COLOR PERCEPTION AND PREFERENCE AMONG OLDER MAP READERS

by

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1 Introduction

Today, most printed maps are produced using computer software. Thus, it is becoming increasingly important to understand how the maps produced using digital media are perceived by different individuals. Prior to the twentieth century, research focusing on the impacts of map-design pertaining to information perception was limited, especially regarding differences that exist among individuals. Influential cartographers like Arthur Robinson and Max Eckert advocated for increased psychological research in the early part of the last century, and recently, more significant emphasis has been focused on the ways individuals perceive information communicated via maps (Montello 2002).

A significant portion of this research concerning individuals' abilities to perceive data symbolized on maps has concerned color, and specifically, color combinations. Especially in the current cartographic climate, which involves increased computer and virtual incorporation of maps, the "right" color choices can play large roles in the map's communicative success. Much of this research, having been concentrated within academia, ignores individual differences among map users. The researchers often test samples consisting of undergraduate or graduate students on color perception and map-design effectiveness and ignore large segments of the population. Applying results acquired using limited samples to the general population is especially presumptuous, as previous research results outside of cartography suggest varying differences in color perception and preference across cultures (D'Hondt and Vandewiele 1983; Wiegersma and De Klerck 1984), genders (Silver and Ferrante 1995; Dittmar 2001; Bimler et al.

2004), and especially age groups (Roy et al. 1991; Silver and Ferrante 1995; Dittmar 2001; Kinnear 2002; Wijk et al. 2002). This thesis attempts to address the generalized nature of these studies by focusing on the differences across age groups, particularly those evident among senior citizens.

1.1 Goals of the Study

Research outside of cartography suggests that color perception changes as one ages (e.g., Silver and Ferrante 1995; Dittmar 2001; Wijk et al. 2002). The goal of this study is both to explore and to acquire a better understanding of how individuals of advanced ages understand and perceive information depicted on color maps. In particular, this research aims to answer four main questions:

1) How well do members of older age groups understand choropleth maps, and do they differ from other age groups?

2) Do the gender or color vision abilities of older individuals impact their ability to interpret the maps? Do these also affect their opinions regarding the aesthetic appeal of the colors?

3) Do different color schemes allow older individuals to interpret the information on choropleth maps more quickly and accurately?

4) How do older individuals rate the varying color schemes in terms of visual appeal?

1.2 Significance

The questions previously highlighted attempt to address problems associated with the manner in which an increasingly growing and often ignored population segment understands and utilizes maps. With increased medical and health care developments, older individuals continue to be important contributors to the community at increasingly advanced ages in life. For example, from 2000 to 2010, the older population of the United States (individuals of 60 years and older) increased from 45,797,200 to 57,085,908, an increase of 24.6% (United States Bureau of the Census). This growing trend is projected to continue in the coming years, reaching an estimated 112,037,396 by 2050, a further increase of nearly 50% (see ***Figure 1.1*** – United States Bureau of the Census). In recent times, individuals of increasing age are working longer than previous generations relative to other age groups (see ***Figure 1.2***). This is significant, as more activity and participation in the workforce creates the increased likelihood of the need to interpret various types of maps.

Also, if there are significant differences in the way elderly people process map information, it follows that cartographic research should adapt practices to serve the elderly population. That is, merely understanding age-related differences is not sufficient. By focusing on issues like those raised in this thesis, future research could potentially lead to improved methods for using color in maps viewed by an increasingly large number of older people.

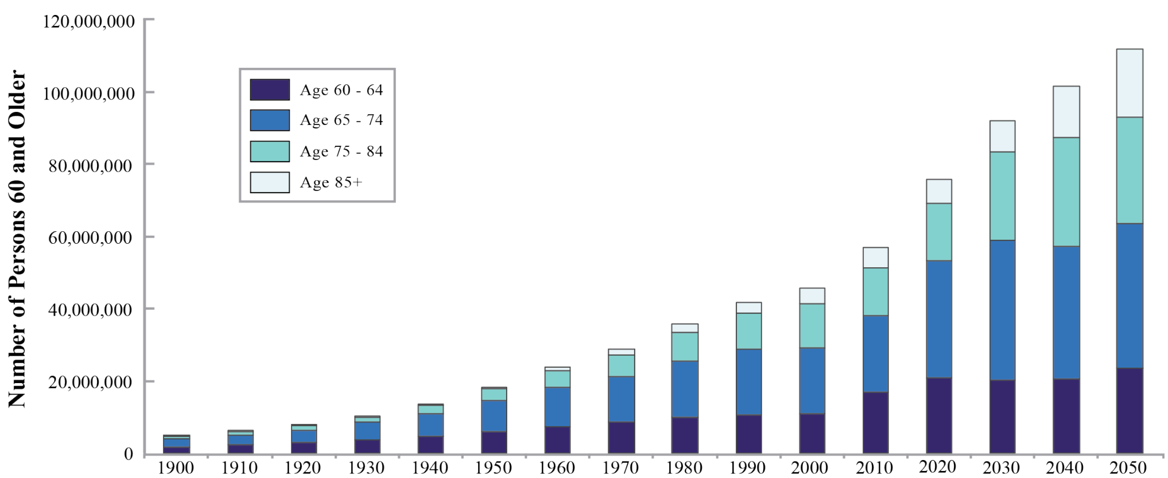

Figure 1.1: Projected population growth of individuals 60 years of age and older from 1900 to 2050 in the United States (Source: U.S. Bureau of the Census)

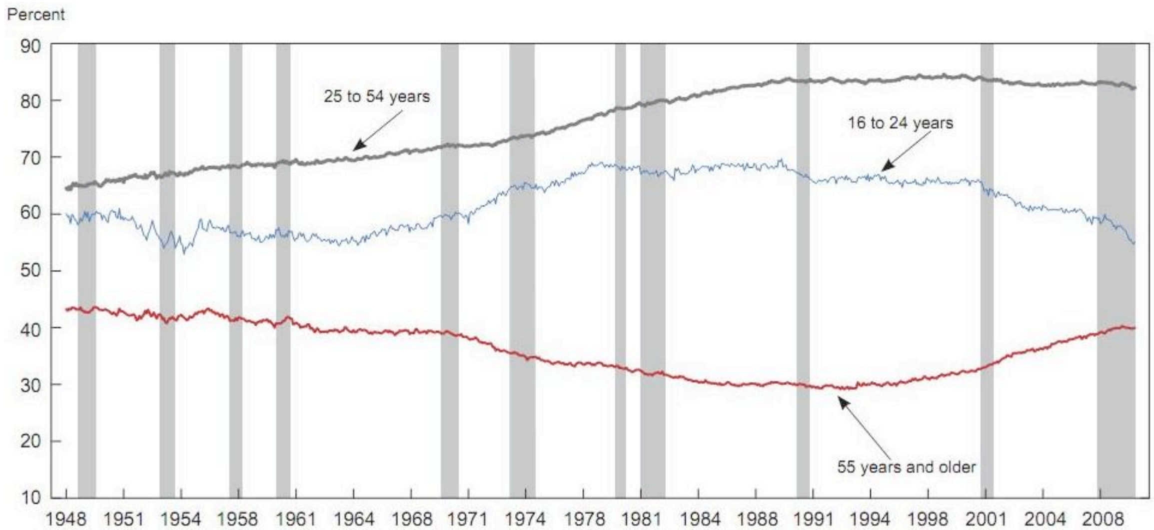

Figure 1.2: Change in the United States' labor composition from 1948 to 2010 by age group (Source: United States Bureau of Labor Statistics, Current Population Survey)

1.3 Hypotheses and Methodology Overview

Based on previous color research in the arts, cognitive sciences, psychology, gerontology, and cartography, five outcomes are postulated based on the questions in the previous section:

1) Older subjects will perform worse compared to those of younger ages in terms of efficiency and accuracy.

2) There will be limited differences between men and women within the age groups in terms of performance, as suggested by Kinnear and Sahraie (2002) and Wijk et al. (2002). However, there will be wider variations in the schemes most preferred by the two genders.

3) Increasing the contrast among the colors by using multiple hues will significantly improve the older individuals' performances on the map-reading tasks.

4) The subjects will find brighter and more fully saturated colors to be the most aesthetically pleasing.

This project adopted both quantitative and qualitative approaches to address these hypotheses. The quantitative aspect objectively evaluated map-reading success under varying color schemes for samples of males and females over the age of 55. This revealed the relative effectiveness of the various schemes and the differences that exist between the genders and age groups. A qualitative focus group was used to explore the thinking processes involved in map-reading tasks. Whereas the quantitative portion showed which color schemes were more effective, the qualitative data shed light on *why* certain schemes were more or less effective.

1.4 Color as a Visual Variable

Before addressing any of the key issues highlighted previously, color needs to be defined in both a physical and physiological sense.

In a strictly physical sense, color is a product of the interaction between light and any object. Human eyes detect the visible light portion of the electromagnetic spectrum (approximately 400 nm to 700nm λ) being reflected or emitted from an object, and the brain interprets this energy as color (Dent et al. 2009). In print cartography, the colors on maps result from this energy being reflected from the paper and ink. Thus, the colors that individuals see on a map are dependent in part on the energy being emitted from a light source, and one map's colors may appear different under varied lighting (Krygier and Wood 2005).

As the light reflected from the map surface enters the human eye, it interacts with different features that focus and sense the wavelengths of light before sending electrical impulses to the brain. Two of the elements within the eye that are especially integral to the color perception of older individuals are the lens and the retina. The lens is the feature of the eye responsible for focusing the light on the retina (a process known as accommodation), and as individuals age, the lens becomes more rigid and weakened (Slocum et al. 2005). This lessens people's ability to accommodate and decreases their ability to effectively process color. As the lens weakens with age, so too does the retina (Panda-Jonas et al. 1995). The retina contains light sensitive nerve cells (rods and cones) that communicate the sensed information to the brain through electrical impulses (Dent et al. 2009). As one ages, the density of these photoreceptors decreases by approximately 0.2% to 0.4% annually (Panda-Jones et al. 1995). Since the cones are responsible for color vision, this decline could substantially limit the abilities of the elderly to distinguish maps' colors.

Once the image has been processed and transmitted to the brain, it is transformed into an array of representations that construct a three dimensional depiction of the real-world object or scene being viewed by the individual, as theorized by David Marr (MacEachren 1995). This study will largely focus on the input to this representational framework, the retinal image, where the initial stimuli interpret light as color.

When describing the differences between the colors perceived by individuals, three visual variables (hue, value, and saturation) are recognized as the perceptual dimensions of color (Dent et al. 2009). The hue of a color corresponds to the dominant wavelength of light that composes a color. While hue is the *qualitative* dimension of color (i.e. there is no sequence of hues for logically depicting ordinal data), value is a *quantitative* dimension (Kyrgier and Wood 2005). Value refers to the lightness / darkness of a particular color while the hue is constant. The third dimension, saturation, relates to the intensity of a particular color, and can be envisioned as a mixture of a dominant hue and gray. More fully saturated colors of one hue will appear more colorful than less saturated values of the same hue. During the course of this thesis, these three visual variables will be addressed during both the color scheme design and performance sections in Chapters 3 and 4, respectively.

Since this study focuses on the color vision abilities of older individuals, it is also necessary to briefly discuss inherited and acquired color-vision impairments. In the United States and Europe, approximately 4% of the population has some form of color-vision impairment, and these defects can play a large role in one's map-reading abilities. The majority of humans are trichromats (vision cells properly match "white" with red, green, and blue); however, a small number have inherited dichromatism (vision cells match "white" with only two of the R, G, B stimuli) (Fletcher and Voke 1985). Hence, color maps designed for normal trichromats may not effectively convey information to dichromatic individuals and must be limited in the range of hues used for symbolization. Color vision also can become increasingly limited by acquired age-related defects. These can be attributed to developed disorders such as glaucoma, cataracts, diabetic retinopathy, macular degeneration, and senility, and each of these disorders could affect color vision differently (Fletcher and Voke 1985). This increases the need to study the subtle differences among those significantly affected by these disorders – the elderly.

1.5 Thesis Structure

The following chapters of this thesis present the background, methods, and results of this study. The next chapter presents previous research laying the basis for this study and emphasizes the various differences that exist pertaining to color perception and appreciation. The third chapter describes the various methods that were used to test the map-reading abilities of older individuals. The results of these tests are provided in Chapter 4 and are followed by concluding remarks and discussion in Chapter 5.

As the population, especially in the developed world, continues to age, it has become increasingly important to understand how older individuals understand and perceive mapped information. This study provides a small glimpse into the issues that need to be addressed to better design maps for an older audience.

2 Review of Relevant Literature

The first significant cognitive research within the field of cartography largely began in the early 1900s, but generally failed to address issues related to color perception until the 1950s (Montello 2002). Before delving into the research topics and results that have been completed over this time period, a formal definition of cognition needs to be provided. Cognition is the study of knowledge structures and the ways in which knowledge is processed. In a larger context, cognition tackles knowledge among varying beings (e.g., machines, animals), but in cartography, cognitive study focuses on humans (Wilson and Keil 1999). Montello (2002) also states that cognition involves various different aspects of knowledge processing that include recollection, perception, erudition, communication, and critical thinking. Since the ability to process knowledge differs among all humans, more recent developments have focused increasingly on the cognitive and perceptual differences among various populations as they relate to color. The evolution of cognitive and perceptual map research will be detailed on the following pages.

Since map research largely has ignored color perception issues related to the elderly population, research within other fields must also be consulted. Research within various fields including psychology, physiology, ophthalmology, gerontology, and art provide relevant insight into the nature of color perception and appreciation among older people. As this research study attempts to bridge the gap that exists between the mapping and cognitive sciences, the importance of understanding the fundamentals of each of these fields as they relate to color perception is particularly essential. Research within all of these fields suggests that age does have a profound impact on one's perception of color, and this section will highlight these changes.

2.1 Early Contributions to Cognitive Map Design

Montello (2002) argues that cognitive map design research traces its roots to Arthur Robinson and his seminal work entitled *The Look of Maps: An Examination of Cartographic Design*. A key issue that Robinson addressed in his research was the relationship between map producers and map users. Robinson (1952) understood that map design techniques potentially could have significant influences on the communicative effectives of maps and was one of the earliest researchers to discuss color usage. Prior to Robinson, much of the research focused on empirical map design and psychophysics because computer-generated maps and color printing still were in their infancy. Beginning with Robinson and corresponding to the improvements of technology that developed rapidly during the second half of the 20th century, color has been increasingly examined by cartographers.

Color usage, especially concerning choropleth mapping, has been a major focus within cartographic literature due to the debate that exists concerning the usefulness of unclassed maps. Dobson (1973) and Monmonier (1977) greatly criticized the unclassed method of choropleth mapping due to suspected "information overload" and the lack of individuals' ability to discriminate individual colors (Gale and Halperin 1982). One experiment attempted to judge the effectiveness of unclassed choropleth maps by having subjects compare unclassed and classed maps. The results of the experiment determined that unclassed maps do not hinder map perception (Muller 1980). Peterson (1979) conducted a similar experiment and determined that the visual quality and communicative ability of the unclassed and classed maps were very similar. This research suggests that the perceived limited ability of individuals to distinguish between maps utilizing large numbers of colors could potentially be questioned.

Mak and Coulson (1991) also performed research on choropleth maps, but the authors' conclusions were much different from those described previously. Their experiments emphasized the limitations of the human eye and the capabilities of the human brain to process increased differences on maps. As determined by Jenks (1963), humans only can perceive seven or eight distinctive lightness values. When a cartographer exceeds those limits, the effectiveness of the map could decline. To test this theory, Mak and Coulson (1991) presented 100 subjects with both classed and unclassed choropleth maps and determined the maps' efficacy by asking the subjects various map-reading questions. The results concluded that people were much more capable of estimating values using the classed choropleth map, while other variables measured by the authors (value discrimination and region-recognition) found no significant differences between the classed and unclassed choropleth maps. Even though their tests indicated that classed maps perform better than unclassed maps, the authors determined that they are not "always 'significantly' better" (Mak and Coulson 1991). The varying results evident in this research concerning classed and unclassed choropleth maps suggest that future research should focus on *why* different results are obtained for different participant groups.

2.2 The Evolution of Research about Color in Maps

Prior to this research concerning the usefulness of unclassed maps, early cognitive research within cartography largely focused on issues other than color usage for one reason: color map production was expensive and rare prior to the era of computer-generated maps. However, advances in this area have resulted in an increased emphasis on color usage and preference in recent years (largely since the late 1970s).

In the mid-1970s, the United States Bureau of the Census began expanding the usage of color within cartography, specifically its usage for representing multiple variables on the same map. These multivariate maps initially were criticized because they often were difficult to interpret and considered to cause "information overload" (Trumbo 1981). Trumbo (1981) and Olson (1981) attempted to answer these criticisms through theoretical and experimental analysis. Trumbo determined, through empirical research, that the schemes utilized by the Census Bureau had significant map interpretation disadvantages. He also concluded that schemes with good color separation and points of zero saturation (white, grays, and black) could be advantageous in determining the relationship between two variables. However, in the author's concluding remarks, he acknowledges that further empirical testing was necessary.

Olson (1981) performed four experiments on undergraduate students to determine the limit of color usage in cartography. These experiments determined that the information extracted from multivariate maps by the subjects did not differ in level of accuracy or quantity, but in "nature" (Olson 1981). Olson suggested that the two-variable map display is almost as important to information extraction as the actual color scheme that represents the two variables. Since uni- and multi-variable maps often convey different messages, as determined by the first experiment in which students were asked to arrange two-variable map legends, a comprehensible legend is necessary. Without a clear explanation of the nature of the color scheme employed, students found it especially challenging to extract information. These multi-variable maps represent the upper limits of color-usage and human ability to perceive large and wide-ranging color changes.

