is unlikely to select a response of 10%. For this reason, the assumption was made that only the two most adjacent patterns to the target pattern are

Figure 7. Counties tested.

considered likely choices. (Only one pattern is adjacent to Patterns 1 and 12).

Using this assumption, all patterns (except 1 and 12) require at least 16 correct responses to be significant ($p = .33$); Patterns 1 and 12 require 23 correct responses ($p = .5$). With this constraint, 158 of the 168 pattern matching responses were significant. The ten non-significant responses were all from 10- and 12-class maps.

Table 9 shows the mean number of correct responses made per pattern considering all color schemes. The means range from a low of 17.14 (out of 34) correct responses for Pattern 4 to a high of 33.57 for Pattern 12. Pattern 8 also had a very high mean number of correct responses ($\overline{X} = 33.14$) and all but pattern 4 had means over 25.

Evaluation of the results by the number of classes per map is presented in Table 10. As expected, the 4-class maps had the highest mean number of correct responses ($\overline{X} = 33.5$); the 12-class maps, the lowest ($\overline{X} = 26.64$). Figure 8 shows a graph of these results.

The results of the pattern differentiability data tabulation are shown in Table 11. Based on the number of incorrect responses, it is apparent that Pattern 4 is indistinguishable from Pattern 5 using the black-dithered patterns. Also, Pattern 4 had a low number of correct responses when paired with Pattern 3. This was true of all color schemes, although the number of correct answers varied from non-significant to significant.

Table 12 shows the results of grouping the patterns by color scheme. The mean number of correct responses per color scheme ranged from 30.96 (royal blue/white) to 28.04 (green/black). An analysis of variance is presented in Table 13 and shows that there are significant differences

TABLE 9

Mean Correct Responses Per Pattern
(N = 34)

Pattern	(A) Number of Times Pattern Presented	(B) Total Possible Correct Responses (A x N)	(C) Total Correct Responses	(D) Mean Correct Responses ($\overline{X}$) (C/A)
1	7	238	226	32.29 (95.0%)
2	14	476	455	32.50 (95.6%)
3	14	476	419	29.93 (88.0%)
4	14	476	240	17.14 (50.0%)
5	21	714	549	26.14 (76.8%)
6	14	476	423	30.21 (88.9%)
7	7	238	178	25.43 (74.8%)
8	21	714	696	33.14 (97.5%)
9	21	714	670	31.90 (93.8%)
10	14	476	392	28.00 (82.3%)
11	14	476	455	32.50 (95.6%)
12	7	238	235	33.57 (98.7%)

TABLE 10

Mean Correct Responses Per Number of Map Classes
(N = 34)

Number of Classes	(A) Number of Times Class Presented	(B) Total Possible Correct Responses (A x N)	(C) Total Correct Responses	(D) Mean Correct Responses ($\overline{X}$) (C/A)
4	14	476	469	33.50 (98.5%)
6	28	952	911	32.53 (95.7%)
8	28	952	797	28.46 (83.7%)
10	56	1904	1642	29.32 (86.2%)
12	42	1428	1119	26.64 (78.4%)

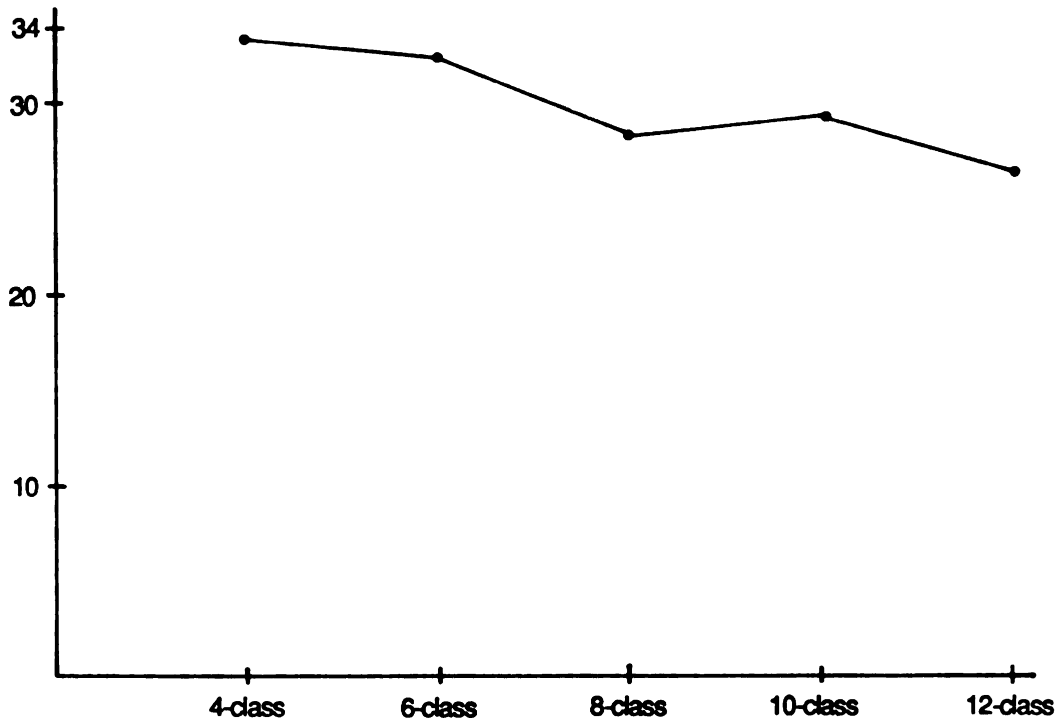


Figure 8. Number of correct responses for maps with different numbers of classes.

TABLE 11

Pattern Differentiability

Color Scheme	Correct Responses Pat. 1	Pat. 2**	Correct Responses Pat. 2	Pat. 3***	Correct Responses Pat. 3	Pat. 4***
R.Blue/White	34	34	34	32	32	23
Red/White	34	34	34	26	26	15†
Mag./White	34	34	33	28	28	19
White/Black	32	32	30	21	21	13†
Yellow/Black	30	32	31	28	28	10†
Green/Black	30	33	30	23	23	17
Cyan/Black	32	33	31	23	23	13†

Color Scheme	Correct Responses Pat. 4	Pat. 5**	Correct Responses Pat. 5	Pat. 6*	Correct Responses Pat. 6	Pat. 7*
R. Blue/White	27	23	34	33	33	31
Red/White	25	22	33	34	34	34
Mag./White	21	26	26	33	33	31
White/Black	12†	19	26	25	25	20
Yellow/Black	15†	16	27	24	24	25
Green/Black	15†	10†	16	18	18	19
Cyan/Black	14†	13†	25	29	29	18