Brewer (1997) also attempted to evaluate this notion of "color overload" through analyzing spectral schemes. Some cartographers have discouraged the usage of colors from across the visible spectrum because changes in hue fail to convey a sense of order and are thus illogical for representing quantitative data. The author's previous writings even supported this claim (Brewer 1994), but later research by Brewer et al. (1997) disputed this belief. In the experiment, students were presented maps consisting of four color schemes representing eight different variables. A series of questions at multiple scales (local, regional, entire map) then was asked to determine which schemes communicated the information best. The results of the experiment largely contradicted previous opinions related to the use of spectral color schemes. Surprisingly, the subjects liked the more colorful maps and the accuracy of the map-reading tasks was equal or superior to other color schemes as long as different lightness values were used in conjunction with the hues. However, the authors emphasized caution when utilizing spectral schemes. Since spectral schemes inherently employ a wide-range of hues, they could potentially cause problems for the 4% of the population with color-vision impairment (Olson and Brewer 1997).

Even though color-vision impaired individuals only compose a small segment of the United States' population, that still equates to nine million people. Olson and Brewer

(1997) sought to better understand the problems encountered by these individuals through evaluating and determining color schemes that would accommodate both normal and color-vision impaired individuals. Their study involving subjects with both normal color-vision and color-vision impairments attempted to judge both groups' abilities not only to discriminate between colors, but also acquire information from maps. The authors concluded that a simple adjustment of the colors on maps to avoid colors that cause confusion for color-vision impaired individuals (minimizing red and green usage) could greatly improve their map-reading abilities. The maps utilized for the study, since encompassing the most utilized color schemes (e.g. spectral, sequential, diverging, and two-variable) of today, also suggested that more accommodating versions of each scheme could allow for high map-reading accuracy for the color-vision impaired individuals while maintaining the same accuracy for those with normal color vision.

Brewer et al. (1997) and Brewer and Pickle (2002) also focused on the usefulness of these various schemes by applying this research to real-world applications (epidemiological choropleth maps). Both studies utilized a common population sample in their experimentation by utilizing students at Pennsylvania State University (mainly undergraduates). By presenting these subjects with multiple-choice test questions, the author's determined that the nature of data classification in addition to color usage have significant effects on the accuracy of choropleth map interpretation. However, the classification schemes that had the highest accuracy for the map-reading tasks are surprising to cartographers. The quantile method (classes contain equal number of enumeration units) and minimum boundary error method (classes determined through analysis of the topology of the enumeration units) were found to be considerably more accurate for the map-reading tasks. The quantile method has often been criticized for its overly simplistic nature and failure to consider the nature of the data's distribution. The author's explanation for this phenomenon again returns to color. Since the quantile method essentially orders the data into equal classes and a sequential, monochrome color scheme is used, the distribution of the data was easier to perceive as compared to the other schemes (Brewer and Pickle 2002). These studies essentially highlighted the complexity of the map-design process, and elements like color, classification scheme, and types of data could greatly affect user accuracy and interpretation.

2.3 Current Color Research Foci Concerning Differences among Subjects

Because many of the color studies on map design discussed above used small, unrepresentative samples to perform their research (e.g., Olson 1981; Brewer et al. 1997; Brewer and Pickle 2002), their conclusions cannot be applied uncritically to the general population. For example, research both within and outside of the cartographic realm has shown that age (e.g., Roy et al. 1991; Silver and Ferrante 1995; Dittmar 2001; Kinnear 2002; Wijk et al. 2002), gender (e.g., Silver and Ferrante 1995; Dittmar 2001; Bimler et al. 2004), and culture (e.g., D'Hondt and Vandewiele 1983; Wiegersma and De Klerck 1984) play significant roles in one's color perception. This also suggests that future research in these areas could provide further insight into how **everyone** understands and appreciates color maps.

2.3.1 Age Differences

Within cartography, studies of the impacts of age on color perception and map-reading abilities have been limited, with the abbreviated set of research focusing primarily on children. Research during the 1960s and 1970s (e.g., Bartz 1971; Sorrell 1978) addressed how color impacts children's abilities to interpret colors on maps. Sorrell's (1978) findings suggest that children are particularly limited in their abilities to perceive wide variations of color, especially regarding changing saturation and value. This suggests that the results of much of the research highlighted in previous sections may not be applicable to younger people. Bartz (1971) finds that the colors used on a map can play a much greater role in a child's perception of importance as compared to an older individual. She also states that children often will perceive areas symbolized with brighter colors as more important. Buckingham and Harrower (2007) also found that children prefer the aesthetic nature of highly saturated colors, while Sorrell (1978) states that they do not prefer "fully" saturated colors. These findings suggest that color perception and appreciation can differ between various age groupings and even within certain groups, thus signaling a need to expand this cartographic research to older individuals.

In order to understand the differences among the various age groups in terms of color perception, color research beyond cartography must be addressed, specifically the psychology and physiological processes that contribute to color vision. As one might surmise, a large number of these studies suggest that both color preferences and perception ability change during the course of a person's life, oftentimes negatively. Early psychological research in this area mirrors that of today, as they showed that these changes have been problematic throughout history. However, this problem largely went unaddressed until the 1940s (Boice et al. 1948).

Boice et al. (1948), one of the first studies to address this issue comprehensively, indicates that development of color-vision impairments, especially among men, largely increases as one ages due to changes with the retina, optical nerve, or visual cortex that contribute to color vision. While men with the various forms of inherited color-vision impairments normally account for approximately 4% of the general population (Olson and Brewer 1997), multiple samples of men in the study consistently had significantly higher impairment rates of 15.8 to 23.8% (Boice et al. 1948). Thus, when designing maps for those of advanced ages, accounting for these impairments is much more important.

More recent findings also suggest that the ability to distinguish between different colors also declines with age. A common method used today to measure color vision is the Farnsworth-Munsell (FM) 100-Hue Test. During this test, subjects are presented with a series of color tiles selected from a uniform chromaticity diagram and are asked to "arrange in consecutive color order" (Farnsworth 1943). Error scores then are calculated and used to determine objectively one's ability to discriminate between colors. Through the utilization of these tests, Roy et al. (1991) and Kinnear and Sahraie (2002) concluded that color discrimination declines consistently as one ages with a peak at 19 years of age. Thus, these tests show that age does play a key role in color perception.

While Kinnear and Sahraie (2002) found that performance on the FM 100-Hue Test deteriorates at older ages, they also found that sensitivity to the various opponent color systems also differs. After the age of forty, sensitivity to the blue-yellow system actually declines more than the red-green. Roy et al. (1991) postulates that this difference in color sensitivity is largely attributable to retinal and pupil changes and the yellowing of the crystalline lens, with the lens changes being the most significant. Of the subjects over the age of 60 that were tested by Roy et al. (1991), 22 of the 29 right eyes and 25 of 27 left eyes were found to have lens changes, while only two individuals under the age of 60 had lens changes in their eyes. This result underscores the need to expand cartographic research concerning older map users because both biological and psychological changes during one's lifetime affect color perception.

In order to fully address color issues in mapping, color preference should also be discussed. Dittmar (2001) found that younger and older adult Germans favored blue and disliked yellow the most. However, beyond those two hues, the preference is a little less obvious. While Dittmar (2001) found that older people prefer green over red, Silver and Ferrante (1995) found that they prefer red over green. Since the two studies were performed using culturally different populations (German and American, respectively), this indicates that age and culture interact in their impact on color preference. However, culture is not a focus of this study, only gender and age. Thus, the results of this study are only applicable to Americans.

With increased medical advances, people also are living much longer; thus results of these studies often fail to include some of the oldest segments of the population. For example, in their research, Roy et al. (1991) and Dittmar (2001) only included individuals up to 81 and 90 years of age, respectively. According to the United States Census Bureau, the US population of individuals 90 years of age and older was approximately 1.9 million in 2010, and this number is projected to quadruple in the next forty years (He and Muenchrath 2011). This indicates a need to address map-design issues affecting those in this extreme age bracket.

One of the first attempts to evaluate the color perception abilities of the “very elderly” discovered, as one may surmise, that 95-year olds are much less able to perceive color differences than 85-year olds (Wijk 2002). One important facet of these results shows that the subjects’ abilities to perceive hue and chroma differences were much worse than their abilities to distinguish between different lightness values. This may indicate that inherited color vision impairments have an impactful effect on color differentiation in these extreme years in life. Also, even though the subjects’ capacity to distinguish colors was found to decline at this advanced age, color preference remained the same compared to the elderly in younger age brackets. Thus, color perception should be the focus of increased mapping studies in the future as the population grays.

2.3.2 Gender Differences

Lloyd and Bunch (2005 and 2008) determined that gender also plays a significant role in map-reading performance. By sampling both male and female subjects and utilizing test questions to judge both reaction time and map-reading accuracy, the results suggested that male individuals performed better than females, especially in terms of accuracy. The female subjects, however, performed better than their male counterparts in mean reaction time, but this shorter processing time did not result in improved accuracy (Lloyd and Bunch 2005).

In color research, the differences evident in the previous study have not been as obvious. Research focusing on gender differences in color preference and perception often contradicts the results of similar studies. Silver and Ferrante (1995), Dittmar (2001), and Bimler et al. (2004) concluded that gender is especially influential in shaping one's color preference. These studies suggest that men prefer red more than women, while women are more favorable towards yellow, pink, black, and purple (Silver and Ferrante 1995; Dittmar 2001). Thus, it seems these differences often are tied to the ways in which males and females "experience" colors and less tied to biological traits inherit in the genders (Bimler et al. 2004). While various studies identify differences, Kinnear and Sahraie (2002) and Wijk et al. (2002) found no variation across genders in terms of color perception and color preference. These results indicate that there is a significant lack of consensus regarding gender differences within cognitive color research, thus highlighting the need to direct more attention to the gender differences in map interpretation and appreciation.

2.4 Color Models and their Usefulness within Cartography

Within cartography, researchers and practitioners alike often use varying specification systems in which to denote and report particular colors (Kimerling 1980). This is problematic because it is difficult to translate colors between systems, as they often are based upon different premises. Also, especially during map creation to map presentation, a multitude of other influences can affect the actual colors. Things like the computer display, the quality of the printer, the type of illuminant interacting with the printed map, and even the paper quality on which the map is printed can all affect the color selected during the initial production stages. Thus, it is important to understand the various models used to define colors.

2.4.1 RGB Model

The RGB (Red, Green, Blue) model is one of the most common color models used today, especially in the digital production of maps. Currently, the most common methods used for producing the color image on a computer monitor are light-emitting diode (LED) and liquid crystal display (LCD). LED displays use multicolor arrays of light to produce the colors viewed on the monitor, while LCDs produce the color image through manipulating multiple light sources through a control device (Moreno and Contreras 2007; Liu et al. 2010). A large number of these displays use an RGB array of LEDs to produce the other colors of the spectrum (Contreras 2007). Thus, when defining colors displayed on these devices, the RGB model is suggested because it allows the user to specify colors directly. However, since the colors produced are dependent on display hardware, the RGB model cannot be used to specify colors unambiguously (Levkowitz and Herman 1993). Furthermore, no display device can produce the full range of colors humans can perceive, thus the RGB space is more limited than perceptual color models (see below). Finally, this model is not useful in print cartography because colors in RGB color space cannot be precisely translated to colors in the CMYK color space, the basis of nearly all printed media.

2.4.2 CMYK Model

While the RGB model adds the three primary colors to produce intermediate colors, the CMYK model is based on the principle of subtraction of light through the mixing of inks (Galer and Horvat 1993). Although the RGB model is one of the most common models used in the digital realm of cartography, the CMYK (Cyan, Magenta, Yellow, Black) model is used widely within printed cartography. The primaries of this model (cyan, magenta, and yellow) both absorb and reflect light to produce the color that one perceives on the piece of paper. Thus, when specifying a color using this model, the practitioner selects 4 values: three for the values of the subtractive primaries and a black value (Galer and Horvat 1993). (A black value is specified because black ink is less expensive and the black produced through mixing the three primaries in equal proportions is often inaccurate.)

Like the RGB model, the CMYK model also has its disadvantages. Most importantly, the range of potential colors is narrower than that of the RGB model (Galer and Horvat 1993). As with RGB, colors in CMYK are hardware dependent. When producing a printed map, each of these issues must be considered.

2.4.3 HSV / HSB and HSL Models

In RGB and CMYK color space, it is not practical to alter systematically saturation and value (brightness). The HSV (Hue, Saturation, Value) / HSB (Hue, Saturation, Brightness) and HSL (Hue, Saturation, Lightness) models allow the producer to vary either hue, saturation, or value, while keeping the other two visual variables constant (Koren 2006). This makes these models especially intuitive to cartographers due to the relationship that exists between the variables specified and those for the colors actually perceived by humans. Hence, they are also a very common model used today.

The HSV and HSL models are very similar in their definitions, but they each have problems associated with them. While the HSV model provides a better representation of saturation, the value tends to represent poorly the brightness of the color as perceived by humans (Koren 2006). Conversely, the HSL model provides a much better depiction of brightness compared to saturation (Koren 2006). When cartographers attempt to adjust the saturation or brightness of a color while keeping hue constant, they often choose HSV when addressing saturation changes and HSL when addressing changes in brightness. However, like the previous two models, both of these models still only are approximations of colors. They do not exactly relate to the psychological qualities of hue, saturation, and value (brightness) (Schwarz 1987).

2.4.4 Perceptual Color Models

Because they are hardware-oriented, the models discussed previously are device-dependent. In addition, the systems are highly nonlinear in that a unit change in a variable (e.g. R or M) does not yield a unit change in perceived color. There are four so-called perceptual models that address these two deficiencies. Two of these, the $L^*a^*b^*$ and $L^*u^*v^*$ systems were developed by the Commission Internationale de l'Eclairage (International Commission on Illumination) and are commonly referred to as the CIE models (Pointer 1981; Wyszecki and Stiles 2000). The third model was developed by the Optical Society of America and is known as the Ljg system (Nickerson, 1981; Hunt 1995). All three are similar in that they are 3D models, are tied to absolute color standards, and are thus device-independent. In addition, each was designed so that perceived color changes are linear in the coordinate variables. However, they are based on different color perception experiments, and scaling among the models is non-linear. There is some evidence that Ljg is superior to the others for large color differences, whereas the CIE models might be better for small differences (Stalmeier and de Weert

1991). The *L*a*b** was chosen for this research because of its availability in standard mapping software.

The *L*a*b** model tries to characterize the color differences of human perception through creating a more uniform color space based on spectrophotometric and mathematic measurements (Kimerling 1980 and Schwarz 1987). Color is depicted in the CIE *L*a*b* model by specifying a lightness value (*L**) and two opponent-color axes: a red / green axis (*a**) and a yellow / blue axis (*b**). While the colors specified in the CIE *L*a*b** system are the same across all measureable media and are international standards, this model's use has been limited in cartography because of the difficulty in relating this model to those used for computer display and printing, RGB and CMYK, respectively. However, the importance of using perceptual models has not escaped attention. For example, Burt et al. (2011) have emphasized the utility of perceptual color models for depicting classed values and associated uncertainties.

A final perceptual model, the Munsell model, is one of the oldest and most widely used (Kimerling 1980). In the Munsell system, colors are uniquely identified based on the specification of hue, value, and chroma where *hue* corresponds to the color's dominant wavelength, *value* corresponds to the luminosity, and *chroma* is proportional to the purity of the color (Tyler and Hardy 1940).

The Munsell model suffers in that it is essentially an analog model and therefore not very useful for production cartographers. In order to print particular colors using the Munsell model, the cartographer must visually compare the color to samples of the actual Munsell colors (Kimerling 1980). This poses major problems because the colors are subjectively based on the visual abilities of the cartographer and can be influenced by both the quality of the samples and light source.

2.4.6 Standardization of Colors within Cartography

The widespread use of the previously identified models highlights the need for color standardization because comparison and translation among the systems is particularly challenging. When studying color within cartography, the usage of the different color models makes replicating and comparing study's results very difficult (Kimerling 1980). Kimerling also underscores the need to standardize the colors used in cartographic research due to the multiple variables that contribute to color perception. Variables like "paper, ink, illumination source, and printing method" can all have profound impacts on a color's appearance (Kimerling 1980). Hence, cartographic researchers should be wary when it comes to specifying and using color.

3 Methodology

The research presented in Chapter 2 strongly suggests that age, gender, and color-vision impairments could play a major role in one's ability to understand and appreciate a map. In order to investigate the questions posed in the introductory chapter of this thesis, both quantitative and qualitative approaches were used. The quantitative portion involved presenting a series of map tasks to older adults and evaluating their performance through test questions. This stage largely attempted to address *if* differing color schemes are more / less useful for communicating spatial information to older age individuals. Following the map test, qualitative information was collected through a group discussion with the participating individuals. In essence, the controlled experiment provided a more objective evaluation of the subjects' perceptual abilities, while the focus group provided further information about *why* the particular maps were effective / ineffective based on certain criteria.

3.1 Map Creation

Several printed choropleth maps were created to test the subjects' map-reading abilities. The maps varied in terms of color scheme, but each depicted the same information using the same areal units. This consistency across the maps improves the ability to compare the results across the different schemes and emphasizes the impact of color in the results.

3.1.1 Map Design

A series of seven choropleth maps (See Appendix B) were designed to represent commonly encountered information (population density) using seven different color schemes. The data used were derived initially from the United States Census Bureau cartographic boundary files (www.census.gov/geo/www/) and were fictionalized during the map production process.

The initial step of the production process involved projecting and classifying this census data (5-digit ZIP code tabulation areas and counties) using ArcGIS 10. ZIP code areas were used to symbolize population density because their sizes are largely determined by population (smaller ZIP codes often have higher population densities) and are also more uniformly shaped than other enumeration units. Next, a fictional country was created by extracting a portion of the ZIP code areas, and fictional states were produced by merging various counties. After classifying the ZIP codes into five classes based on their area, the map was exported, and the final maps were completed using Adobe Illustrator.

Once in Illustrator, seven versions of the country were created and symbolized using seven varying color schemes (two spectral and five sequential). To account for possible biases associated with the subjects' familiarity with and pre-existing knowledge of the subject area, each of the seven maps was then rotated, mirrored, or mirrored & rotated. As a result, each map would appear unique to the reader, even though the maps were only different in terms of perspective. Also, this change in perspective diminished the possibility that learning would impact map search times.

In the final step of the production process, four cities (Cities A – D) and 16 states (A-M) were labeled randomly on each of the maps. Thus, when the subjects encountered each of the maps, they needed to perform the same general process to both find the locations of interest and answer the questions based upon those locations. All of these steps were necessary to compare quantitatively the results of the seven tests.

The creation of these fictitious maps also was useful to ensure that the areas depicted would be relatively similar in terms of shape and size. The shape of an area can impact one's ability to interpret differences within the area, especially regarding less compact areas; similarly, relatively large areas often can be too visually prominent. In reality, these problems are quite common and can reduce a map's effectiveness. For example, when glancing at a population density map of the US by state, Wyoming will often stand out simply due to the relatively large size and compactness of the state, while smaller / less compact states with larger population densities will be less distinct. Avoiding these types of problems is paramount in this study because the goal is to assess the communicative effectiveness of different color schemes, not different areal shapes and sizes.

3.1.2 Color Schemes

As stated previously, each of the seven choropleth maps used a different color scheme that is relatively common within cartography. The five sequential schemes were derived from ColorBrewer 2.0 (colorbrewer2.org), software designed specifically by Cindy Brewer to produce "readable" thematic maps with "good colors" (Brewer et al. 2003). Even though the steps between each color are not equidistant in terms of perception, these color schemes were designed and tested to be "identifiably different" (Brewer et al. 2003). These color schemes also were used because the online and print versions of ColorBrewer provide the colors' definitions in many of the common color models (RGB, CMYK, L*a*b*, and Munsell) allowing for easy specification. The four color sequential schemes (the fifth grayscale sequential scheme will be detailed later) are as follows:

- Single hue: light to dark green
- Single hue: dark to light purple
- Multi-hue: light yellow to orange to dark red
- Multi-hue: dark blue to light green

These four schemes were chosen to investigate the effects that hue, value, and color sequence have on the subjects' ability to quickly and accurately interpret maps. The first two schemes had a constant hue, but differed in terms of value and color sequence. When dealing with population density data, many choropleth maps often are symbolized using a light to dark sequential color scheme. In other words, light areas have low population densities, and darker areas' populations are denser. While this was the premise used in creating the first of the single hue schemes, the second scheme inverts the order (darker areas have low population densities) to evaluate the effects that diverging from the norm have on map-reading abilities.

Two multi-hue sequential schemes also were used similarly to determine if changes in hue *and* lightness improve or impair map perception. Hypothetically, schemes that use hue and lightness differences to symbolize sequential data should improve the reader's abilities because combining multiple visual variables increases the perceptual differences between each of the classes (MacEachren 1995). But as highlighted previously, color vision and hue discrimination tend to deteriorate with age. In this research, testing these multi-hue color schemes may show if there is a significant improvement among older individuals.

While each of the five colors in the four sequential color schemes was created to be distinguishable from the adjacent colors based upon their value, hue did change across each of the four schemes. For example, even though the two single hue sequential schemes were both created with similar sequences of values, they still used two spectrally distinct hues (green and purple). Thus, no direct comparisons will be made between these schemes. Only each scheme's overall effectiveness will be evaluated.

Sequential color schemes are optimal for symbolizing ordinal population density information because there also is an intuitive order to the colors, and spectral schemes are rarely used as they do not provide the same perceptual order. However, when one distinguishes between different classes, hue changes could potentially be more obvious than lightness and saturation changes. This is especially true for older individuals whose vision might have declined with age. Thus, two spectral schemes also were evaluated to test this hypothesis. The first scheme was calculated using the HSB color model. As discussed above, HSB is a cylindrically defined color space in which users can define a color based on saturation percentage, value percentage, and hue angle. The spectral scheme was designed to vary systematically the hue angle in this three-dimensional space while keeping the brightness and saturation percentages similar. The second spectral scheme was adapted from a color scheme designed by Gretchen Peterson (2009). While similar to the first spectral scheme, the second one reduced the saturation and brightness values as well. These two maps also provide information about user preference in addition to the effects of hue change. Their inclusion attempts to determine if older individuals find maps with colors from throughout the spectrum to be more aesthetically pleasing.

While color is the basis of this research, a grayscale scheme was tested because of its widespread use, especially within printed cartography. Due to the difficulty and cost that accompanies printing color maps, grayscale is often the optimal scheme (Green and Horbach 1998). From academic journals to newspapers, people encounter and examine grayscale maps continually. The grayscale scheme adapted from ColorBrewer simply symbolized each of the five colors as percentage black using the CMYK model with each color approximately 20% greater than its preceding color. Combined with the six maps detailed previously, this diverse series of maps were used to test the hypotheses stressed at the beginning of this thesis. (For actual samples of the colors used, see ***Figure 3.1***. Each of the seven color schemes are also specified in RGB, CMYK, and HSB formats in Appendix A and CIE $L^*a^*b^*$ in Appendix B at the conclusion of this thesis.)

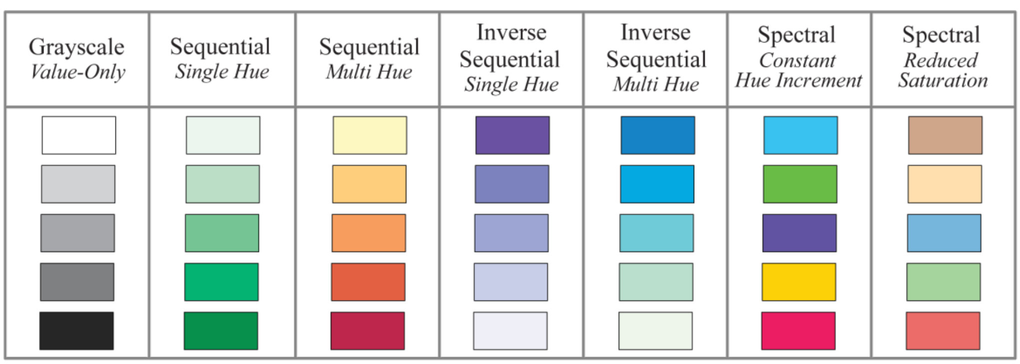

Figure 3.1: Color schemes tested (detailed specifications in Appendices A & B)

3.2 Map Testing

The main test sequence of the study presented the seven maps to groups of individuals older than 55 years of age. Six separate groups were tested across the states of Maryland and Wisconsin under similar conditions between August and October 2011.

Each of the participants that consented to participate in the study spent approximately one hour viewing and evaluating the color schemes. Upon completing the seven map tests, further information was gathered from the individuals to better understand the effectiveness of both the schemes and the tests themselves. Both the quantitative and qualitative data obtained using these methods will be elaborated upon in the results section that follows this chapter.

3.2.1 Pre-Testing

Before administering the tests to the participating individuals, a series of sample maps were used both to explain the research objectives and to familiarize subjects with map reading. Also, initial personal information was collected that would be used to evaluate the differences among visually-impaired, gender, and age groups.

Subjects and Testing Environment

The subjects for the study included 50 independent-living individuals ranging from 58 to 92 years of age. All were residents of a retirement or independent-living community and still largely active. Having active and still independent individuals for this study was especially important because the addition of subjects without most of their full complement of faculties may add unquantifiable biases to the statistical results (i.e., possible misinterpretation of the questions or failure to process the map). Also, senior citizens in need of a higher level of care (e.g. nursing homes and assisted living) are less likely to encounter and use maps in their daily lives.

The retirement and independent living communities used in the study were chosen because of their wide variation of individuals and willingness to participate. This wide range included people across the socio-economic and educational spectrums. Initially, the researcher made contact with 40 locations across the Madison, Wisconsin and Baltimore, Maryland metropolitan areas to find interested venues and participants. Community coordinators from six locations (three in each of the Baltimore and Madison areas) responded with interest and those locations were used for the study.

A problem with testing across different venues, especially related to color testing, is controlling each of the environments. As color perception is directly related to the nature of light's interaction with both the map and participants' eyes, the lighting at each of the sites needed to be as similar as possible. Even though it was impractical to ensure that the illuminants at each venue were exact, rooms at each location were chosen that provided consistent and uniform lighting. Also, each room provided sufficient space and tranquility so that the participants could focus and complete the test without distraction.

Map Familiarization

Before administering the test, an unrelated series of maps were presented to the participating individuals in the form of a map gallery. Using approximately four maps, the historical development of color's use in cartography was described with the purpose of communicating the need to understand the positives and negatives associated with using color to present geographic information. This map gallery also was used to familiarize individuals with the maps and map elements needed to answer the test questions. Upon completion of the map gallery, a final sample map similar to the test maps was presented.

During this beginning stage of the study, an instruction sheet (see Appendix B) also was distributed that detailed the aspects of the tests and provided a sample of possible test questions and answers. To avoid confusion, every possible answer and question pair was outlined to ensure that the subjects answered each question with the correct type of answer during the actual test. After outlining the specifics of the test and answering participants' questions, the final sample map was used to review each of the sample questions. Whereas the test maps depicted theoretical data, the sample map presented the actual population density of the state of Wisconsin using the same classification scheme in order to familiarize them with the map legend and symbolization. Both of these were identically formatted to mirror those found on the test maps.

Biographical and Color-Vision Data Collection

For analytical purposes, personal information was collected from the participants. Previous cartographic and color research suggests that age (Bartz 1971; Sorrell 1978; Roy et al. 1991; Kinnear 2002) and gender (Silver and Ferrante 1995; Dittmar 2001; Bimler et al. 2004; Lloyd and Bunch 2005) influence both color perception and preference. To test the viability of this hypothesis, a biographical sheet was handed out asking for the participants' age and gender. In order to ensure confidentiality during this study, the subjects also were instructed not to write their names on the sheet to reassure the individuals that their personal information would not be traceable back to them.

On the biographical information sheet, each individual was asked to disclose if they had any known issues that could impair their ability to distinguish between different colors. In addition, individuals were asked to record any information that they believed could negatively influence their ability to answer questions requiring map analysis. Following the third test map, the subjects' color-vision abilities also were evaluated via Ishihara Tests. During the test, six colored plates consisting of a series of dots of varying size and color were presented to the participants, and each person was asked to identify a number formed by the pattern. If they incorrectly interpreted the number or failed to see it at all, that would indicate the possibility that the individuals may be color-vision impaired. However, even though the Ishihara Test is one of the most widely used and efficient tests for detecting color-vision deficiencies, the Ishihara plates used in this study are only a subset of the complete test and will not identify rarer color-vision impairments like tritanopia (Birch 1997).

3.2.2 Quantitative Methods

Following the collection of biographical information, test packets consisting of seven envelopes were handed out to each participant. Each envelope, labeled one through seven, contained both a map and a series of twenty questions about the map. To avoid biases that accompany improvement and increased familiarity with the test, the order of the maps was randomized. The random numbers used to seed each set of maps were derived from a random number generator developed by Mads Haahr (random.org). Unlike many of the common randomizing algorithms that only generate pseudo-random numbers, this method provides a “true” random number set by eliminating the predictability inherent in mathematic formulas.

Test Questions

A series of twenty questions were distributed within each envelope to judge the effectiveness of each color scheme for communicating information. Each question sheet had the same questions, but similar to the map order, every five questions were arranged randomly. This gave individuals the impression that they were answering different questions for every map, but of course each question on one map could be related directly to the questions on all of the other maps. The subjects were given three minutes to complete as many of the twenty questions as possible. However, only the first five questions were used for the comparative analysis because the participants were only expected to complete those in the allotted time. All subsequent questions were used only to quantify the speed at which each map could be analyzed. If one map had more questions answered, this possibly indicates that the associated color scheme could be interpreted more quickly.

The first five questions used for comparative analysis were designed with different map use objectives in mind, and differed from each other in terms of sophistication (identify, compare, and rank) and search level (elementary and general). The *identify* objective asks users to examine a single feature; the *compare* objective is used to determine the similarities / differences between two or more features; and the *rank* objective has the map reader order the map features based on particular criteria (Roth 2011). As one progresses through this hierarchy from identify to rank (with compare in between), one would expect the users' performances to decrease due to the increased sophistication of the task. In terms of search level, *elementary* tasks address individual features, while *general* tasks involve interaction with multiple features (Andrienko et al. 2003). ***Table 3.1*** describes each of the five questions based on interaction objective and search level. (See Appendix C for a sample question sheet.)

Example Map Question	***Objective Primitive***	***Search Level***
What is the population density of City B?	Identify	Elementary
The population density of State L is__ than State A?	Compare	General
Which of the four cities on the map (A, B, C, or D) has the highest population density?	Rank	Elementary
What is the majority population density of State E?	Rank	General
What is the majority population density of State B?	Rank	General

Table 3.1: Questions used for map test and their respective objective primitive and search level

Confidence Level

While answering each of the test questions, participants also were asked to rate their level of confidence and the ease at which the answer was determined. Their confidence level was rated on a one to five scale. A confidence value of '1' indicated that the answer could not be determined by the subject and that the answer was a complete guess. A level of '5' signified that the answer was easy to determine and indicated full confidence that the answer was correct. Values '2' through '4' represented intermediate confidence rankings. This data helped to validate the research findings by indicating if the correct answers were attributable to auspicious guesses rather than deduced from the map.

3.2.3 Preference Evaluation and Discussion

Following the completion of each of the seven series of twenty questions, the subjects were instructed to place each map and question sheet into their respective folders and place the packet aside. Before adjourning, data was collected to better identify user preferences and evaluate the testing process. The subjects first identified their favorite and least favorite maps based on various criteria. A cognitive interview then was proctored by the researcher in which the individuals elaborated upon their opinions and provided insight into common issues with maps that they encounter during their daily lives.

Map Rankings

A brief questionnaire first was distributed to each of the participants in order to address user color preferences. On the questionnaire, the individuals initially were asked to identify the best and worst maps in terms of their communicative effectiveness. Next, they were instructed to rank the maps based simply upon their aesthetic appeal. Finally, taking each of the previous answers into account, the subjects evaluated each of the maps in terms of their overall efficacy. This sheet also was used to help the subjects think more critically about each of the maps and served as a springboard for the focus group portion of study.

Focus Groups

To better understand *why* certain maps and color schemes yielded better performance measures or were more preferred, a series of six focus groups were also held in conjunction with the map tests. As defined by Morgan (1996, p. 130), "[A focus group is] a research technique that collects data through group interaction on a topic determined by the researcher." For this study, the discussion focused on understanding how the individuals rated each of the color schemes and identified important general map reading issues they faced. This interaction also provides the researcher with important information "on the extent of consensus and diversity among the participants," thus explaining the results of the map test portion of the study (Morgan 1996, p. 139). Follow-up focus groups were also an appealing choice because they encourage interaction between the participants and are less affected by moderator bias than more traditional interviews (Monmonier and Gluck 1994). The following paragraphs describe how this part of the study was organized, moderated, and analyzed.

During the initial planning stage, the goals of the sessions were identified to address the questions posed in Section 1.1. Specifically, the focus group addresses the last two questions that seek to identify which color schemes were informatively and aesthetically preferred. Also, a focus group protocol (see ***Table 3.2***) was developed during this stage to outline the discussion. This helped to ensure that comparisons and consensuses can be made across each of the six separate groups. Even though focus groups of this type should last approximately an hour, in this case the design goal was only thirty minutes as the group would follow a map test lasting forty-five to sixty minutes.

During the actual moderated sessions, the researcher acted as the moderator – the individual responsible for leading the discussion and keeping the individuals focused on the particular questions (Roth 2009). In previous focus groups, the typical focus group size ranges from four to twelve individuals (Twohig and Putnam 2002). During each of the six sessions, an average of eight individuals participated (with a minimum of three and a maximum of thirteen). Because they had time constraints five of the fifty individuals that participated in the map test did not participate in the follow-up focus group. Since this number only represented about 10% of all participants and the participants that remained were largely representative of the total, this was not expected to bias the results. Each session lasted approximately twenty minutes, and participant responses were recorded (using a laptop) by the moderator.

Question Type	***Question Description***
Transition	We will now move to the next portion of the study. We will discuss the particulars about the test maps, and expand this discussion to issues that you may encounter in your daily life.
Introduction	We will first address each of the test maps individually based on the rankings identified previously, and then we will address map-reading issues that you encounter frequently.
Test Map Questions (Discuss each map – A to G – individually)	How many of you regarded this map as informatively-effective? Probe: Why was this map especially effective? Probe: Do any experiences in your lives influence this opinion? How many of you regarded this map as visually-appealing? Probe: What about this map supports this opinion? Probe: Do any experiences in your lives influence this opinion?
General Map Questions	Do you encounter any map-reading problems during your daily lives? Probe: How would you improve this problem? What are the most common types of maps that you encounter? Probe: What aspects of these maps are problematic? Probe: How would you improve these maps?
Denouement	Are there any final comments or questions?

Table 3.2: The focus group protocol divided into five sections: 1) a transition statement, 2) an introduction to the discussion, 3) a series of test map questions, 4) a series of more general map questions, and 5) a conclusion.

During the discussion, each of the maps was addressed individually and comparatively. While the subjects' objectives during the test were to answer the questions correctly and as quickly as possible, the discussion asked them to think more critically about each of the maps. Also, individuals were encouraged to expand their opinions beyond this study to address the wider problems that older individuals face regarding map reading. Following the discussion section, the data acquisition portion of the study was concluded.