Color Scheme	Correct Responses Pat. 7	Pat. 8*	Correct Responses Pat. 8	Pat. 9**	Correct Responses Pat. 9	Pat. 10***
R. Blue/White	31	34	32	31	21	20
Red/White	34	34	34	34	28	18
Mag./White	31	34	27	33	28	21
White/Black	20	32	31	34	31	33
Yellow/Black	25	34	34	32	32	30
Green/Black	19	34	34	34	31	28
Cyan/Black	18	34	33	33	32	24

Color Scheme	Correct Responses Pat. 10	Pat. 11***	Correct Responses Pat. 11	Pat. 12**
R. Blue/White	20	30	33	34
Red/White	18	28	33	34
Mag./White	21	31	33	32
White/Black	33	31	34	34
Yellow/Black	30	34	33	33
Green/Black	28	32	34	34
Cyan/Black	24	32	34	34

* Pair from 8-class map
** Pair from 10-class map
*** Pair from 12-class map
† Not significant at .05 level

TABLE 12

Mean Correct Responses Per Color Scheme

Pattern	R.Blue/Wh.	Red/White	Mag./White	White/Bl.	Yellow/Bl.	Green/Bl.	Cyan/Black
1 (10)	34	34	34	32	30	30	32
2 (10)	34	34	34	32	32	33	33
(12)	34	34	33	30	31	30	31
3 (6)	34	33	32	33	32	34	33
(12)	34	26	28	21	28	28	23
4 (10)	27	25	21	12†	15†	15†	15†
(12)	23	15†	19	13†	10†	17	13†
5 (4)	34	34	34	33	34	33	31
(8)	34	33	26	26	27	16	25
(10)	23	22	26	19	16	10†	13†
6 (6)	33	33	33	33	28	34	33
(8)	33	34	33	25	24	18	29
7 (8)	31	34	31	20	25	19	18
8 (6)	34	33	34	33	33	34	34
(8)	34	34	34	32	34	34	34
(10)	32	34	27	31	34	34	33
9 (4)	34	34	34	34	34	33	33
(10)	31	34	33	34	32	34	33
(12)	21	28	28	31	32	31	32
10 (6)	32	32	31	31	29	30	33
(12)	20	18	21	33	30	28	24
11 (10)	33	33	33	34	34	33	34
(12)	30	28	31	34	34	32	32
12 (10)	34	34	32	34	34	33	34
Total	743	733	722	690	692	673	685
$\overline{X}$	30.96	30.54	30.08	28.75	28.83	28.04	28.54
s^2	20.8	30.4	21.03	46.02	43.7	57.26	49.9
s	4.56	5.51	4.58	6.78	6.61	7.57	7.06

Note: The number in parentheses denotes the number of classes on the map from which the response was made.

† Not significant at the .05 level

between the seven treatment means ($F = 18.07$, $F_{\alpha .05}(6,161) = 2.0986$).

The mean number of correct responses for the three white-dithered color schemes is 30.53. The four black-dithered color schemes average 28.54 correct responses. These statistics are shown in Table 14. Table 15 presents the analysis of variance performed on the two groups. The observed F-ratio of 54.46 shows a significant difference between the means of the two groups ($F_{\alpha .05}(1,6) = 5.9874$).

Discussion

Subjects were able to discriminate the dithered patterns in the choropleth map context with surprising accuracy. Of the 168 matches, only 10 had an insufficient number of correct answers to be significant. Accuracy was high for the 4-, 6-, 8-, 10-, and 12-class maps, although the number of correct responses did drop off as the number of classes increased.

When looked at individually, most of the patterns were correctly identified from the legend. Patterns 1 and 12 (solid dark and light color area fills) were almost always matched (95.0% and 98.7% correct responses respectively). Patterns 2 and 3 (dark background with light colored pixels arranged in a triangular lattice) were also easily distinguished (95.6% and 88.0% correct), as were Patterns 10 and 11 (light background with dark colored pixels arranged in a triangular lattice, 82.3% and 95.6% correct). Patterns 8 and 9 also had a high proportion of correct answers (97.5% and 93.8%). These patterns were the redesigned 50% and 60% value patterns. Their textural differences from the other patterns probably aided their correct selection.

Only three patterns (4, 5, and 7) were mismatched fairly often.

TABLE 13

Analysis of Variance of Color Scheme Treatments

Source	Sum of Squares	d.f.	Mean Square	F-ratio
Treatments	181.08	6	30.18	18.07*
Error	269.11	161	1.67	
Total	450.19	167		

* Significant at the .05 level

TABLE 14

Mean Correct Responses Per Dither Color Type

	White Dither	Black Dither
	743	690
	733	692
	722	673
		685
Total	2198	2740
$\overline{X}$	732.7	685.0
s^2	220.67	218.0
s	14.85	14.76

TABLE 15

Analysis of Variance of Dither Color Type Treatments

Source	Sum of Squares	d.f.	Mean Square	F-ratio
Treatments	3981.75	1	3981.75	54.46*
Error	438.67	6	73.11	
Total	4420.42	7		

* Significant at the .05 level

Patterns 4 and 5 were patterns with dark backgrounds and light colored, regularly arranged foreground pixels. Pattern 4 had the lowest percentage of correct responses (50.0%) of any pattern. Pattern 5 was matched 76.8% of the time. Pattern 7 was the redesigned 40% value pattern; it was matched correctly only 74.8% of the time. These patterns were probably too similar in value percentage and in texture to adjacent patterns to allow correct identification from the legend.

If Patterns 4, 5, and 7 are considered indistinguishable from other patterns used in the mapping context, only nine patterns remain differentiable. These patterns are shown in Figure 9. All of these patterns were matched correctly 82.3% of the time or more. An equal number of patterns on each side of the 50% value pattern (Pattern 8) are included in these patterns. However, Patterns 2 and 3 have very little difference in percentage value (5.0 and 8.3, respectively), but visually they were fairly consistently discriminated from one another.

If higher standards are used to determine pattern distinguishability, fewer patterns remain. If, for instance, the requirement of 90% correct matches was imposed, the number of patterns included drops to six (Patterns 1, 2, 8, 9, 11, and 12). The values of these patterns are: 0%, 5%, 50%, 60%, 95% and 100% respectively. If 95% correct responses are required, only five patterns remain; pattern 9 (60%) is eliminated.

The percentage of correct responses for the varied number of classes per map suggests that 4- and 6-class maps can be made using distinguishable patterns. The patterns of the 4-class maps were matched correctly 98.5% of the time; the 6-class maps, 95.7%. Accuracy dropped off for the 8-class map (83.7%) and 10-class (86.3%) maps. The 12-class map elicited only 78.4% correct responses. If a map requires that patterns be matched

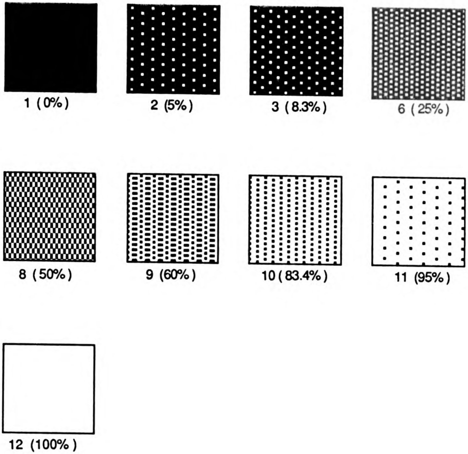


Figure 9. Simulated examples of patterns judged to be differentiable in Study 2. The numbers in parentheses indicate the value percentage of the patterns.

correctly 90% to 95% of the time, no more than 6 or 7 classes should be used.

With respect to the ability to match identical patterns over different color schemes, subjects were correct most often on patterns using white as one of the colors. Conversely, the black-dithered patterns were not matched correctly as often. This difference may be due to the black background color of the screen for both types of test slides. The black background may enhance the contrast of the white-dithered patterns, making them more distinguishable than their black-dithered counterparts. The white-dithered slides used a total of three colors, which may provide more visual cues than the black-dithered slides that used only two colors.

CHAPTER 5

SUMMARY AND CONCLUSIONS

The purpose of this study was to create a set of dithered patterns on a CRT monitor and evaluate the use of the patterns in a cartographic context. The results of the study indicate that dithered patterns can indeed be used to create distinguishable area fill for maps on CRTs with limited color palettes. Using only two colors, up to nine patterns (seven dithered, two solid color) can be used on a map and be matched accurately with the legend by most people. If greater accuracy is required on a map, sets of 5 or 6 patterns can be culled from the larger set. The study has also pointed out which types of dithered patterns are appropriate for use on CRT maps and which should be avoided for cartographic use.

Some aspects of previous cartographic research are applicable to the use of dithered patterns on CRT maps. The findings of Williams (1958) on pattern value perception were replicated to some extent in this study: subjects overestimated the values of dark patterns and underestimated the lighter ones. As Castner and Robinson (1969) noted, the value of coarse patterns is difficult to estimate; this was also evident in the present study. The patterns were necessarily coarse because of the resolution of the CRT screen. Tufte (1983) cautioned against the use of patterns with optical effects; it was difficult to create a range of patterns without moirés or great textural differences. Finally, the present study limits the number of classes used on CRT maps to 6 or 7, as had many previous cartographic studies.

However, the creation of area patterns on a new device, the CRT, has brought out some problems not encountered in more traditional cartographic research. The resolution of the CRT monitor necessitates that dithered patterns must be coarse, a feature considered inappropriate for mapping. Finer textured patterns than those created here are just not possible unless screen resolution increases. The screen also affects the patterns themselves. If regularly spaced patterns are to be created, it is difficult to create middle-value patterns without visible textural elements. The problem here is that the use of textural differences in patterns of a series is usually avoided in cartography unless mapping nominal classes of data. In addition, the way in which the patterns are presented, emitted light, is very different from the traditional printed patterns which use reflected light for viewing. The contrasting luminance of the various colors used and the size of the colored area both influence how or if the pattern will be perceived.

Despite these problems, the present study shows that dithered patterns can be used effectively to make aesthetically-pleasing choropleth maps on CRTs. Subjects were able to match most patterns with the legend, especially when the number of classes was few and the difference in value between the patterns was great. Subjects were most accurate when matching patterns of low luminance (royal blue, red, and magenta) dithered with white. These patterns were also considered the most visually pleasing by the subjects.

Although choropleth maps were chosen to display the patterns in this study, dithered patterns could be used on any CRT map image requiring area fill patterns, such as shaded isoline maps, dasymetric maps, or land use maps. Random dithered patterns could also be useful for unclassed choropleth maps. The use of dithered patterns might have helped in differentiating patterns for software applications such as MICROPIPS and DIDS.

Dithered patterns are not necessary for all CRT maps. In this study, the solid color patterns were matched more often than most of the dithered patterns. On expensive monitors with a large palette, dithered patterns should be used sparingly, if at all, and only if necessary to the map design. The addition of pattern elements will only make the map more noisy and perhaps confuse the purpose of the map. However, on CRTs with limited palettes, especially the 4- and 8-color monitors, dithering can extend the range of values available and yield a more pleasing map to the viewer.

The CRT is becoming an increasingly acceptable medium for the display of maps. Although more research is certainly needed on the perceptual properties of the device itself, cartographic research using CRTs and the design of algorithms and applications for use on the device are underway. Further research on dithered patterns should center on the development of faster algorithms, and on the creation of patterns in the middle-value range, patterns with less texture, and patterns with random pixel spacing for use in unclassed choropleth maps.

Dithered patterns offer more flexibility to the map designer when working with restrictive inexpensive CRT monitors. Like any patterns for cartographic use, however, thought should be given to cartographic conventions while designing maps using dithered patterns. Care should be taken that patterns have no disturbing optical effects, and they should have no obvious textural differences if used for mapping quantitative data.