3.2.4 Spectrophotometric Measurements

As described during the literature review, desired printed colors may look completely different when translated to or from another medium (e.g. the computer). Even though the colors used in this study are not equally spaced perceptually, each color was designed produced to be as easily distinguishable as possible from the others within the scheme. However, ensuring that these colors were equivalently differentiable after printing posed a major challenge. To better specify the colors used in this study and understand if the colors became less distinct upon printing or changed significantly from those desired, the colors used were specified using the CIE $L^*a^*b^*$ model. This model was chosen because it mirrors human visual perception and can be measured for both the digital and printed maps unlike each of the other schemes. The CIE $L^*a^*b^*$ values for the digital maps were defined by inputting the CMYK values for each into Adobe Photoshop's Color Picker. The values for the printed maps were measured using a spectrophotometer (an instrument for measuring the abilities of materials to reflect or transmit light).

The following section provides an analysis of the printed colors that each subject viewed. These results strongly highlight the need to standardize color schemes for printed map production.

Appendix B depicts a series of spectral reflectance curves for the colors printed on the final maps acquired through spectrophotometric measurements. Each of these lines represents the percentage of light reflected across the spectrum for each color and subsequently the light reflected back to the participants' eyes. For example, a comparison of the two spectral color schemes shows that the first scheme reflects considerably more light across the majority of the colors. Also, as evident in the first five color schemes, as the colors get lighter, the reflectance of the dominant wavelengths increases. These changes allow the map readers to perceive the various class distinctions and answer questions based on the information. (Note: the dashed curve for the value-only scheme symbolizes the reflectance of "white".)

However, even though the spectral reflectance curves illustrate differences across each of the printed colors, ***Table 3.3*** and Appendix B also shows that the printed colors were fairly different from the colors chosen digitally. By comparing the *CIE L*a*b** values for both the computer-generated and printed colors, it is evident that the majority of the measured printed colors had much lower *L** values than their computer-generated counterparts. This difference indicates that less light is being reflected to the viewers' eyes, thus most of the colors became darker upon printing.

In addition to the darkening of the colors attributable to the printer, there were also differences regarding the *a** (green / red) and *b** (blue / yellow) axes. Across the value-only, single hue sequential, and inverse sequential schemes, most (19 out of 20) of the *a** values of the computer-generated colors were lower than those measured from the paper maps. Therefore, the colors actually used for the study were redder than the colors initially chosen. Conversely, the majority (6 out of 10) of the two spectral schemes' colors had higher *a** values when produced digitally (more green).

While the changes to the *a** values were different across the various color schemes, the *b** values changed consistently. For each of the schemes, the majority of the colors had lower *b** values when printed, often considerably so. Consequently, the printed colors were also largely bluer than those chosen on the computer. These changes indicate that some of the colors were much different than those initially chosen. However, these differences are fairly uniform across each of the schemes, and the colors remained differentiable. For that reason it seems likely that deviations from the design colors played a limited role in the results.

The exhibited differences between the computer-generated and printed colors in this study's maps highlight the need to better standardize the colors used in thematic mapping. Color choices are difficult to make, especially when designing for different map media using varying color models. Therefore, further adaptation of the *CIE L*a*b** color model is recommended based upon these results. While the RGB and CMYK models are used often for digital and printed maps, respectively, their gamuts do not coincide, and their colors often cannot be translated exactly. In addition, these models are also largely reliant on the individual devices with which the colors are produced. Conversely, the *CIE L*a*b** model is device independent and interchangeable across various media. Thus, in order to better communicate, translate, and standardize the colors used to produce maps, the *CIE L*a*b** or one of the other standardized perceptual models should be increasingly utilized.

Color Scheme	*Description*	*Changes When Printed*
	Grayscale scheme designed to only distinguish classes using value / lightness	Each of the five colors (except for the second one) became darker, and they all became more red and blue
	Green sequential scheme that uses increased value to distinguish between classes	Each of the five colors became darker and more red; the first three are more blue; and the last two are more yellow
	Multi hue sequential scheme that changes in both hue and value for each class	Each of the five colors became darker and more blue, while each color (except for the first one) became more green
	Purple sequential scheme that uses saturation to distinguish between classes; scheme is inverted to equate low densities with dark and highly saturated colors	The second, fourth, and fifth colors became lighter, more red, and more blue; the first color became darker, more green, and more yellow; and the third color became darker, more red, and more blue
	Multi hue sequential scheme that uses saturation and hue to distinguish between classes; scheme is inverted to equate low densities with dark and highly saturated colors	The first color became lighter, more red, and more yellow; the second color became lighter, more red, and more blue; and the third, fourth, and fifth colors became darker, more red, and more blue
	Spectral scheme designed to use only hue to distinguish between classes; increments the hue angle in equal intervals using HSV color model	Each color became darker; the first and second colors because more red and more blue; and the third, fourth, and fifth colors became more green and more yellow
	Spectral scheme adapted from Peterson (2009) to lessen the saturation of each hue in order to determine if the participants appreciate less saturated color schemes	Each color became darker and more blue; the first, second, and fifth colors became more green; and the third and fourth colors became more red

Table 3.3: Description of each color scheme and explanation of how the colors changed when they were printed

4 Results

In the introductory chapter, several questions were posed in order to better address how retirement-aged, still independent individuals understand and appreciate colored maps.

Through the use of quantitative testing and qualitative discussion, this study addressed these questions to determine if color usage on maps should be re-evaluated, especially when communicating with older people. This chapter provides a summary of the test results and answers to these multifaceted questions. Also, at the conclusion of this chapter, an analysis of the colors devised and the colors actually printed will be provided to identify changes to the colors during printing.

To better evaluate each color scheme's effectiveness and variation, each of the color schemes will be referenced based on those detailed in ***Figure 1*** (see Section 3.1.2). Throughout this discussion of the results, it must be noted that several participants chose to withdraw from the study after the test began. None of their results are included in these analyses. In addition, three of the individuals that did complete the entire map test failed to answer one to two of the sample maps. Their results *have* been included in these results.

4.1 Overall Performance

To evaluate the overall effectiveness of each color scheme, the five questions that were asked during testing were categorized based on the objective primitives detailed in Section 3.2.2 (see Appendix C for a sample of the questions asked). As proposed in Section 3.2.2, increasing the sophistication of the interaction objective should decrease the users' performance, and the results highlighted in ***Table 4.1*** support this hypothesis to a large degree.

Map Question	*Value-only Scheme*	*Sequential (normal) #1*	*Sequential (normal) #2*	*Sequential (inverse) #1*	*Sequential (inverse) #2*	*Spectral Scheme #1*	*Spectral Scheme #2*
Point Identify (elementary) mean = 82.70%	90.00%	80.85%	93.75%	**60.00%**	81.63%	78.72%	**94.00%**
Area Compare (general) mean = 85.26%	**96.88%**	90.63%	89.29%	**60.98%**	82.93%	87.50%	94.59%
Point Rank (elementary) mean = 63.43%	67.35%	71.74%	64.00%	**32.65%**	55.32%	75.00%	**78.00%**
Area Rank (general) #1 mean = 75.89%	77.55%	72.92%	80.85%	**55.10%**	77.08%	**87.23%**	81.25%
Area Rank (general) #2 mean =65.68%	69.39%	**73.33%**	71.43%	**48.94%**	55.10%	71.43%	70.00%
Overall Performance *mean = 74.02%*	**79.04%**	**77.06%**	**78.83%**	**51.27%**	**70.09%**	**79.65%**	**82.98%**

Table 4.1: Subjects' performance (percent correct) for each color scheme
(**Green** = highest perecentage; **Violet** = lowest percentage)

The results in ***Table 4.1*** show that inverting the sequential schemes to illogically equate low attribute values with darker colors had a profound impact on the overall performance, thus illustrating that deviating significantly from the norms of color usage can negatively affect the usefulness of a given map. Another interesting observation evident for most of the five questions is the performance of the two spectral schemes. While these schemes are inherently unable to show patterns across mapped areas and are thus rarely used to symbolize ordinal data, they largely outperform the other more common schemes for general and elementary map questions. This indicates that hue changes may be more perceptive to older individuals as their ability to distinguish saturation and value changes declines along with visual acuity.

The most striking number (79.04%), however, is the overall performance of the grayscale (value-only) scheme, which has the third best performance behind only the two spectral schemes. This is surprising because value is the only visual variable that is used to distinguish between densities, while the others incorporate saturation and value as well. This unexpectedly high performance possibly could be tied to the individual's personal experiences with maps, especially during their formative years. Studies have shown that memory and learning experiences during one's childhood can have a major impact on map-reading abilities (e.g., Matthews 1980; Lloyd and Bunch 2008). Since color-printed maps were much less common 60-80 years ago and monochrome newspapers were a predominant method for communicating geographic information at that time, the participant's experience and constant practice with value-only color schemes could contribute to their improved ability to interpret the grayscale map. However, this result's magnitude should not be overstated, as only the readers' performance on the lowest two levels of the objective hierarchy (identify and comparison) greatly outperformed the sequential color schemes. This indicates that the use of value-only schemes may be inappropriate for ranking tasks.

To determine if there is significant variation amongst each of the seven color schemes, a single factor analysis of variance (ANOVA) test was run. An ANOVA test was chosen because it limits the chance of wrongly rejecting the null hypothesis that would accompany a comparison of multiple t-tests (Bluman 2009). In order to properly perform an ANOVA test, two assumptions must be made. First, the populations used to acquire the sample must exhibit a normal or near normal distribution. Secondly, the distribution of variance should be equal within the population (Burt et al. 2009). Given the distribution of the samples and variation of the individual samples, both of these suppositions were assumed. For this test, the objective was to reject the null hypothesis that the means of the seven schemes are equal[1]. The results of this test are detailed in ***Table 4.2***.

Source of Variation	*SS*	*df*	*MS*	*F*	*p-value*	$F_{critical}$
Between Groups	3.603938	6	0.600656	9.411888	1.45E-09	2.125271
Within Groups	21.69843	340	0.063819			
Total	1846.128	344				

Table 4.2: Single factor ANOVA test performed on the seven color schemes ($\alpha = 0.05$)

Since the *F* test value (9.411888) is greater than the *F critical* value (2.125271), the null hypothesis can be rejected at the 95% confidence interval based on this sample. This means that the population means and the dissimilarities observed in ***Table 4.1*** are statistically different in terms of the readers' overall performance. Based on these results, it can be concluded that the color schemes impact the individuals' ability to answer the test questions correctly.

Since the results of the ANOVA test allow us to reject the null hypothesis, Scheffé's post-hoc test was utilized to locate which color schemes were significantly different from the others. The results of this test are summarized in ***Table 4.3***. These results indicate that the individuals' performance on the first inverted sequential color scheme (Map D) significantly differed from each of the others (the test statistics calculated by comparing the means are greater than the *F' critical* value of 12.7156). This indicates that breaking from current-day conventions greatly alters and limits a map's

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[1] $H_0 = \mu_{ValueOnly} = \mu_{Sequential\#1} = \mu_{Sequential\#2} = \mu_{InverseSequential\#1} = \mu_{InverseSequential\#2} = \mu_{Spectral\#1} = \mu_{Spectral\#2}$

H_A = at least one μ does not equal the others effectiveness, at least when communicating information to older individuals.

	A	*B*	*C*	*D*	*E*	*F*	*G*
A	0.00	0.11	1.03	**30.33**	0.00	3.69	0.63
B	0.11	0.00	1.79	**33.73**	0.15	5.01	0.21
C	1.03	1.79	0.00	**20.16**	0.93	0.81	3.26
D	**30.33**	**33.73**	**20.16**	0.00	**29.75**	**12.86**	**40.03**
E	0.00	0.15	0.93	**29.75**	0.00	3.49	0.71
F	3.69	5.01	0.81	**12.86**	3.49	0.00	7.34
G	0.63	0.21	3.26	**40.03**	0.71	7.34	0.00

***Bold** = significant differences

Table 4.3: Results of Scheffé test used to determine if each of the color schemes performed significantly different from the others

4.2 Age and Map-Reading Performance

Based on the statistics acquired in the previous section, it was determined that the color schemes alone did not significantly hinder the individuals' ability to extract information from the maps, except for scheme D. The next step of this study's analysis attempted to determine if age explains the differences exhibited in the performance results among the older age groups. Given the increasing longevity of retirement-age individuals, the age range of the elderly continues to expand. This analysis could identify if there is a significant decline in map performance in the years after age 59. ***Figure 4.2*** displays the age range of the individuals included in this analysis.

Regression analysis was used to search for a relationship between age and performance. Specifically, a linear regression of performance on age was performed to determine if a relationship exists between age and performance (see ***Table 4.4)***.

The results suggest that there is a statistically significant relationship between age and map-reading ability at the 95% confidence level among older individuals. Based on the coefficient of determination, about 36% of the overall variation of the users' map-reading performance can be explained by age. This indicates that even though the results

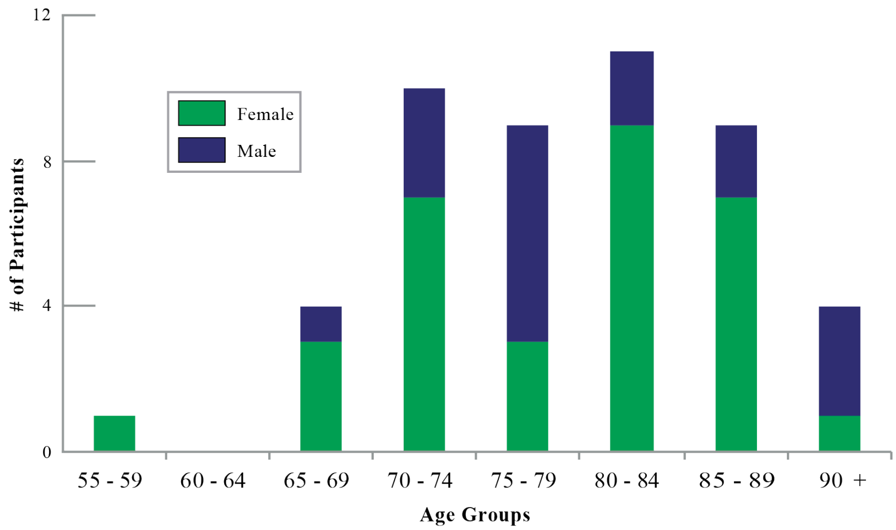

Figure 4.2: Subjects' gender across the various age groups

	n	R^2	*Std. Error of Estimate*	*Coefficient*	*Std. Error of Regression*	*t*	*p-value*
Male	17	0.359	0.139	-0.014	0.005	-2.897	0.011
Female	31	0.003	0.154	-0.001	0.003	-0.313	0.757
Both	48	0.082	5.583	-0.213	0.105	-2.026	0.049

Table 4.4: Results of linearly regressing map-reading performance on age

suggest that age and performance are inversely correlated, the strength of this association is modest and should be further evaluated with a larger and more representative sample.

After regressing overall performance on age across the entire sample, female and male subjects were analyzed individually to determine if there is a gender aspect to this relationship (see ***Table 4.4***). At the 95% confidence level, only the male participants' performance correlates with age, however, with only 31 females in the sample, the chances of encountering a Type-II error are high, and it would be a mistake to conclude that age and performance are not related among women. Future research should focus on increasing the sample size to identify if this relationship exists for females.

When aggregated to depict overall performance, the previous results have shown that age and map-reading ability are inversely correlated, although they do not show which of the maps' characteristics contributed the greatest to that relationship. To evaluate each color scheme's impact, the subjects' performance for each map was regressed on age (see ***Table 4.5***). Based on this analysis, it appears only performance on the value-only (grayscale) scheme and the second inverse sequential scheme are significantly related to age at the 95% confidence level. The R^2 values suggest fairly weak negative relationships, with 19.3% and 15.6% of the variation of performance can be explained by age, respectively.

The effects of age on the subjects' performance cannot be seen for the multiple hue sequential (p = 0.290) and two spectral schemes (p = 0.891 and 0.682). This largely supports the hypotheses in Section 1.3. Since hue differences are easier to distinguish than value and saturation changes, these multiple hue spectral schemes logically performed better throughout the sample. However, the maps tested in this study only address the more elementary levels of map-reading and do not address more sophisticated

Color Scheme	*n*	R^2	*Std. Error of Estimate*	*Coefficient*	*Std. Error of Regression*	*t*	*p-value*
Value-only Scheme	47	0.193	0.188	-0.013	0.004	-3.284	0.002
Sequential (normal) #1	47	0.003	0.298	0.002	0.006	0.340	0.736
Sequential (normal) #2	48	0.027	0.219	-0.005	0.004	-1.135	0.262
Sequential (inverse) #1	48	0.024	0.299	-0.006	0.006	-1.070	0.290
Sequential (inverse) #2	47	0.156	0.247	-0.014	0.005	-2.889	0.006
Spectral Scheme #1	47	0.000	0.234	-0.001	0.004	-0.138	0.891
Spectral Scheme #2	47	0.004	0.155	-0.001	0.003	-0.412	0.682

Table 4.5: Results of linearly regressing each map's performance on age

map-reading tasks. Therefore, trends across the entire mapped area are not apparent using spectral schemes, and thus these schemes often are avoided when representing ordinal data (Brewer 1997).

While the two spectral schemes are unable to communicate order effectively, sequential schemes such as those used in this study have been widely applied to this quantitative data. Thus, these results suggest that combining the positive aspects of each of these schemes (i.e., the contrast between the hues in the spectral schemes and logical order of the sequential schemes) would produce both a more informative and aesthetically-pleasing map. This suggestion supports Brewer's (1997) findings which determined that multi-hue schemes can be designed to parallel sequential schemes and even outperform them.

Differences between each of the questions also were addressed by regressing the performance for each question on age. These results indicate that if any relationship exists between age and the sophistication of the map-reading task, it is not evident within this study (see ***Table 4.6***) at the 95% confidence level. Thus, increasing the sophistication

Map Question	*n*	*R^2*	*Std. Error of Estimate*	*Coefficient*	*Std. Error of Regression*	*t*	*p-value*
Point Identify (elementary)	46	0.017	0.136	0.002	0.003	0.885	0.381
Area Comparison (general)	48	0.071	0.231	-0.008	0.004	-1.869	0.068
Point Rank (elementary)	48	0.061	0.286	-0.009	0.005	-1.725	0.091
Area Rank (general) #1	48	0.031	0.226	-0.005	0.004	-1.219	0.229
Area Rank (general) #2	45	0.015	0.196	-0.003	0.004	-0.812	0.421

Table 4.6: Ordinary least squares linear regression using age and question type

of the test objectives did not limit the ability of participants to process and understand the map.

4.3 Age, Confidence, and Speed

Much of the statistics and analyses described in the previous sections address how retirement-age individuals extract information from the maps. In addition to map-reading accuracy, confidence and speed also are important considerations during the design process. To determine if there is a relationship between these two variables and the age of the subjects, confidence and speedwas individually regressed on age (see ***Table 4.7***). At the 95% confidence level, there is no relationship between age and either speed or confidence. This is surprising because previous research by Gaylord and Marsh (1975) discovered that both objective speed and the time needed to mentally process spatial information declines with age, while this study found no significant decline. However, it must be noted that the measurement used to judge the individuals' speed differed between the two studies and could potentially contribute to the deviating results.

	n	R^2	*Std. Error of Estimate*	*Coefficient*	*Std. Error of Regression*	*t*	*p-value*
Speed	48	0.057	1.646	-0.052	0.031	-1.674	0.101
Confidence	48	0.037	0.377	0.010	0.007	1.287	0.205

Table 4.7: Results of linearly regressing participants' speed and confidence on age

In ***Table 4.7***, the speed and confidence of the individuals did not significantly relate to their age. However, the results of these linear regressions do not provide information about the impact of the color schemes. To address this issue, two separate one-way ANOVA tests were used to determine if any significant differences exist across each map (see ***Tables 4.8*** and ***4.9***). Based on the results (both *F* test statistics are less than their respective *F critical* values), there is not enough evidence to reject the null hypothesis of no difference between at least two of the means for either confidence or speed.

Source of Variation	*SS*	*df*	*MS*	*F*	*p-value*	$F_{critical}$
Between Groups	3.173935	6	0.528989	1.064597	0.383559	2.125672
Within Groups	166.4587	335	0.496891			
Total	169.6326	341				

Table 4.8: Single factor ANOVA test performed on the subjects' confidence rating for each scheme

Source of Variation	*SS*	*df*	*MS*	*F*	*p-value*	$F_{critical}$
Between Groups	56.6623	6	9.443716	1.78376	0.101601	2.12543
Within Groups	1789.465	338	5.294276			
Total	1846.128	344				

Table 4.9: Single factor ANOVA test performed on the subjects' speed for the seven color schemes

4.4 Overall Preference

While communicating geographic information effectively and accurately to readers is the most important aspect of map design, aesthetics must still be a focal point of cartographic theory (Kent 2005). Creating visually stimulating and pleasing maps should always be a consideration during the design process. Hence, in addition to addressing the communicative effectiveness of the schemes, the aesthetics of each of them were also addressed. To measure this, each individual was asked to indicate the best and worst scheme based on a set of defined criteria (see ***Table 4.10***).

Figure 4.3 displays the numbers of individuals that rated each map the best in terms of communicative effectiveness, visually-appealing nature, and overall effectiveness. Again, similar to the results of the map test, the highest-rated color

	Best Informatively	*Best Visually*	*Best Overall*	*Worst Informatively*	*Worst Visually*	*Worst Overall*
Value-only Scheme	4.3%	0.0%	2.1%	23.4%	**46.9%**	13.5%
Sequential (normal) #1	6.4%	16.7%	12.6%	6.4%	4.2%	2.1%
Sequential (normal) #2	25.5%	7.3%	15.8%	8.5%	2.1%	2.1%
Sequential (inverse) #1	4.3%	8.3%	4.2%	**47.9%**	26.0%	**64.6%**
Sequential (inverse) #2	2.1%	6.3%	4.2%	3.2%	4.2%	13.5%
Spectral Scheme #1	**29.8%**	29.2%	24.2%	8.5%	12.5%	2.1%
Spectral Scheme #2	27.7%	**32.3%**	**36.8%**	2.1%	4.2%	2.1%

*__Bold__ = highest percentage per category

Table 4.10: Percentages of subjects that rated each color scheme highest in each of the six categories n=50)

schemes were overwhelmingly the two spectral schemes. Individuals clearly favored the more "colorful" appearance of these schemes over those that simply differed in terms of value and saturation. Thus, these results support my initial hypothesis that variable hue and more fully saturated colors are preferred over the others. This corroborates previous research findings that suggest that individuals prefer spectral schemes (e.g., Brewer et al. 1997; Buckingham and Harrower 2007). In terms of the schemes' informative nature, the multi-hue sequential scheme was preferred nearly as often as the two spectral schemes. Again, this indicates that color schemes that use hue change, in addition to saturation and/or value variation, could best suit older individuals.

The subjects' lack of preference for the value-only scheme, however, is unexpected given the relatively good performance of the scheme during testing (see ***Table 4.1***). In the previous sections, the grayscale scheme was shown to perform third best overall behind only the two spectral schemes (see ***Table 4.1***), but the individuals did not acknowledge this post-testing. Only two individuals rated the scheme as

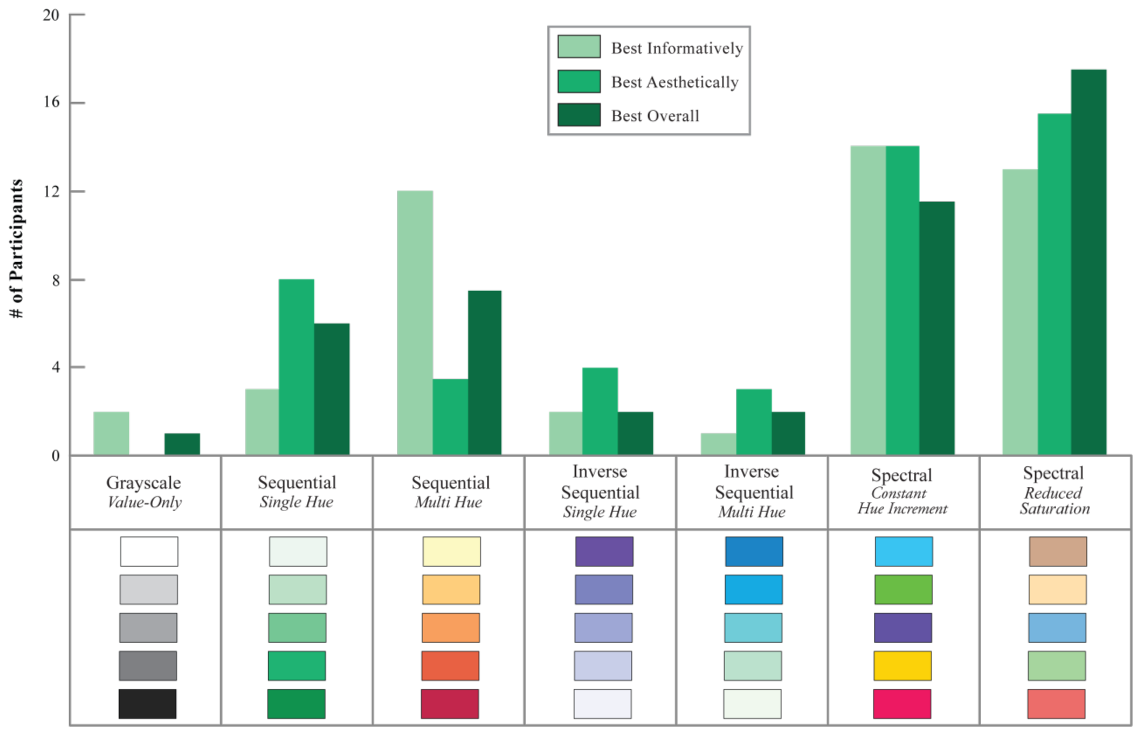

Figure 4.3: Totals for each map based on the maps' ability to communicate the information effectively, aesthetically-pleasing nature of the colors, and overall effectiveness

informatively effective, and only the two non-conventional schemes were preferred less often based on this criterion. The individuals' overall rating of the grayscale scheme is even more surprising as the two color schemes that performed the worst during testing and deviating significantly from the norm were actually preferred over the grayscale scheme. However, since color was the main subject of this research, grayscale and monochrome schemes were not a strong focus of this study, and future research should consider the utility of these schemes for communicating to a wider audience, not just older individuals.

The multi-hue schemes were preferred more often, while the grayscale and single hue inverted sequential schemes were rated especially poorly by the participants (see

Figure 4.4). Again, as apparent in ***Figure 4.3***, the individuals were strongly against the usage of the value-only and inverted color schemes to symbolize ordinal data. During the discussion portion that followed the test, subjects indicated that these schemes' relative lack of contrast greatly contributed to these poor ratings.

An especially interesting aspect is the performance of the multiple hue sequential color scheme relative to the grayscale one. Across each of the three ratings, the value-only scheme was much less liked by the participants. This indicates that even non-conventional color schemes can be more visually appealing and informative if there is adequate contrast among the colors and text. (See Section 4.6 for the participants' reasoning for these rankings).

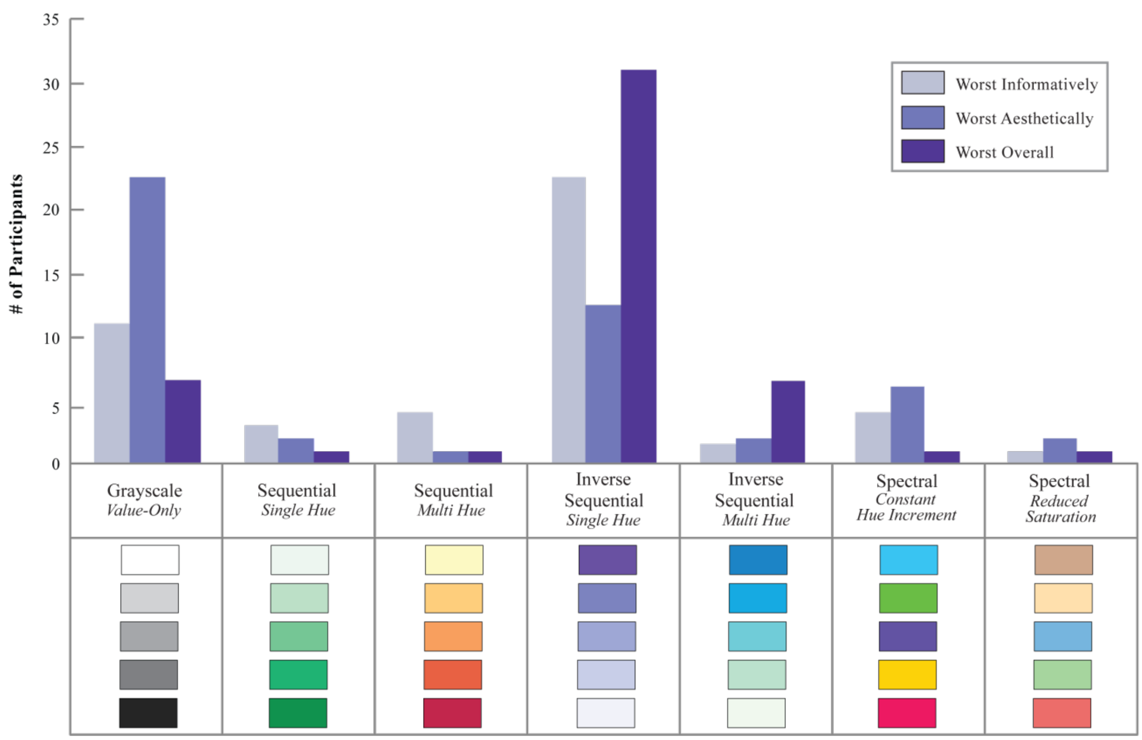

Figure 4.4: Totals for each map based on the maps' lack of ability to communicate the information effectively, poor visual nature of the colors, and lack of overall effectiveness

4.5 Gender Preferences and Perception

As discussed in the literature review, previous findings suggest that gender and the different experiences of men and women play important roles in defining an individual's color preferences and map-reading ability. The ability to identify gender-related differences was hindered by the small sample size and the overwhelmingly female composition of the sample, as is evident in ***Figure 4.5.*** The high female/male ratio is consistent with the longer life expectancy of women and the fact that older women largely outnumber their male counterparts (Humes 2005; Shrestha 2006). Since only 17 male individuals were tested in the study, this limits the ability to generalize these results to a wider audience, and suggests that future studies should focus on better understanding gender's effect on map-reading abilities.

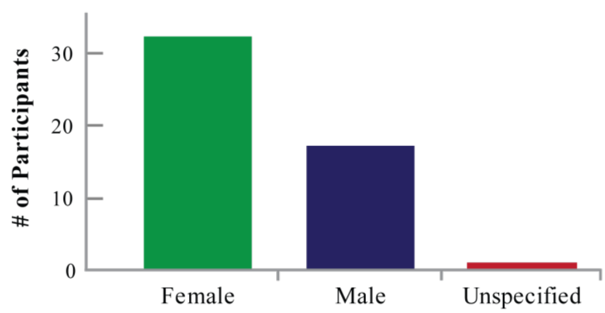

Figure 4.5: Gender of participating individuals (n=50) in the study

In Section 4.4, it was shown that the participants in the study significantly preferred the schemes that used a wider range of the spectrum with more contrast and brightness of the colors. To expand on these results, the participants' preferences also were compared across the genders to explore potential differences between men and women (see ***Figure 4.6***).

As was apparent in the participants' overall preference, the spectral schemes were overwhelmingly preferred by both genders. Half of the female participants and three-quarters of the male participants acknowledged that the two spectral schemes were by far the most effective. This high preference for these schemes suggests that using hue change to communicate classed thematic data could potentially be more effective than saturation and value changes, especially for lower order map objectives.

The results also show that women rated the two sequential schemes much higher than the men across the three ratings. For example, 39% of the female participants rated the sequential schemes to be the most informative, while only 18% of the male participants rated them highest. The large percentage difference between men and women for the most visually-pleasing (31% for women, 18% for men) and best overall (34% for women, 18% for men) color schemes also support the conclusion that women tended to more strongly prefer the schemes that were able to communicate order.

In addition to contrasting the most favored schemes, the worst ranked schemes also were compared across the genders (see ***Figure 4.7)***. These results suggest that there is a clearer consensus across the genders concerning the schemes that individuals dislike versus the ones they like. Just as the overall consensus was that the two inverse sequential schemes are unappealing (78.1%), a majority of both men and women equally rated these schemes poorly (65% and 85%, respectively). While many of the individuals strongly objected to the use of these unconventional schemes, no women and only two men rated the normal sequential scheme poorly. These results suggest that deviating from normal cartographic conventions greatly decreases the effectiveness and visual-appeal of a map for both men and women.

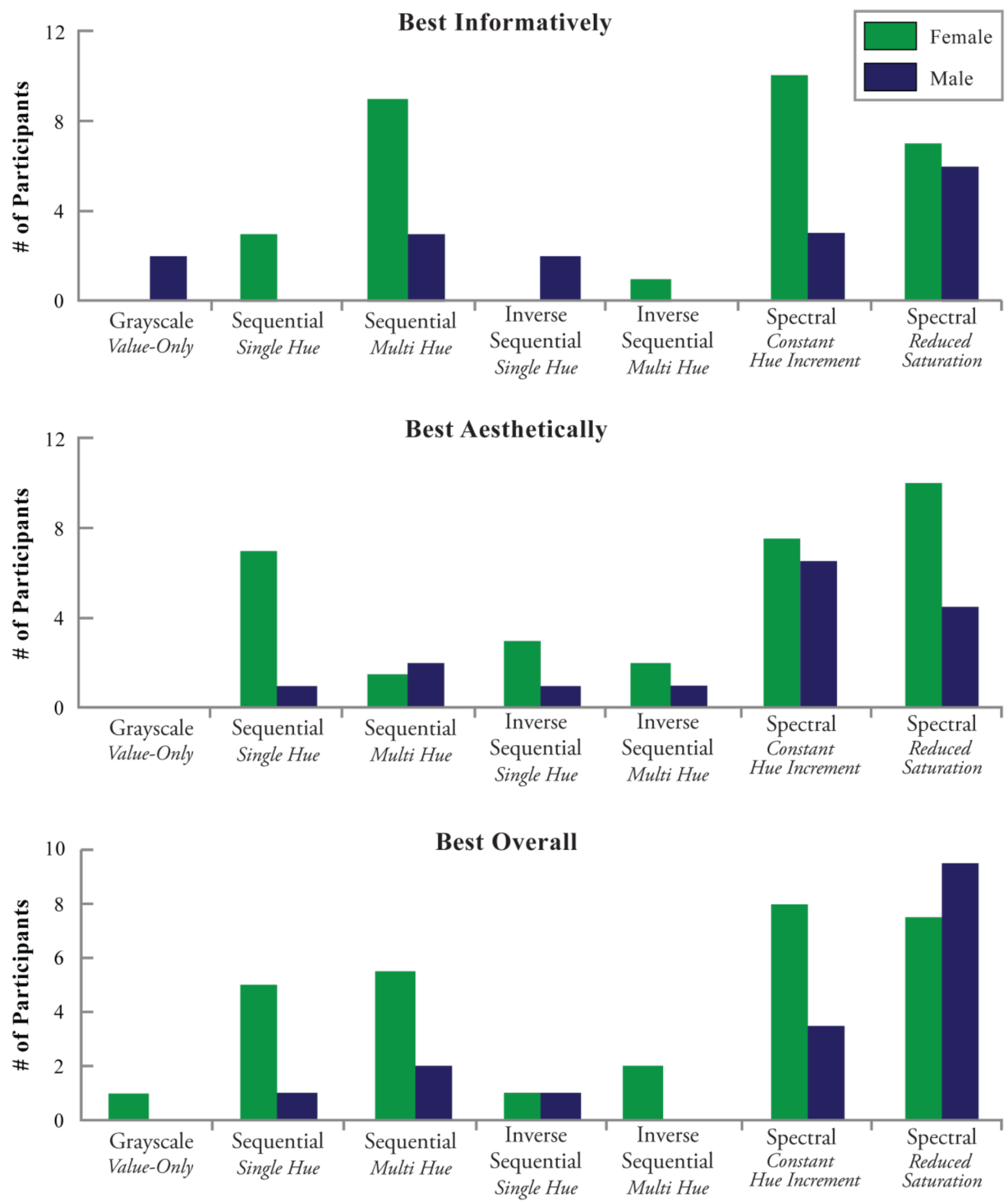

Figure 4.6: Totals of most preferred maps for male and female subjects

However, even though both genders agreed that the inverted schemes were the worst overall, there was a distinct difference between the men and women's opinions regarding the value-only scheme. While a plurality of both men (47.1%) and women (48.3%) agreed that the grayscale map was the least visually-appealing, a large