APPENDICES

APPENDIX A

BASIC Computer Program to Create Dithered Patterns

```
10   REM   This program will create two dithered patterns in the center
           of the screen.  First, the outline of two boxes are drawn.
           These boxes are then filled with a background color and a
           dithered pattern in a foreground color.  All parameters (fore-
           ground and background colors and the horizontal and vertical
           increments) for the dithered patterns are specified by the
           user.  The original box outlines are then erased, leaving only
           the dithered patterns on the screen.
20   REM
30   REM   Arrays X and Y contain the x- and y-coordinates of the box
           outlines.
40   REM   Variables MIDX1, MIDX2 and MIDY are the coordinates within
           the two boxes.  These coordinates are used to fill the boxes with
           the background colors.
50   REM
60   CLS
70   DATA 225,100,335,100,335,160,225,160,365,100,475,100,475,160,365,160
80   DATA 275,420,125
90   DIM X(8),Y(8)
100  FOR I=1 TO 8
110    READ X(I),Y(I)
120  NEXT I
130  READ MIDX1,MIDX2,MIDY
140  PRINT "Enter the background color, foreground color, horizontal in-
            crement, and vertical increment for the first box."
150  INPUT BACKGROUND1
160  INPUT FOREGROUND1
170  INPUT HORIZONTAL1
180  INPUT VERTICAL1
190  PRINT "Enter the background color, foreground color, horizontal in-
            crement, and vertical increment for the second box."
200  INPUT BACKGROUND2
210  INPUT FOREGROUND2
220  INPUT HORIZONTAL2
230  INPUT VERTICAL2
240  CLS
250  REM      This will plot the two boxes on the screen.
260  GOSUB 500
270  REM      This will fill box 1 with the background color.
280  GOSUB 600
290  REM      This will fill box 2 with the background color.
300  GOSUB 630
310  REM      This will dither box 1 with the foreground color.
320  GOSUB 660
```

```
330  REM      This will dither box 2 with the foreground color.
340  GOSUB 1030
350  REM      This will erase the box outlines by drawing them in
              black.
360  GOSUB 930
370  REM      This will label the boxes "a" and "b".
380  GOSUB 890
390  END

500  REM      Subroutine to plot the boxes
510  FOR I=1 TO 3
520    LINE (X(I),Y(I))-(X(I+1),Y(I+1)),3
530  NEXT I
540  LINE (X(4),Y(4))-(X(1),Y(1)),3
550  FOR I=5 TO 7
560    LINE (X(I),Y(I))-(X(I+1),Y(I+1)),3
570  NEXT I
580  LINE (X(8),Y(8))-(X(5),Y(5)),3
590  RETURN

600  REM      Subroutine to fill box 1
610  PAINT (MIDX1,MIDY),BACKGROUND1,3
620  RETURN

630  REM      Subroutine to fill box 2
640  PAINT (MIDX2,MIDY),BACKGROUND2,3
650  RETURN

660  REM      Subroutine to fill box 1 with dithered pattern
670  REM      The variable INCREMENT is used to check for odd or even
              rows of pixels.  If INCREMENT is odd, then the foreground
              pixel must be offset to create the triangular grid.
680  REM      The variable J is used to check if the number of the cur-
              rent row is evenly divisible by the vertical increment.
              If it is, then the row is dithered; if it is not, then
              the row is ignored.
690  INCREMENT=0
700  FOR J=100 TO 160
710    IF J/VERTICAL1 - INT(J/VERTICAL1) = 0 THEN 800
720    INCREMENT=INCREMENT+1
730    FOR I=226 TO 334
740      IF INCREMENT/2 - INT(INCREMENT/2) = 0 THEN 780
750      IF I+HORIZONTAL1>334 THEN GOTO 790
760      IF (I/HORIZONTAL1) - INT(I/HORIZONTAL1)=0 THEN PSET(I+
           (HORIZONTAL1/2),J),FOREGROUND1
770      GOTO 790
780      IF I/HORIZONTAL1 - INT(I/HORIZONTAL1)=0 THEN PSET(I,J),
           FOREGROUND1
790    NEXT I
800  NEXT J
810  RETURN

890  REM     Subroutine to label the boxes
900  LOCATE 15,32
```

```
910  PRINT "a               b"
920  RETURN

930  REM       Subroutine to plot boxes
940  FOR I=1 TO 3
950    LINE (X(I),Y(I)) -(X(I+1),Y(I+1)),0
960  NEXT I
970  LINE (X(4),Y(4)) - (X(1),Y(1)),0
980  FOR I=5 TO 7
990    LINE (X(I),Y(I)) - (X(I+1),Y(I+1)),0
1000 NEXT I
1010 LINE (X(8),Y(8)) - (X(5),Y(5)),0
1020 RETURN

1030 REM    Subroutine to fill box 2 with dithered pattern
1040 INCR=0
1050 FOR J=100 TO 160
1060   IF J/VERTICAL2 - INT(J/VERTICAL2) = 0 THEN 1150
1070   INCR=INCR+1
1080   FOR I=366 TO 474
1090     IF INCR/2 - INT(INCR/2) = 0 THEN GOTO 1130
1100     IF I+HORIZONTAL2>474 THEN GOTO 1140
1110     IF (I/HORIZONTAL2)-INT(I/HORIZONTAL2)=0 THEN PSET(I+
           (HORIZONTAL2/2),J),FOREGROUND2
1120     GOTO 1140
1130     IF I/HORIZONTAL2 - INT(I/HORIZONTAL2) = 0 THEN PSET(I,J),
           FOREGROUND2
1140   NEXT I
1150 NEXT J
1160 RETURN
```

APPENDIX B

BASIC Computer Program to Create a Choropleth Map with Dithered Patterns

```
10   CLS
20   KOUNT=0
30   DIM BACKGROUND(12),FOREGROUND(12),HSPACE(12),VSPACE(12)
40   FOR I=1 TO 12
50     READ BACKGROUND(I),FOREGROUND(I),HSPACE(I),VSPACE(I)
60   NEXT I
70   DATA 1,1,10,10
80   DATA 1,7,10,2
90   DATA 1,7,6,2
100  DATA 1,7,4,2
110  DATA 1,7,6,1
120  DATA 1,7,4,1
130  DATA 1,7,40,40
140  DATA 1,7,50,50
150  DATA 7,1,40,40
160  DATA 7,1,6,1
170  DATA 7,1,10,2
180  DATA 7,1,10,10
190  REM      Read the number of classes for the map
200  N=4
210  REM      Draw legend boxes and fill with appropriate patterns
220  FOR I=0 TO N
230    LINE(135,106+I*12) - (165,106+(I-1)*12),3
240  NEXT I
250  LINE(135,106) - (135,106+(I-1)*12),3
260  LINE(165,106) - (165,106+(I-1)*12),3
270  XMIN=135
280  XMAX=165
290  FOR Q=1 TO N
300    LOCATE 9+Q,10
310    PRINT USING "          class ##",Q
320    YMIN=106+(Q-1)*12
330    YMAX=106+Q*12
340    IF Q=1 THEN PATTERN=1
350    IF Q=2 THEN PATTERN=5
360    IF Q=3 THEN PATTERN=9
370    IF Q=4 THEN PATTERN=12
380    IF PATTERN=7 OR PATTERN=9 OR PATTERN=8 THEN GOTO 390 ELSE GOTO
         410
390    IF PATTERN=8 THEN GOSUB 7000 ELSE GOSUB 6000
400    GOTO 420
410    GOSUB 4000
420  NEXT Q
```

```
430  FOR I=0 TO N
440    LINE(135,106+I*12) - (165,106+I*12),0
450  NEXT I
460  LINE(135,106) - (135,106+(I-1)*12),0
470  LINE(165,106) - (165,106+(I-1)*12),0
480  DIM X(319),Y(319)
490  DIM POINTDICT(50)
500  OPEN "B:MIPTS.DAT" FOR INPUT AS #1
510  REM        Read in the data from an external file
520  FOR I=1 TO 319
530    INPUT #1, X(I),Y(I)
540  NEXT I
550  REM      Variable COLOUR is the color of the state outline
560  COLOUR=3
570  REM      Now plot the state outline
589  RESTORE 8000
590  FOR K=1 TO 85
600    READ NUMPOINTS
610    FOR I=1 TO NUMPOINTS
620      READ POINTDICT(I)
630    NEXT I
640    FOR I=1 TO NUMPOINTS-1
650      LINE(X(POINTDICT(I)),Y(POINTDICT(I))) - (X(POINTDICT(I+1)),
            Y(POINTDICT(I+1))),COLOUR
660    NEXT I
670    LINE(X(POINTDICT(NUMPOINTS)),Y(POINTDICT(NUMPOINTS))) - (X
         (POINTDICT(1)),Y(POINTDICT(1))),COLOUR
680    READ XMIN,XMAX,YMIN,YMAX,PATTERN
690    IF PATTERN=7 OR PATTERN=9 OR PATTERN=8 THEN GOTO 700 ELSE GOTO
         720
700    IF PATTERN=8 THEN GOSUB 7000 ELSE GOSUB 6000
710    GOTO 730
720    GOSUB 4000
730  NEXT K
740  REM        Redraw state outline in black
750  RESTORE 8000
760  FOR K=1 TO 85
770    READ NUMPOINTS
780    FOR I=1 TO NUMPOINTS
790      READ POINTDICT(I)
800    NEXT I
810    FOR I=1 TO NUMPOINTS-1
820      LINE(X(POINTDICT(I)),Y(POINTDICT(I))) - (X(POINTDICT(I+1)),
           Y(POINTDICT(I+1))),0
830    NEXT I
840    LINE(X(POINTDICT(NUMPOINTS)),Y(POINTDICT(NUMPOINTS))) -
         (X(POINTDICT(1)),Y(POINTDICT(1))),0
850    READ XMIN,XMAX,YMIN,YMAX,PATTERN
860  NEXT K
870  COLOR 0
880  LOCATE 1,1
890  END

2000 REM    Pavlidis' algorithm for polygon fill
```

```
2010 DY=-1
2020 DX=1
2030 ABOVE=0
2040 BELOW=0
2050 IF POINT(I-DX, J+DY)=3 THEN ABOVE=ABOVE+1
2060 IF POINT(I-DX, J-DY)=3 THEN BELOW=BELOW+1
2070 WHILE POINT(I,J)=3
2080   IF POINT(I,J+DY)=3 AND POINT(I-DX,J+DY)<>3 THEN ABOVE=ABOVE+1
2090   IF POINT(I,J-DY)=3 AND POINT(I-DX,J-DY)<>3 THEN BELOW=BELOW+1
2100   I=I+1
2110   KOUNT=KOUNT+1
2120   IF PATTERN=7 AND KOUNT=5 THEN KOUNT=0
2130   IF PATTERN=8 AND KOUNT=4 THEN KOUNT=0
2140   IF PATTERN=9 AND KOUNT=5 THEN KOUNT=0
2150   GOTO 2070
2160 WEND
2170 IF POINT(I-DX,J+DY)<>3 AND POINT(I,J+DY)=3 THEN ABOVE=ABOVE+1
2180 IF POINT(I-DX,J-DY)<>3 AND POINT(I,J-DY)=3 THEN BELOW=BELOW+1
2190 RETURN

4000 REM   Subroutine to fill most polygons
4010 INC=0
4020 FOR J=YMIN TO YMAX
4030   IF J/VSPACE(PATTERN)-INT(J/VSPACE(PATTERN))<>0 THEN INC=INC+1
4040   IF VSPACE(PATTERN)=1 THEN INC=INC+1
4050   COUNT=0
4060   I=XMIN
4070   WHILE I<=XMAX
4080     IF POINT(I,J)=3 GOTO 5020
4090     IF COUNT/2-INT(COUNT/2)>0 THEN GOSUB 4200
4100     I=I+1
4110     GOTO 4070
4120     GOSUB 2000
4130     IF ABOVE=1 AND BELOW=1 THEN COUNT=COUNT+1
4140     GOTO 4070
4150   WEND
4160 NEXT J
4170 RETURN

4200 REM    Subroutine to fill patterns
4210 IF VSPACE(PATTERN)=1 GOTO 4230
4220 IF J/VSPACE(PATTERN)-INT(J/VSPACE(PATTERN)=0 THEN 4280
4230 IF INC/2-INT(INC/2)=0 THEN 4260
4240 IF I/HSPACE(PATTERN)-INT(I/HSPACE(PATTERN))=0 THEN PSET(I,J),
         FOREGROUND(PATTERN) ELSE PSET(I,J),BACKGROUND(PATTERN)
4250 GOTO 4290
4260 IF I/HSPACE(PATTERN)-INT(I/HSPACE(PATTERN))=.5 THEN PSET(I,J),
         FOREGROUND(PATTERN) ELSE PSET(I,J),BACKGROUND(PATTERN)
4270 GOTO 4290
4280 PSET(I,J), BACKGROUND(PATTERN)
4290 RETURN

6000 REM    Subroutine to fill 40% and 60% patterns
6010 INCR=0
```

```
6020 FOR J=YMIN TO YMAX
6030   COUNT=0
6040   KOUNT=0
6050   I=XMIN
6060   WHILE I<=XMAX
6070     IF POINT(I,J)=3 GOTO 6130
6080     IF COUNT/2-INT(COUNT/2)>0 THEN GOSUB 6200
6090     KOUNT=KOUNT+1
6100     IF KOUNT=5 THEN KOUNT=0
6110     I=I+1
6120     GOTO 6150
6130     GOSUB 2000
6140     IF ABOVE=1 AND BELOW=1 THEN COUNT=COUNT+1
6150   WEND
6160   INCR=INCR+1
6170   IF INCR=2 THEN INCR=0
6180 NEXT J
6190 RETURN

6200 REM   Subroutine to fill every fifth pixel
6210 IF INCR=0 THEN GOTO 6220 ELSE GOTO 6240
6220 IF KOUNT=3 THEN PSET(I,J),FOREGROUND(PATTERN) ELSE PSET(I,J),
         BACKGROUND(PATTERN)
6230 GOTO 6250
6240 IF KOUNT=0 OR KOUNT=1 THEN PSET(I,J),FOREGROUND(PATTERN) ELSE
         PSET(I,J),BACKGROUND(PATTERN)
6250 RETURN

7000 REM     Subroutine to fill 50% pattern
7010 INCR=0
7020 FOR J=YMIN TO YMAX
7030   COUNT=0
7040   I=XMIN
7050   KOUNT=0
7060   WHILE I<=XMAX
7070     IF POINT(I,J)=3 THEN 7130
7080     IF COUNT/2-INT(COUNT/2)>0 THEN GOSUB 7300
7090     I=I+1
7100     KOUNT=KOUNT+1
7110     IF KOUNT=4 THEN KOUNT=0
7120     GOTO 7060
7130     GOSUB 2000
7140     IF ABOVE=1 AND BELOW=1 THEN COUNT=COUNT+1
7150     GOTO 7060
7160   WEND
7170   INCR=INCR+1
7180   IF INCR=4 THEN INCR=0
7190 NEXT J
7200 RETURN

7300 REM   Subroutine to fill pattern
7310 IF INCR=0 OR INCR=1 THEN GOTO 7320 ELSE GOTO 7350
7320 REM   Fill blue, blue, white, white (for example)
7330 IF KOUNT=0 OR KOUNT=1 THEN PSET(I,J),FOREGROUND(PATTERN) ELSE
```

```
        PSET(I,J),BACKGROUND(PATTERN)
7340 GOTO 7370
7350 REM   Fill white, white, blue, blue (for example)
7360 IF KOUNT=2 OR KOUNT=3 THEN PSET(I,J),FOREGROUND(PATTERN) ELSE
        PSET(I,J),BACKGROUND(PATTERN)
7370 RETURN

8000 DATA 5,311,141,142,143,310,532,567,130,144,4
8010 DATA 10,202,203,204,209,210,211,227,226,225,224,450,485,109,118,7
        .
        .   (these lines contain the point dictionary)
        .
8880 DATA 7,293,292,165,166,167,295,296,552,590,232,247,6
8890 DATA 5,313,317,221,241,229,424,452,145,157,9
```