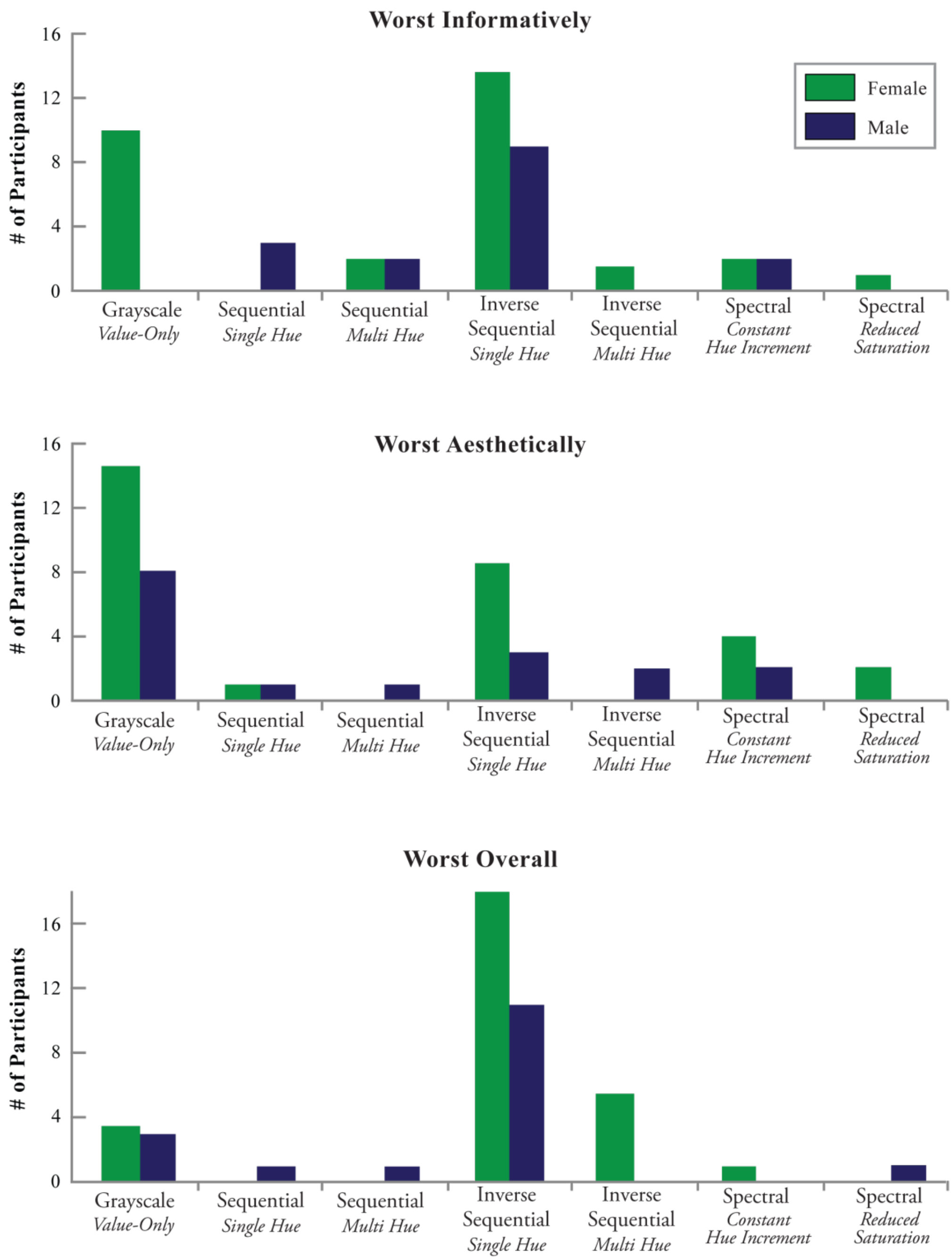

Figure 4.7: Totals of least preferred maps for male and female subjects

percentage of the female participants also rated it the worst scheme for communicating the information (33.3%). This rating, though, largely conflicts with the overall performance of the female subjects. In the test portion of the study, the value-only scheme performed nearly as well as the multi-hue schemes (less than 2 percentage point difference) among female participants, while the scheme was actually much less effective for communicating to the male individuals that actually had more favorable opinions (see ***Table 4.11***). This again supports the need to better understand the efficacy of the wide array of visual variables for communicating to the elderly.

Map Question	*Value-only Scheme*	*Sequential (normal) #1*	*Sequential (normal) #2*	*Sequential (inverse) #1*	*Sequential (inverse) #2*	*Spectral Scheme #1*	*Spectral Scheme #2*
Male mean = 73.26%	74.80%	73.53%	71.08%	55.29%	73.53%	77.65%	82.06%
Female mean = 72.56%	80.78%	72.58%	81.56%	46.67%	66.94%	81.94%	82.40%

Table 4.11: Percentages of correct answers for each map across genders

The performance statistics in ***Table 4.11*** largely support previous research findings indicating that there are no major differences between men and women in terms of color perception, even though small variations do exist (Kinnear and Sahraie 2002; Wijk et al. 2002). Although both men and women performed equally well overall, two small differences were evident. There was a ten percentage point difference between each gender's performance on the multi-hue sequential scheme, and women also performed much worse on the single hue inverted sequential scheme. However, given the relatively small number of participants, these results could be attributable to sampling and participant errors unrelated to the maps, and thus, future research should focus on expanding the sample size to better investigate these differences.

4.6 Qualitative Map Discussion Results

After testing the participants' map-reading abilities and acquiring their rankings for the various color schemes, the last part of the study involved discussing the users' experience with both the test maps and maps encountered during their daily lives. Most of the individuals echoed many of the results highlighted previously, but one major trend permeated each focus group: the *experience* of color.

Many of the individuals indicated that the color schemes they rated highest largely resulted from the feelings the schemes evoked. Some of the individuals stated that their most aesthetically-pleasing schemes reminded them of colors and color combinations by which they were frequently surrounded, and some suggested that past experiences shaped these opinions as well. For example, one individual preferred the single hue sequential scheme because of its perceived relationship to the colors of her garden. Since the color green had a special meaning and significance, it strongly affected the preference of the one individual. Thus, users' experiences with the colors played a profound role in the preferences described in Sections 4.4 and 4.5.

During the discussion, the majority of the participants' opinions were especially favorable towards the spectral color schemes. Individuals indicated that the increased differences between the classes and contrast between the text and features enhanced their abilities to determine the answers quickly and accurately. They also strongly favored the spectral schemes for their visual-appeal. As one individual summarized simply, "I just like a lot of colors," and many of the others concurred with the individual's sentiment.

In addition to addressing the issues related to the color schemes utilized for this study, general map-reading issues also were addressed. Because most of the participants are retired, their recent experiences with maps are largely those encountered in magazines and newspapers and those having utilitarian value (e.g., GPS and road maps). However, even though the individuals consistently encounter maps like these in their daily lives, many indicated that these maps were becoming increasingly hard to read. Although none of the individuals indicated that they had been diagnosed with color-vision impairments, the natural breakdown of vision does limit the ability to read text. For example, the smallest font size was fourteen for the maps in this study. Even though that size is larger than those found in many commercially produced maps, participants indicated that it was not large enough. This poses a major problem for designing maps, especially for individuals of this age group, because the map media, size of the map, and feature sizes often constrain the text to relatively smaller sizes. Digital maps potentially could improve this by allowing the users to control the size of the text and zoom to better visualize the information. However, individuals above the age of 55 have the lowest Internet usage, and only 25% of the United States' households of individuals 60 years of age and older own a personal computer (Kiel 2005). Thus, designing digital maps for the elderly does not help a significant portion of today's older population that does not have access to this technology. Thus, even though future generations of older individuals may have increased technological knowledge-bases, future research should focus on expanding upon this study to better design static maps for the current elderly population.

5 Conclusion and Future Directions

In the introductory portion of this thesis, four important questions were posed that addressed issues related to designing maps effectively for the elderly. Considering the relatively small size of the non-random sample used to address these questions, future research should focus on expanding upon some of the broader issues derived from this study. In this chapter, the results from Chapter 4 will be summarized based upon each of these questions, and future research considerations will be outlined to acquire a more holistic understanding of how aging influences map-reading abilities.

5.1 Summary of Research

In this section, each of the five questions raised in Chapter 1 are answered individually.

1) *How well do members of older age groups understand choropleth maps, and do they differ from other age groups*?

- Among individuals of retirement age, map-reading performance declines (~20% per year).
- As individuals age, they have no more difficulty with sophisticated interpretation tasks than less sophisticated tasks (at least regarding identify, compare, and rank objectives).
- There is no relationship between age and performance when using spectral color schemes.
- The time needed to mentally process choropleth maps and overall confidence does not vary significantly across age groups.

2) Do the gender or color-vision impairments of older individuals impact their ability to interpret the maps? Do these also affect their opinions regarding the aesthetic appeal of the colors?

- Only the male subjects' abilities significantly declined with age.
- When initially questioned, no individuals indicated having any color-vision impairments. Although six individuals performed poorly on the Ishihara Tests, the results did not equate to decreased map-reading abilities. Thus, the performance of older individuals with acquired color-vision deficiencies could not be addressed adequately in this study.
- Female participants rated the sequential schemes much higher than the men across the three ratings used in the study.
- Women ranked the value-only scheme much worse than the male participants.
- Older individuals prefer spectral schemes more than sequential ones.

3) Do different color schemes allow older individuals to interpret the information on choropleth maps more quickly and accurately?

- There is no significant difference between each of the seven color schemes in terms of map-reading speed.
- Color schemes that diverge from normal cartographic conventions considerably limit the maps' effectiveness.
- Spectral schemes, even though poorly suited for symbolizing ordinal data, perform better regarding the readers' abilities to identify, rank, and compare mapped information.

4) How do older individuals rate the varying color schemes in terms of visual appeal?

- Like younger age groups, older individuals prefer spectral and "colorful" schemes as well.
- The elderly do not rate grayscale schemes highly in terms of visual appeal.
- The aesthetic appreciation of color schemes is largely related to the individuals' experiences and relationship with the colors.

In order to mitigate the problems associated with these four questions, special measures should be taken when designing maps for individuals sixty-five years of age and older. Due largely to the decline of vision over time, type size should be increased to accommodate these individuals. Color contrast, especially in terms of value and saturation, needs to be increased as well. Finally, as suggested by the quantitative test and individual feedback, spectral schemes with inherent lightness / value changes are best for communicating to the elderly

In summary, this research suggests that age does influence the abilities of individuals to accurately interpret choropleth maps, and these differences are consistent with the scientific community's current understanding of the ways individuals process color and the effects of aging. While this research does not exhaustively address each of the problems outlined previously, it does provide insight into the extent of these issues and suggestions for future research foci. These future considerations are highlighted in Section 5.2.

5.2 Future Research Directions

While this study focused on the relationship between age and choropleth map-reading abilities, future research should investigate the problems older individuals encounter when reading any type of map. Color is only one of the many visual variables used to symbolize geographic phenomena, and these other factors can influence the communicative effectiveness of maps as well. Thus, future cartographic studies should also attempt to answer the following questions:

1) What roles do other traits (e.g., culture, race, and ethnicity) and experiences play in older individuals' map-reading abilities?
2) Can the results acquired through this relatively small and non-random sample be corroborated with larger and more representative samples?
3) Does gender significantly influence map color perception and preference among the elderly?
4) Are spectral color schemes useful for higher level map-reading tasks?

5) How can map typography be improved to better communicate text to individuals of advanced ages, especially in terms of size and contrast?

6) How does color map perception change from childhood to late adulthood?

Cartographic research over the past 30 years has strongly focused on color and its influences on the effectiveness of maps. However, it has been shown that age largely has been ignored in previous research, especially regarding older people. This is surprising because individuals aged 55 and older are becoming increasingly influential members of the workforce and are using maps later in life. This study attempted to address the issues related to map perception and preference among individuals of this age group and concluded that age does influence choropleth map-reading ability.

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A Color Schemes

Grayscale

Value-Only

CMYK	0 0 0 3	0 0 0 20	0 0 0 41	0 0 0 61	0 0 0 85
RGB	247 247 247	204 204 204	150 150 150	99 99 99	37 37 37
HSB	200 0 100	200 1 83	216 3 67	216 4 52	220 0 15

Sequential Scheme

Single Hue

CMYK	7 0 7 0	27 0 27 0	55 0 55 0	78 0 75 60	86 18 94 5
RGB	236 246 238	188 224 199	118 198 149	1 178 114	5 145 77
HSB	132 4 96	138 16 88	143 40 78	158 99 70	151 97 57

Sequential Scheme

Multiple Hue

CMYK	1 0 29 0	0 20 59 0	0 45 70 0	5 77 80 0	18 98 64 5
RGB	254 248 195	255 206 124	248 159 94	229 97 66	192 39 76
HSB	54 23 100	38 51 100	25 62 97	11 71 90	345 80 75

Inverse Sequential Scheme

Single Hue

CMYK	70 79 0 0	55 48 0 0	38 30 0 0	20 15 0 0	5 4 0 0
RGB	105 81 162	125 130 191	158 167 213	200 206 232	239 239 248
HSB	258 50 64	235 35 75	230 26 84	229 14 91	240 4 97

Inverse Sequential Scheme

Multiple Hue

CMYK	82 40 0 0	72 14 0 0	52 0 15 0	27 0 23 0	5 0 7 0
RGB	22 131 198	11 171 227	113 204 216	187 225 205	239 247 237
HSB	203 89 78	196 95 89	187 48 85	148 17 88	108 4 97

Spectral Scheme

Constant Hue Increment

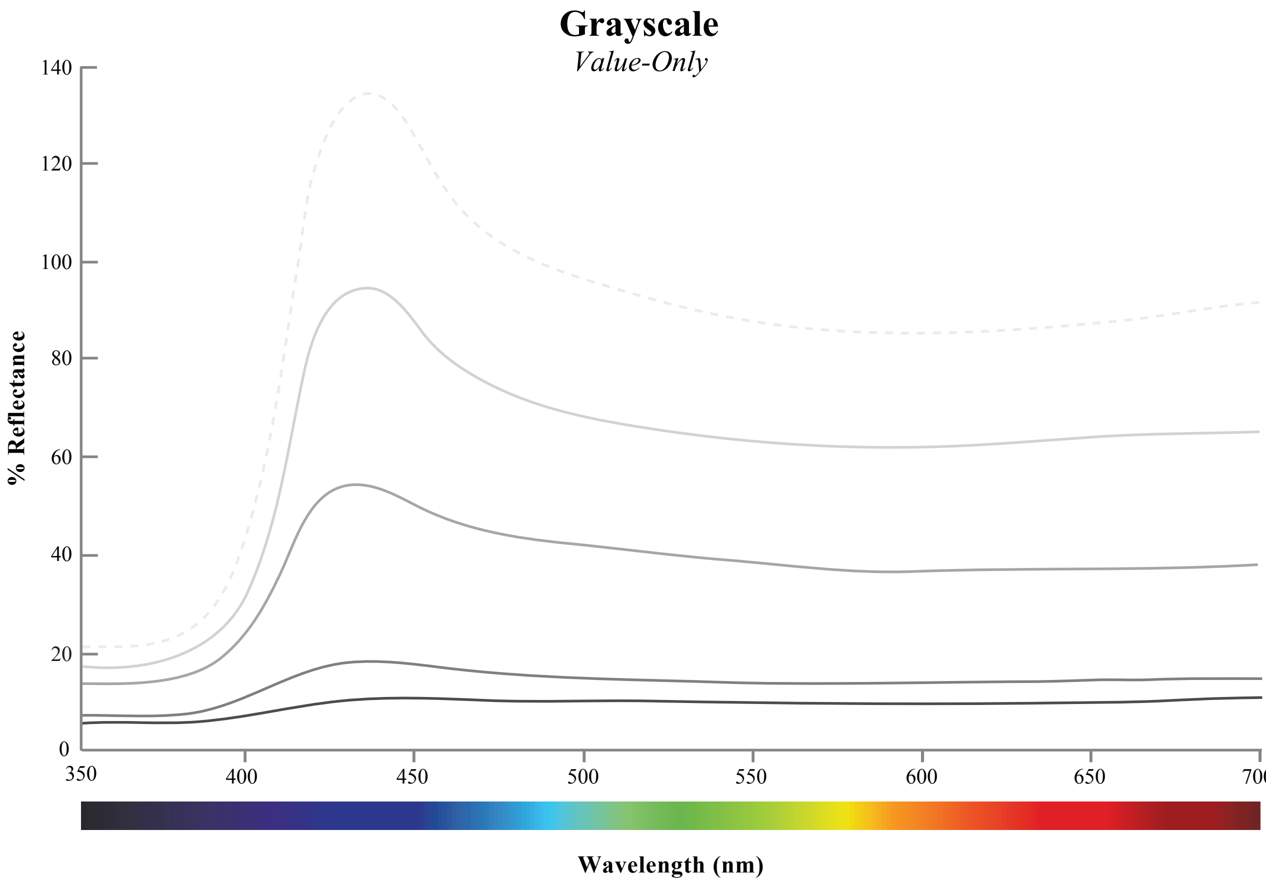
CMYK	63 2 0 0	63 0 100 0	73 78 0 0	1 16 99 0	0 98 43 0
RGB	56 194 241	106 189 69	98 83 163	254 210 8	237 28 98
HSB	196 0 100	102 63 74	251 49 64	49 97 100	340 88 93