APPENDIX C

CONSENT FORM

1. I have freely consented to take part in a scientific study being conducted by Ann Goulette under the supervision of Judy M. Olson, Professor.

2. The study has been explained to me and I understand the explanation that has been given and what my participation will involve.

3. I understand that I am free to discontinue my participation in the study at any time without penalty.

4. I understand that the results of the study will be treated in strict confidence and that I will remain anonymous. Within these restrictions, results of the study will be made available to me at my request.

5. I understand that my participation in the study does not guarantee any beneficial results to me.

6. I understand that, at my request, I can receive additional explanation of the study after my participation is completed.

PERCEPTION OF DITHERED PATTERNS: Signed:___________________________

Date:_____________________________

ADDENDA

1. The purpose of this study is to improve the design of computer-generated maps.

2. I understand that the expected length of my participation is 30 minutes.

APPENDIX D

TEST BOOKLET AND INSTRUCTIONS

Study 1

You will see a slide showing a set of boxes ranging in color from solid blue to solid white. If the left-most box is 0% blue and the right-most box is 100% blue, estimate the percentage of blue for the remaining boxes.

	0%	____	____	____	____	____	100%
Box	1	2	3	4	5	6	7

Now you will see sets of similar slides containing the same value scale you just saw and another scale using different colors. Please make estimations of the percentages for the new color schemes as you did for the first slide. Then, make a decision as to whether the patterns in the new color scheme are more or less differentiable or the same as the original set of patterns.

1. 0% ____ ____ ____ ____ ____ 100%

   ______ Less differentiable
   ______ More differentiable
   ______ Same amount of differentiation

   .
   .
   .
   .

6. 0% ____ ____ ____ ____ ____ 100%

   ______ Less differentiable
   ______ More differentiable
   ______ Same amount of differentiation

You will be shown slide of pairs of patterns. You should decide if the two patterns have the same percentage of blue or if they are distinctly different from one another. If they appear to be different, you should indicate which of the patterns (Pattern A or Pattern B) seems to contain the greatest percentage of blue. Please make only one response per slide.

1. _____ A and B are the same
   _____ A is bluer than B
   _____ B is bluer than A

2. _____ A and B are the same
   _____ A is bluer than B
   _____ B is bluer than A

.
.
.
.

60. _____ A and B are the same
    _____ A is bluer than B
    _____ B is bluer than A

Study 2

INSTRUCTIONS

You will be shown slides of a map of the State of Michigan. The person giving the test will point to a county on the map. You should match the pattern used to display that county with its appropriate legend box and write the number of the pattern on the test form. For example, if the county is colored green, find the green box in the legend and write the number of that box on this sheet. Please try to work quickly.

SLIDE 1

1. Class _____
2. Class _____

SLIDE 2

3. Class _____
4. Class _____
5. Class _____
6. Class _____

.
.
.
.

SLIDE 34

161. Class _____
162. Class _____
163. Class _____
164. Class _____
165. Class _____
166. Class _____

SLIDE 35

167. Class _____
168. Class _____

APPENDIX E

DATA VALUES AND CLASSES

County Name	% Change in Unemployment	4-class map Cls.	4-class map Pat.	6-class map Cls.	6-class map Pat.	8-class map Cls.	8-class map Pat.	10-class map Cls.	10-class map Pat.	12-class map Cls.	12-class map Pat.
Alcona	9.1	2	5	2	3	3	5	3	4	4	4
Alger	6.1	2	5	3	6	4	6	5	6	6	6
Allegan	5.5	3	9	4	8	5	7	6	7	7	7
Alpena	2.2	4	12	5	10	6	8	8	9	9	9
Antrim	7.6	2	5	3	6	4	6	4	5	5	5
Arenac	9.4	2	5	2	3	3	5	3	4	4	4
Baraga	4.2	3	9	4	8	5	7	7	8	8	8
Barry	5.7	3	9	4	8	5	7	6	7	7	7
Bay	7.2	2	5	3	6	4	6	4	5	5	5
Benzie	4.2	3	9	4	8	5	7	7	8	8	8
Berrien	7.5	2	5	3	6	4	6	4	5	5	5
Branch	6.8	2	5	3	6	4	6	5	6	6	6
Calhoun	5.7	3	9	4	8	5	7	6	7	7	7
Cass	7.5	2	5	3	6	4	6	4	5	5	5
Charlevoix	5.0	3	9	4	8	5	7	6	7	7	7
Cheyboygan	0.5	4	12	6	12	7	10	9	11	10	10
Chippewa	4.1	3	9	4	8	5	7	7	8	8	8
Clare	5.7	3	9	4	8	5	7	7	8	7	7
Clinton	4.0	3	9	4	8	5	7	7	8	8	8
Crawford	6.9	2	5	3	6	4	6	5	6	6	6
Delta	3.2	3	9	5	10	6	8	7	8	8	8
Dickenson	2.0	4	12	5	10	6	8	8	9	9	9
Eaton	4.0	3	9	4	8	5	7	7	8	8	8
Emmett	1.7	4	12	5	10	6	8	8	9	9	9
Genessee	9.4	2	5	2	3	3	5	3	4	4	4
Gladwin	6.8	2	5	3	6	4	6	5	6	6	6
Gogebic	2.0	4	12	5	10	6	8	8	9	9	9
Gr. Traverse	0.8	4	12	6	12	7	10	9	11	10	10
Gratiot	2.0	4	12	5	10	6	8	8	9	9	9
Hillsdale	5.4	3	9	4	8	5	7	6	7	7	7
Houghton	0.5	4	12	6	12	7	10	9	11	10	10
Huron	4.2	3	9	4	8	5	7	7	8	8	8
Ingham	4.0	3	9	4	8	5	7	7	8	8	8
Ionia	4.0	3	9	4	8	5	7	7	8	8	8
Iosco	9.1	2	5	2	3	3	5	3	4	4	4
Iron	-2.2	4	12	6	12	8	12	10	12	12	12
Isabella	2.7	3	9	5	10	6	8	8	9	9	9
Jackson	5.6	3	9	4	8	5	7	6	7	7	7
Kalamazoo	3.0	3	9	5	10	6	8	8	9	9	9
Kalkaska	0.8	4	12	6	12	7	10	9	11	10	10

County Name	% Change in Unemployment	4-class map Cls.	4-class map Pat.	6-class map Cls.	6-class map Pat.	8-class map Cls.	8-class map Pat.	10-class map Cls.	10-class map Pat.	12-class map Cls.	12-class map Pat.
Kent	1.9	4	12	5	10	6	8	8	9	9	9
Keweenaw	0.5	4	12	6	12	7	10	9	11	10	10
Lake	8.8	2	5	2	3	3	5	3	4	4	4
Lapeer	6.7	2	5	3	6	4	6	5	6	6	6
Leelanau	0.8	4	12	6	12	7	10	9	11	10	10
Lenawee	7.6	2	5	3	6	4	6	4	5	5	5
Livingston	6.7	2	5	3	6	4	6	5	6	6	6
Luce	2.0	4	12	5	10	6	8	8	9	9	9
Mackinac	0.2	4	12	6	12	7	10	9	11	11	11
Macomb	6.7	2	5	3	6	4	6	5	6	6	6
Manistee	1.9	4	12	5	10	6	8	8	9	9	9
Marquette	7.5	2	5	3	6	4	6	4	5	5	5
Mason	6.9	2	5	3	6	4	6	5	6	6	6
Mecosta	1.7	4	12	5	10	6	8	8	9	9	9
Menominee	3.9	3	9	4	8	5	7	7	8	8	8
Midland	6.8	2	5	3	6	4	6	5	6	6	6
Missaukee	2.8	3	9	5	10	6	8	8	9	9	9
Monroe	6.6	2	5	3	6	4	6	5	6	6	6
Montcalm	7.9	2	5	3	6	4	6	4	5	5	5
Montmorency	17.0	1	1	1	1	1	1	1	1	1	1
Muskegon	4.9	3	9	4	8	5	7	6	7	7	7
Newaygo	8.2	2	5	3	6	3	5	4	5	5	5
Oakland	6.7	2	5	3	6	4	6	5	6	6	6
Oceana	4.9	3	9	4	8	5	7	6	7	7	7
Ogemaw	-1.6	4	12	6	12	8	12	10	12	12	12
Ontonagon	6.1	2	5	3	6	4	6	5	6	6	6
Osceola	8.0	2	5	3	6	4	6	5	5	5	5
Oscoda	11.0	1	1	2	3	2	3	2	2	3	3
Ostego	0.3	4	12	6	12	7	10	9	11	11	11
Ottawa	1.9	4	12	5	10	6	8	8	9	9	9
Presque Isle	13.3	1	1	1	1	2	3	2	2	2	2
Roscommon	12.0	1	1	2	3	2	3	2	2	3	3
Saginaw	9.1	2	5	2	3	3	5	3	4	4	4
St. Clair	6.7	2	5	3	6	4	6	5	6	6	6
St. Joseph	6.7	2	5	3	6	4	6	5	6	6	6
Sanilac	9.8	2	5	2	3	3	5	3	4	4	4
Schoolcraft	3.6	3	9	4	8	5	7	7	8	8	8
Shiawasee	9.4	2	5	2	3	3	5	3	4	4	4
Tuscola	8.9	2	5	2	3	3	5	3	4	4	4
Washtenaw	2.9	3	9	5	10	6	8	8	9	9	9
Wayne	6.7	2	5	3	6	4	6	5	6	6	6
Wexford	2.8	3	9	5	10	6	8	8	9	9	9

APPENDIX F

SLIDE PRESENTATION ORDER IN STUDY 2

SLIDE 1 (4-cl. green)
- Lake
- Washtenaw

SLIDE 2 (6-cl. yellow)
- Gladwin
- Gratiot
- Ingham
- Oscoda

SLIDE 3 (6-cl. white)
- Gratiot
- Ingham
- Oscoda
- Gladwin

SLIDE 4 (8-cl. white)
- Alcona
- Cass
- Wexford
- Clinton

SLIDE 5 (12-cl red)
- Ostego
- Shiawasee
- Presque Isle
- Roscommon
- Ottawa
- Gr. Traverse

SLIDE 6 (6-cl. red)
- Oscoda
- Ingham
- Gladwin
- Gratiot

SLIDE 7 (6-cl. r. blue)
- Gratiot
- Gladwin
- Oscoda
- Ingham

SLIDE 8 (6-cl. cyan)
- Ingham
- Oscoda
- Gladwin
- Gratiot

SLIDE 9 (10-cl. green)
- Roscommon
- Genessee
- Ionia
- Ogemaw
- Montmorency
- Manistee
- Ostego
- Montcalm

SLIDE 10 (8-cl. green)
- Cass
- Clinton
- Alcona
- Wexford

SLIDE 11 (12-cl. cyan)
- Presque Isle
- Gr. Traverse
- Roscommon
- Ottawa
- Shiawasee
- Ostego

SLIDE 12 (8-cl. yellow)
- Wexford
- Clinton
- Alcona
- Cass

SLIDE 13 (8-cl. magenta)
- Alcona
- Clinton
- Cass
- Wexford

SLIDE 14 (4-cl. magenta)
- Lake
- Washtenaw

SLIDE 15 (10-cl. white)
- Genessee
- Ionia
- Manistee
- Montcalm
- Montmorency
- Ogemaw
- Ostego
- Roscommon

SLIDE 16 (4-cl. yellow)
- Washtenaw
- Lake

SLIDE 17 (12-cl. white)
- Gr. Traverse
- Ostego
- Ottawa
- Presque Isle
- Roscommon
- Shiawasee

SLIDE 18 (8-cl. cyan)
- Wexford
- Clinton
- Cass
- Alcona

SLIDE 19 (6-cl. green)
- Gratiot
- Oscoda
- Gladwin
- Ingham

SLIDE 20 (12-cl. green)
- Presque Isle
- Shiawasee
- Ostego
- Roscommon
- Gr. Traverse
- Ottawa

SLIDE 21 (12-cl. magenta)
- Ottawa
- Ostego
- Shiawasee
- Presque Isle
- Gr. Traverse
- Roscommon

SLIDE 22 (10-cl. red)
- Ostego
- Genessee
- Manistee
- Roscommon
- Montcalm
- Montmorency
- Ionia
- Ogemaw

SLIDE 23 (12-cl. r.blue)
- Roscommon
- Presque Isle
- Ottawa
- Gr. Traverse
- Ostego
- Shiawasee