Spectral Scheme

Reduced Saturation

CMYK	19 35 46 0	0 12 35 0	51 15 4 0	36 0 49 0	3 71 52 0
RGB	207 167 139	255 224 174	119 182 220	167 213 158	235 109 105
HSB	25 33 81	37 32 100	203 46 86	110 26 84	2 55 92

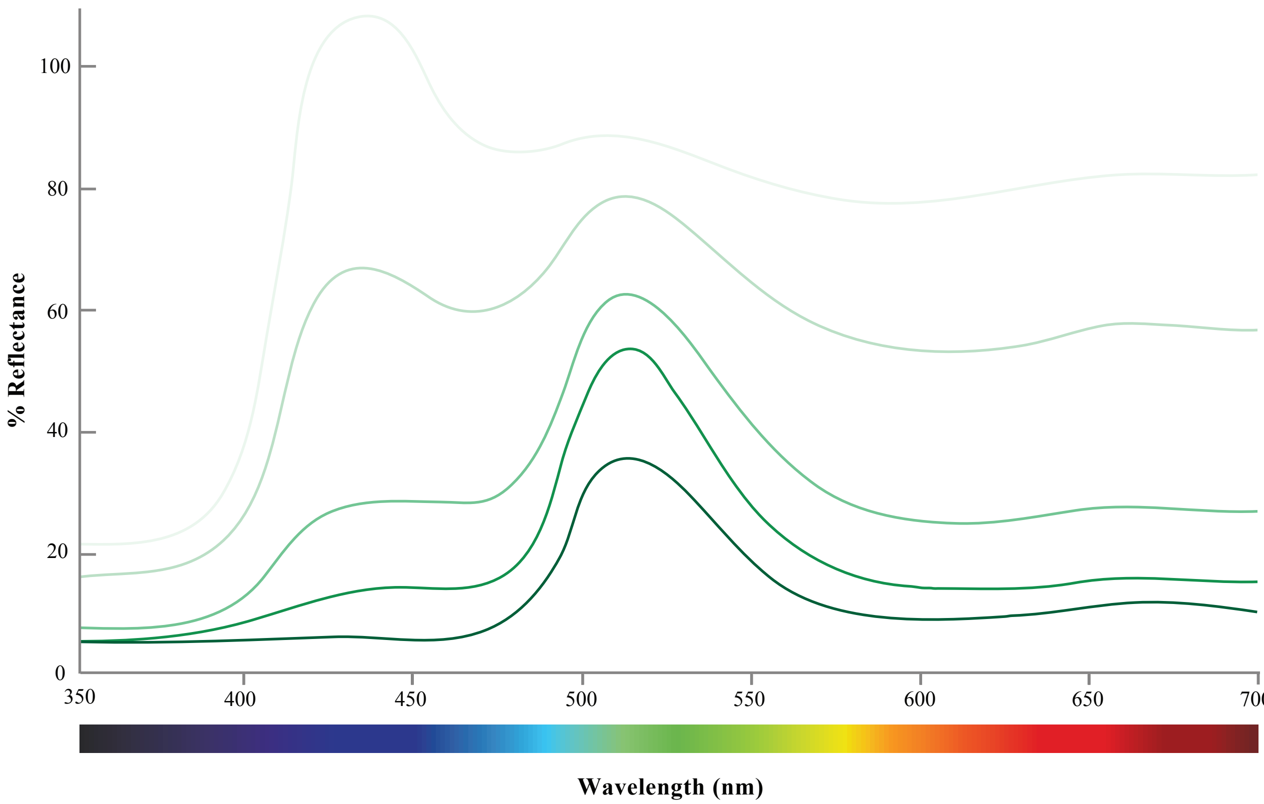
B | Color Measurements



Computer-Generated	L*	100	84	69	54	38
	a*	0	0	0	0	0
	b*	0	-1	-2	-2	-1
Measured	L*	96.19	84.51	68.81	44.41	36.48
	a*	4.54	3.63	2.5	1.06	0.42
	b*	-17.53	-14.75	-11.28	-6.25	-3.79
Difference	ΔL*	3.81	-0.51	0.19	9.59	1.52
	Δa*	-4.54	-3.63	-2.5	-1.06	-0.42
	Δb*	17.53	13.75	9.28	4.25	2.79

Sequential Scheme

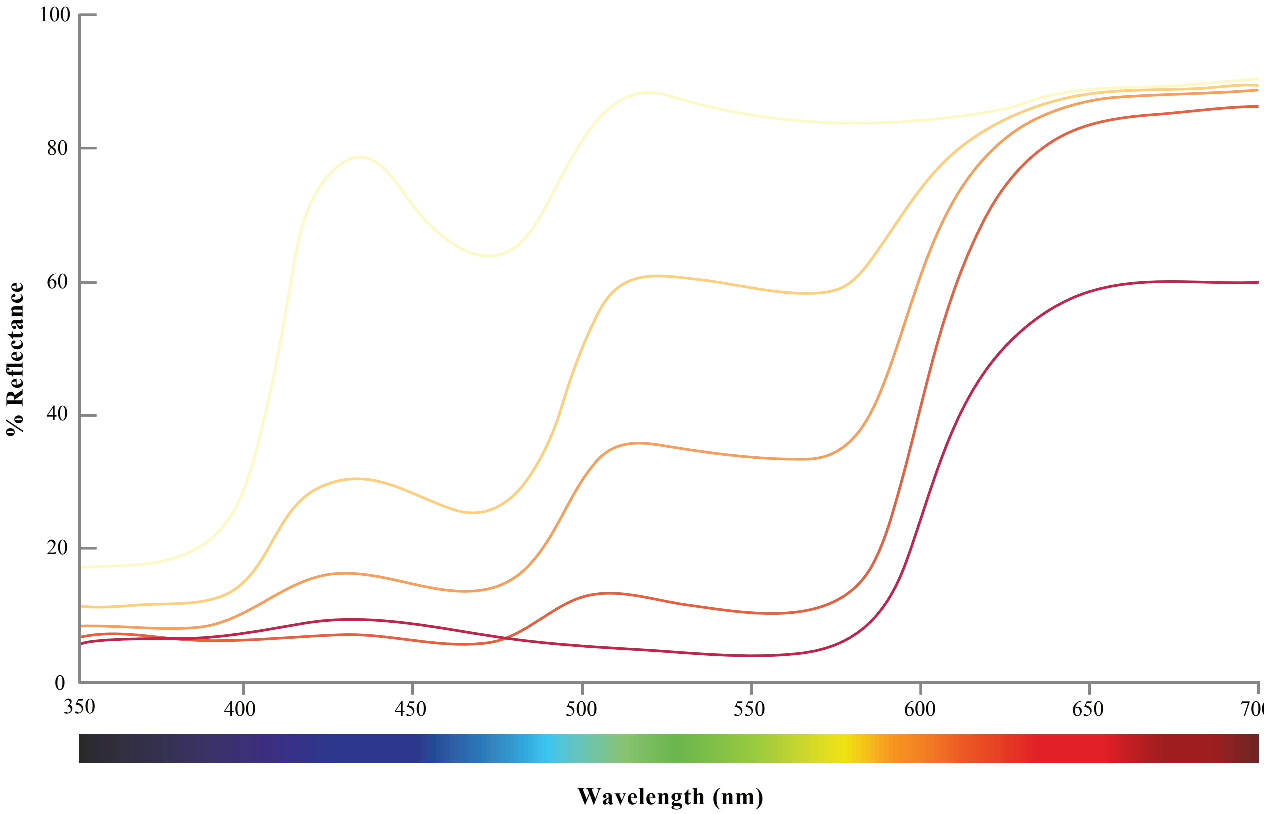
Single Hue



Computer-Generated	L*	96	86	73	64	52
	a*	-5	-16	-33	-51	-47
	b*	3	8	16	21	28
Measured	L*	93.03	83.94	68.57	59.82	49.31
	a*	0.1	-12.65	-31.24	-44.39	-39.59
	b*	-9.32	0.47	12.64	23.41	28.99
Difference	ΔL*	2.97	2.06	4.43	4.18	2.69
	Δa*	-5.1	-3.35	-1.67	-6.61	-7.41
	Δb*	12.32	7.53	3.36	-2.41	-0.99

Sequential Scheme

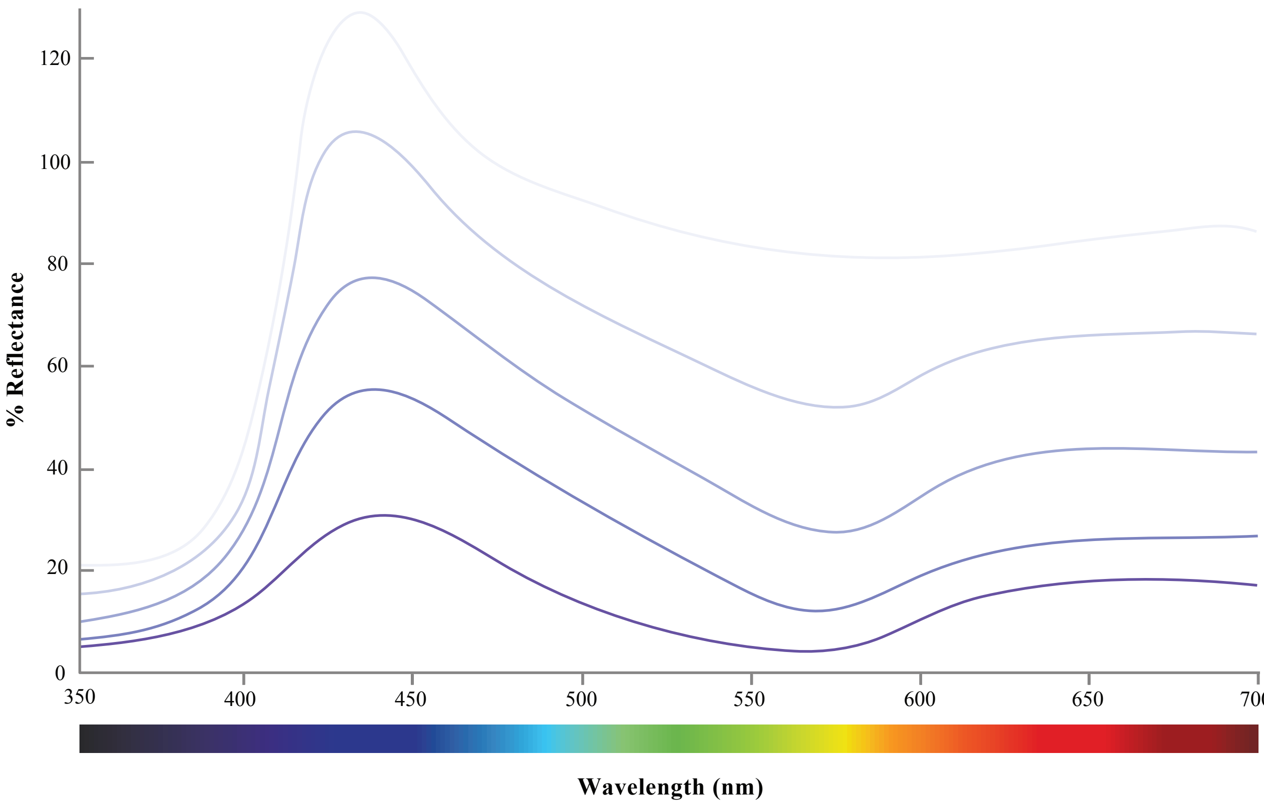
Multiple Hue



Computer-Generated	L*	96	86	73	58	44
	a*	-3	11	29	52	62
	b*	25	48	47	44	20
Measured	L*	93.17	81.85	69.31	52.11	40.87
	a*	-2.09	4.86	19.91	43.86	46.31
	b*	9.95	36.37	39.14	33.46	11.4
Difference	ΔL*	2.83	4.15	3.69	5.89	3.13
	Δa*	-0.91	6.14	9.09	8.14	15.69
	Δb*	15.05	11.63	7.86	10.54	8.6

Sequential Scheme

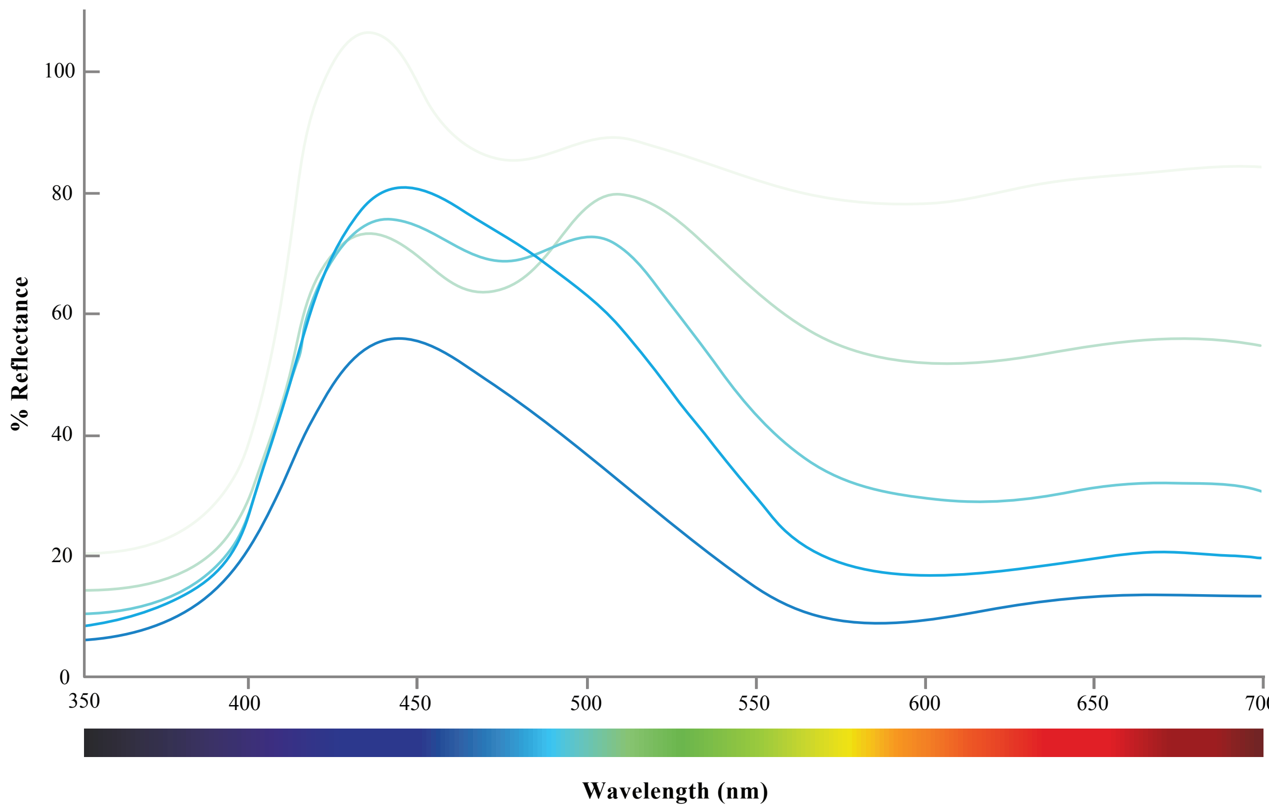
Single Hue



Computer-Generated	L*	40	55	69	82	94
	a*	24	8	4	1	1
	b*	-39	-31	-23	-13	-3
Measured	L*	37.7	55.01	68.74	82.99	94.15
	a*	22.92	10.25	7.81	6.69	4.14
	b*	-35.63	-35.84	-30.89	-24.44	-17.73
Difference	ΔL*	2.3	-0.01	0.26	-0.99	-0.15
	Δa*	1.08	-2.25	-3.81	-5.69	-3.14
	Δb*	-3.37	4.84	7.89	11.44	14.73