SLIDE 24 (6-cl. magenta)
- Oscoda
- Gladwin
- Gratiot
- Ingham

SLIDE 25 (10-cl. cyan)
- Manistee
- Ostego
- Montmorency
- Genessee
- Ogemaw
- Roscommon
- Ionia
- Montcalm

SLIDE 26 (4-cl. r. blue)
- Lake
- Washtenaw

SLIDE 27 (10-cl. r. blue)
- Montcalm
- Ostego
- Montmorency
- Genessee
- Roscommon
- Manistee
- Ogemaw
- Ionia

SLIDE 28 (8-cl. red)
- Wexford
- Alcona
- Cass
- Clinton

SLIDE 29 (10-cl. magenta)
- Manistee
- Roscommon
- Montcalm
- Ogemaw
- Montmorency
- Ostego
- Genessee
- Ionia

SLIDE 30 (10-cl. yellow)
- Roscommon
- Ostego
- Ogemaw
- Montmorency
- Montcalm
- Manistee
- Ionia
- Genessee

SLIDE 31 (8-cl. r. blue)
- Clinton
- Alcona
- Wexford
- Cass

SLIDE 32 (4-cl. cyan)
- Washtenaw
- Lake

SLIDE 33 (4-cl. red)
- Lake
- Washtenaw

SLIDE 34 (12-cl. yellow)
- Ostego
- Shiawasee
- Presque Isle
- Roscommon
- Ottawa
- Gr. Traverse

SLIDE 35 (4-cl. white)
- Washtenaw
- Lake

BIBLIOGRAPHY

BIBLIOGRAPHY

Brassel, K. A model for automatic hill-shading. The American Cartographer, Vol. 1(1), 1974, pp. 15-27.

Carter, J. R. Computer Mapping: Progress in the '80's. Washington, DC: Association of American Geographers, Resource Publications in Geography, 1984.

Castner, H. W., & Robinson, A. H. Dot area symbols in cartography: The influence of pattern on their perception. Technical Monograph, No. CA-4. Washington, DC: American Congress of Surveying and Mapping, 1969.

Dent, B. D. Principles of Thematic Map Design. Reading, MA: Addison-Wesley, 1985.

Foote, K. E. Reviews of geographic software: Atlas AMP. The Professional Geographer, Vol. 37(4), 1985, pp. 492-493.

Gossette, F. Software review: PRODESIGN II: The easy to use CAD system. The American Cartographer, Vol. 13(2), 1986, pp. 168-171.

Groop, R. E., & Smith, R. M. Matrix line printer maps. The American Cartographer, Vol. 9(1), 1982, pp. 19-24.

Groop, R. E. Software review: Desktop Information Display System (DIDS) Version 2.0. The American Cartographer, Vol. 12(2), 1985, pp. 174-176.

Haber, R. N., & Wilkinson, L. Perceptual components of computer displays. IEEE Computer Graphics and Applications, Vol. 2(3), 1982, pp. 23-35.

Hobbs, L. C. Computer graphics display hardware. IEEE Computer Graphics and Applications, Vol. 1(1), 1981, pp. 25-39.

Jenks, G. F., & Knos, D. S. The use of shaded patterns in a graded series. Annals of the American Association of Geographers, Vol. 51, 1961, pp.316-334.

Jensen, J. R. Software review: MICROPIPS Personal Image Processing System/The Telesys Group, Inc. The American Cartographer, Vol. 13(1), 1986, pp. 81-85.

McGranaghan, M. Symbol and background value effects in choropleth maps for CRT display. Technical Papers 45th Annual Meeting. ACSM, Washington, DC, 1985, pp. 356-363.

McGranaghan, M. Interaction of saturation and value in color choropleth maps for CRT display. Technical Papers, 46th Annual Meeting. ACSM, Washington, DC, 1986, pp. 76-84.

Machover, C. CRT graphics terminals. Computer Graphics and Art, May, 1977, pp. 16-29.

Michigan Statistical Abstract. Detroit, MI: Wayne State University Press, 1981.

Morrison, J. L., & Mendoza, G. Software review: AutoCAD Drafting Package. The American Cartographer, Vol. 13(3), 1986, pp. 269-274.

Murch, G. The effective use of color: Perceptual principles. Tekniques, Vol. 8(1), 1984, pp. 4-9.

Pavlidis, T. Filling algorithms for raster graphics. Computer Graphics and Image Processing, Vol. 10, 1979, pp. 126-141.

Pavlidis, T. Algorithms for Graphics and Image Processing. Rockville, MD: Computer Science Press, 1982.

Photo, Vol. 5, Issue 67, pp. 1841-1843.

Plumb, G. A., & Slocum, T. A. Alternative designs for dot-matrix printer maps. The American Cartographer, Vol. 13(2), 1986, pp. 121-133.

Ryan, D. Computer Programming for Graphical Displays. Monterey, CA: Brooks/Cole Engineering Division, 1983.

Slocum, T. A., & McMaster, R. B. Gray tone versus line plotter area symbols: A matching experiment. The American Cartographer, Vol. 13(2), 1986, pp. 151-164.

Smith, R. M. Improved areal symbols for computer line-printed maps. The American Cartographer, Vol. 7(1), 1980, pp. 51-57.

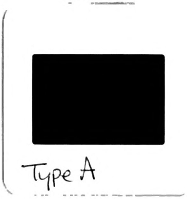
Taylor, D. R. F. Some conclusions and new challenges. In Taylor, D. R. F. (ed.), Graphic Communication and Design in Cartography. New York: John Wiley and Sons, 1983, pp. 285-307.

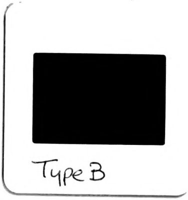
Truckenbrod, J. R. Effective use of color in computer graphics. Computer Graphics, Vol. 15(3), 1981, pp. 83-90.

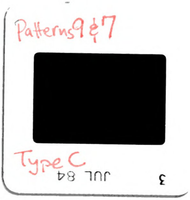
Tufte, E. R. The Visual Display of Quantitative Information. Cheshire, CN: Graphics Press, 1983.

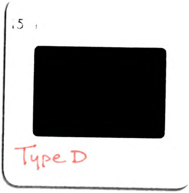
White, D. The ODYSSEY System for display and analysis of geographic information. In Moore, D. A. (ed.), Cartographic and Statistical Data Bases and Mapping Software. Cambridge, MA: Harvard Library of Computer Graphics, 1980, pp. 225-254.

Williams, R. L. Map symbols: Equal-appearing intervals for printed screens. Annals of the Association of American Geographers, Vol. 48, 1958, pp. 132-139.


Type A


Type B


Patterns 9 & 7
Type C
JUL 84
3


Type D