Inverse Sequential Scheme

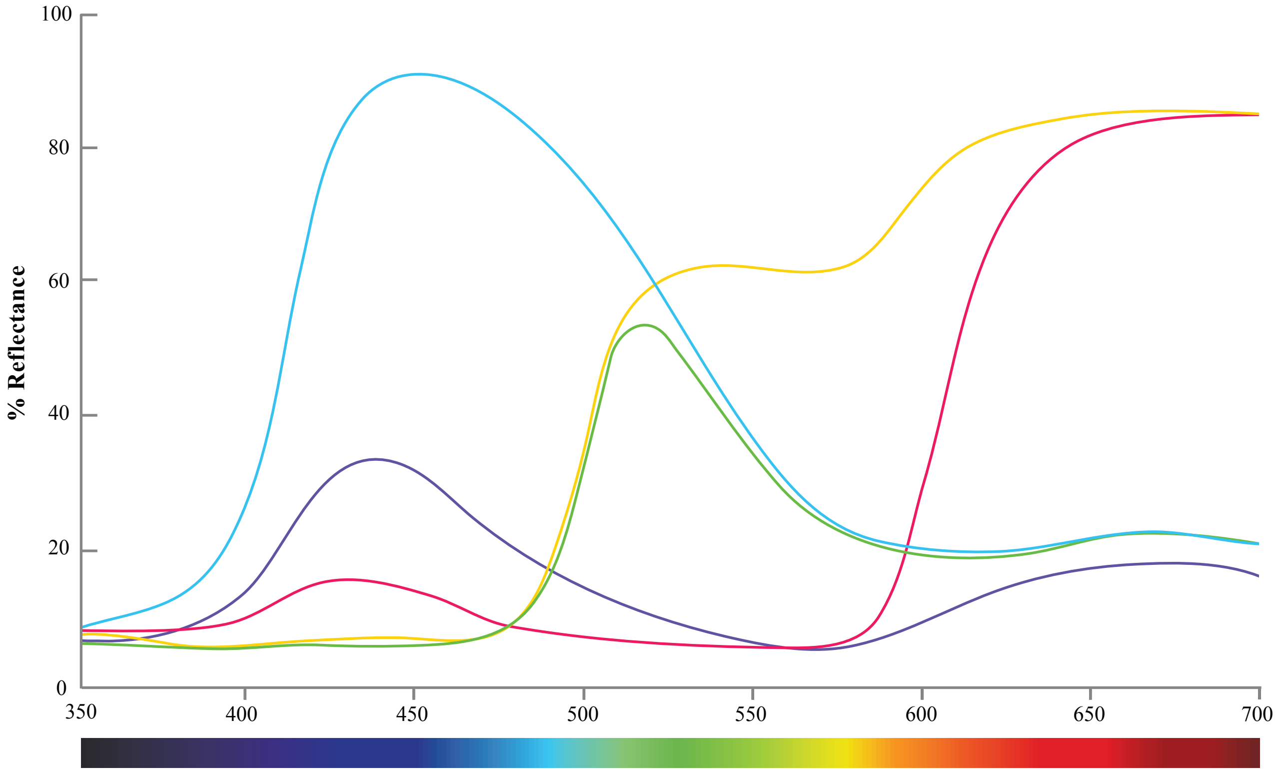
Multiple Hue



Computer-Generated	L*	52	65	76	86	96
	a*	-11	-23	-25	-15	-4
	b*	-43	-38	-15	4	4
Measured	L*	52.22	66.44	74.82	83.75	93.09
	a*	-4.16	-13.85	-18.35	-12.33	-0.05
	b*	-41.4	-39.1	-21.42	-3.82	-7.97
Difference	ΔL*	-0.22	-1.44	1.18	2.25	2.91
	Δa*	-6.84	-9.15	-6.65	-2.67	-3.95
	Δb*	-1.6	1.1	6.42	7.82	11.97

Spectral Scheme

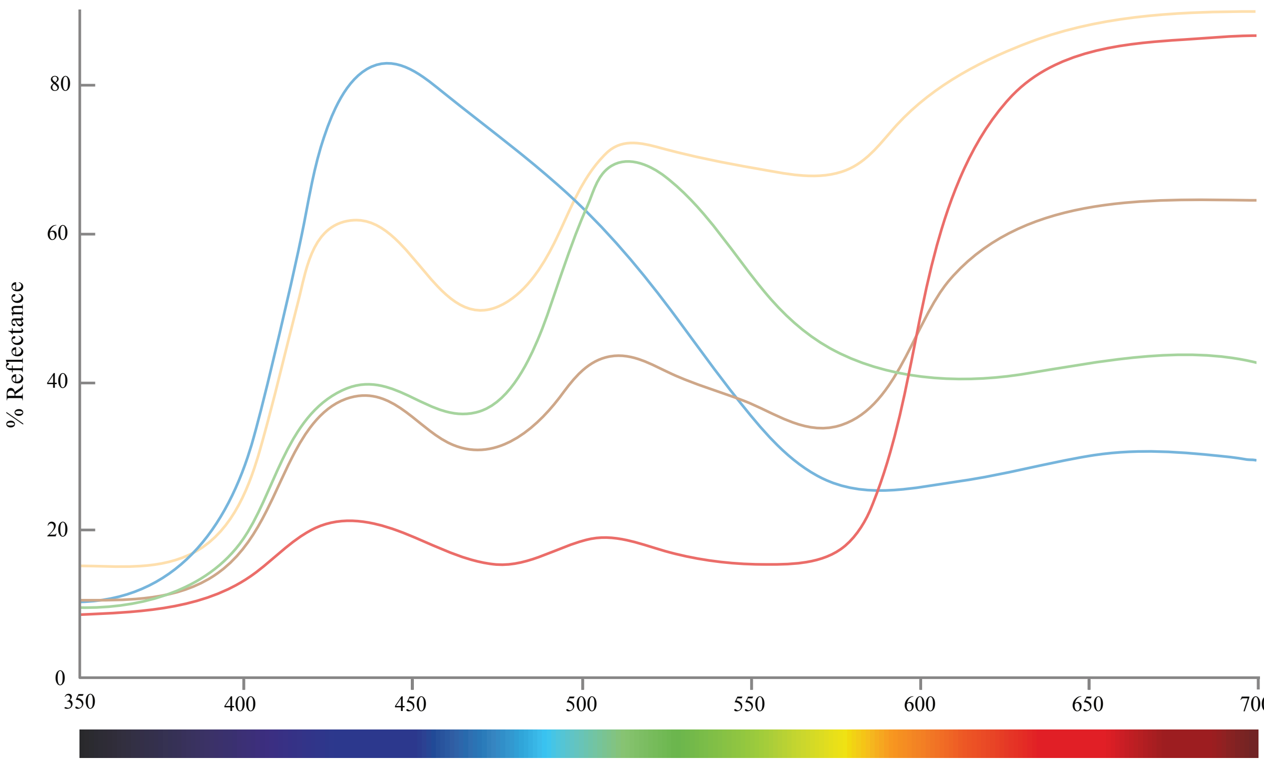
Constant Hue Increment



		Cyan	Green	Violet	Yellow	Magenta
Computer-Generated	L*	72	69	40	86	52
	a*	-25	-43	22	5	76
	b*	-35	50	-42	86	19
Measured	L*	70.92	61.67	37.71	80.69	45.28
	a*	-18.17	-39.62	21.39	1.42	56..98
	b*	-38.55	49.48	-37.21	78.6	5.82
Difference	ΔL*	1.08	7.33	2.29	5.31	6.72
	Δa*	-6.83	-3.38	0.61	3.58	19.02
	Δb*	3.55	0.52	-4.79	7.4	13.18

Spectral Scheme

Reduced Saturation



		Tan	Light yellow	Blue	Green	Red
Computer-Generated	L*	71	91	71	80	62
	a*	12	6	-14	-23	50
	b*	21	29	-26	22	27
Measured	L*	70.11	87.1	70.36	76.84	57.74
	a*	8.29	3.65	-8.88	-21.14	40.37
	b*	8.14	12.92	-33.57	14.02	12.91
Difference	ΔL*	0.89	3.9	0.64	3.16	4.26
	Δa*	3.71	2.35	-5.12	-1.86	9.63
	Δb*	12.86	16.08	7.57	7.98	14.09

C | Test Materials

Instruction Sheet

1. Do not skip any questions
2. Confidence level indicates ease in determination of answer and confidence in answer
   1 = hard to determine / answer is a guess a 5 = easy to determine / answer known exactly
3. Answer the questions in order
4. Cities will be always be labeled as City + Capital Letter
   Example: City E
5. States are identified by black boundaries with Capital Letter
   Example: A, B, C
6. For questions asking for comparison, answers will be HIGHER, LOWER, or THE SAME.
7. Majority territory = identify which density covers the highest percentage of the state
   Answers will be LOW, MODERATELY LOW, MODERATE, MODERATELY HIGH, and HIGH
8. Intensity of colors on one map DOES NOT compare to other maps
9. Some questions ask for numerical answers: i.e. a count of states with particular densities

---

Examples of all possible questions:

1. The population density of the northern portion of State L is ____________________________ than southern portion.

   Possible answers are HIGHER, LOWER, or THE SAME

2. Which of the cities has the lowest population density?

   Possible answers are A, B, C, D or multiple cities if more than one has the same low density

3. The population density of State I is ___________________________________ than state L.

   Possible answers are HIGHER, LOWER, or THE SAME

4. What is the majority population density of State H?

   Possible answers are LOW, MODERATELY LOW, MODERATE, MODERATELY HIGH, or HIGH

5. What is the highest population density within State B?

   Possible answers are LOW, MODERATELY LOW, MODERATE, MODERATELY HIGH, or HIGH

6. a. How many areas of LOW population density does State D possess? OR
   b. How many states possess majority territory with MODERATELY HIGH density?
   Possible answers are any number

Test Questions

What is the majority population density of State E?___________________________________

Confidence Level: 1 2 3 4 5

What is the population density of City B? ____

Confidence Level: 1 2 3 4 5

The population density of State L is __________________________________ than State A?

Confidence Level: 1 2 3 4 5

Which of the four cities on the map (A, B, C, or D) has the highest population density? _____

Confidence Level: 1 2 3 4 5

What is the majority population density of State B? _________________________________

Confidence Level: 1 2 3 4 5

What is the population density of City A? ____

Confidence Level: 1 2 3 4 5

The population density of State G is ___________________________________than State F?

Confidence Level: 1 2 3 4 5

Which of the four cities on the map (A, B, C, or D) has the lowest population density?______

Confidence Level: 1 2 3 4 5

What is the highest population density within State A?_______________________________

Confidence Level: 1 2 3 4 5

Which of the states has the largest area of HIGH population density? __________________

Confidence Level: 1 2 3 4 5

State J has how many areas of MODERATE population density? ______________

Confidence Level: 1 2 3 4 5

What is the majority population density of State K? _____________________________________

Confidence Level: 1 2 3 4 5

What is the population density of City C? ____

Confidence Level: 1 2 3 4 5!

What is the majority population density of State I? ______________________________________

Confidence Level: 1 2 3 4 5

The northern portion of State E is __________________________ than the southern portion?

Confidence Level: 1 2 3 4 5

How many states have majority territory with **BOTH** LOW and MODERATELY LOW population densities? ______________

Confidence Level: 1 2 3 4 5

State M has how many areas of MODERATELY LOW population density? _______________

Confidence Level: 1 2 3 4 5

What is the population density of City D? ____

Confidence Level: 1 2 3 4 5!

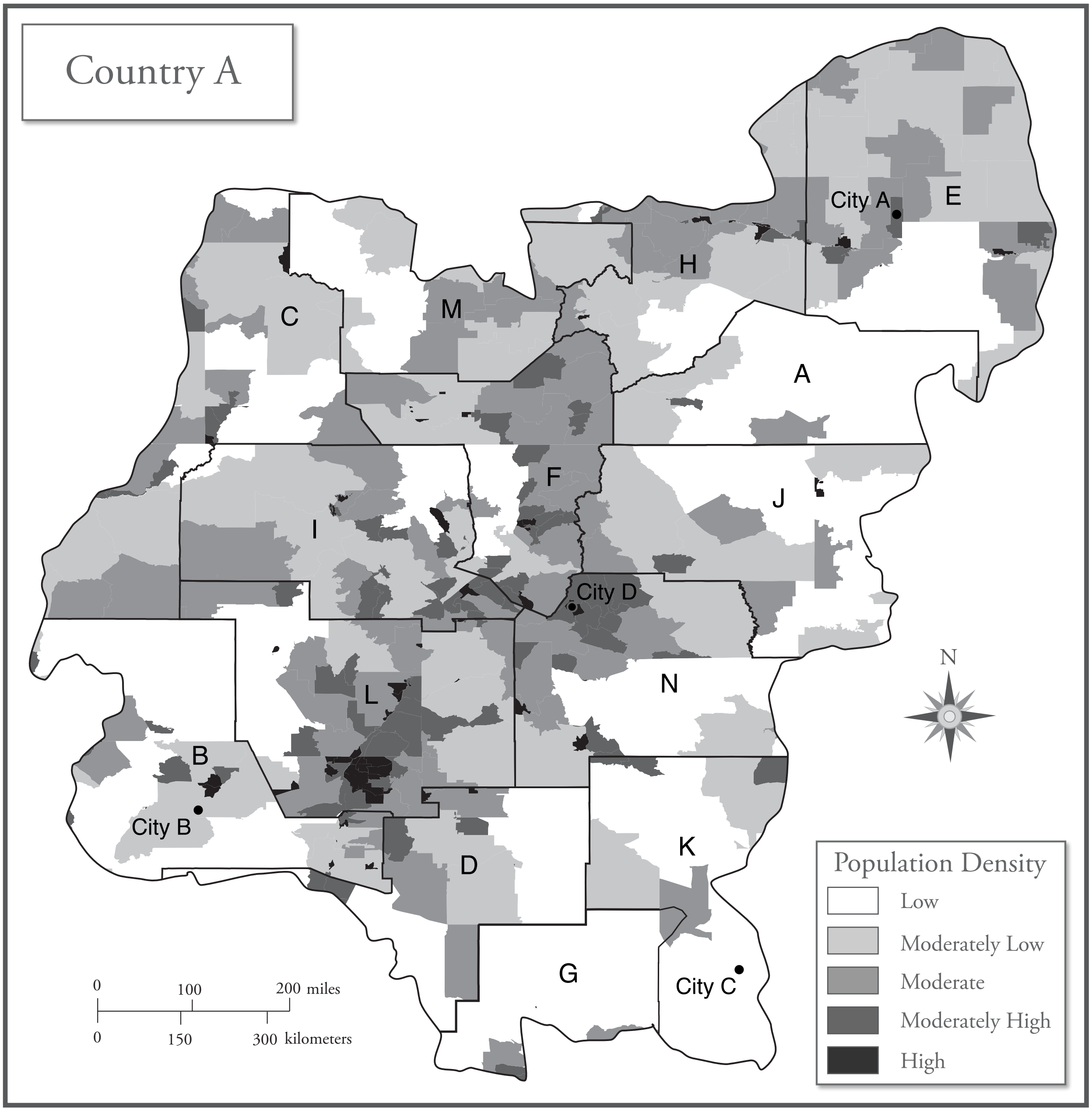
!

State H has how many areas of HIGH population density? _____________

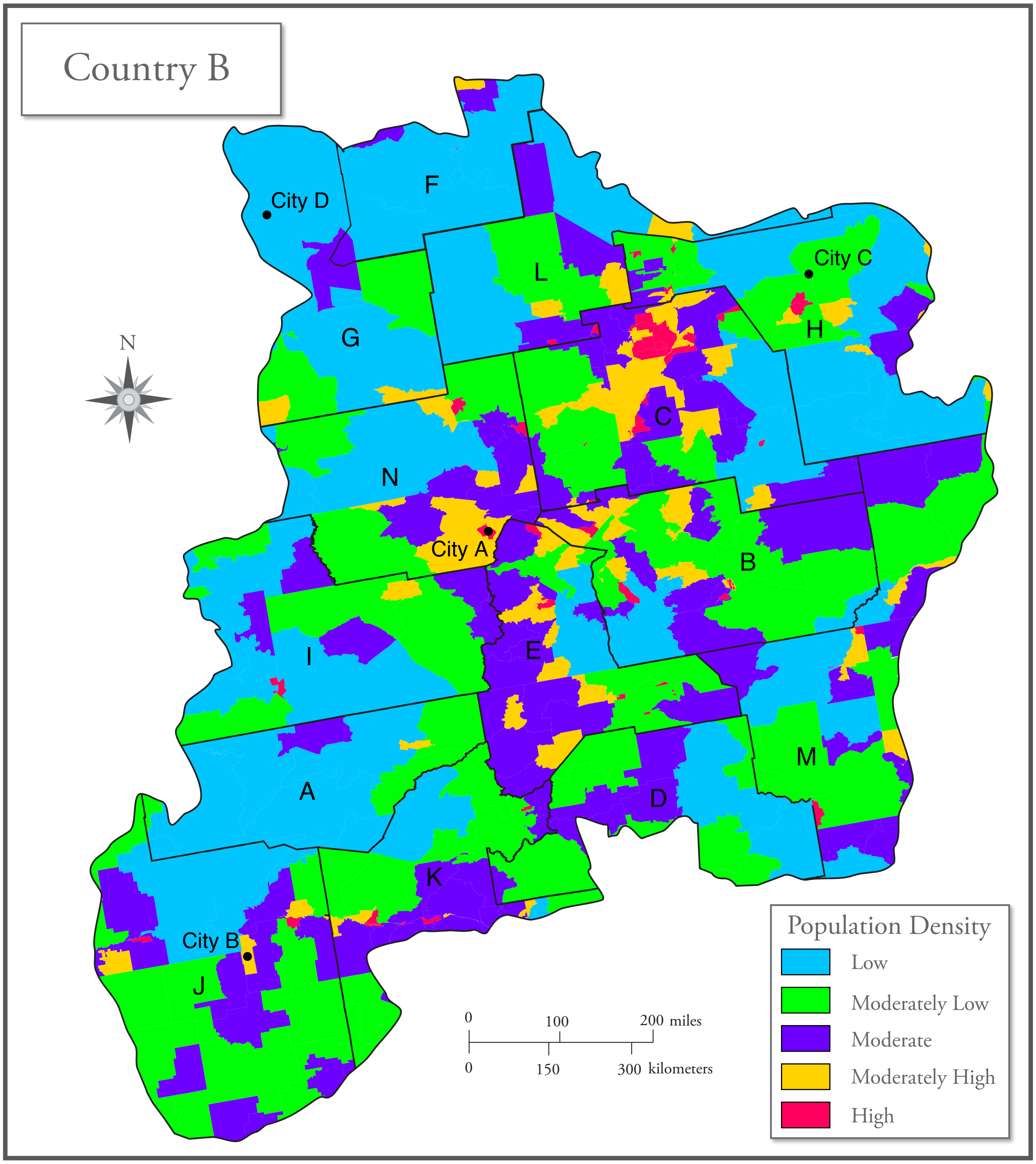
Confidence Level: 1 2 3 4 5

How many states possess each of the five population density? __________________________

Confidence Level: 1 2 3 4 5



Country A
City A
E
H
C
M
A
F
J
I
City D
N
N
B
L
City B
D
K
G
City C
0
100
200 miles
0
150
300 kilometers
Population Density
Low
Moderately Low
Moderate
Moderately High
High


Country B
City D
F
L
City C
H
G
N
C
City A
B
I
E
M
A
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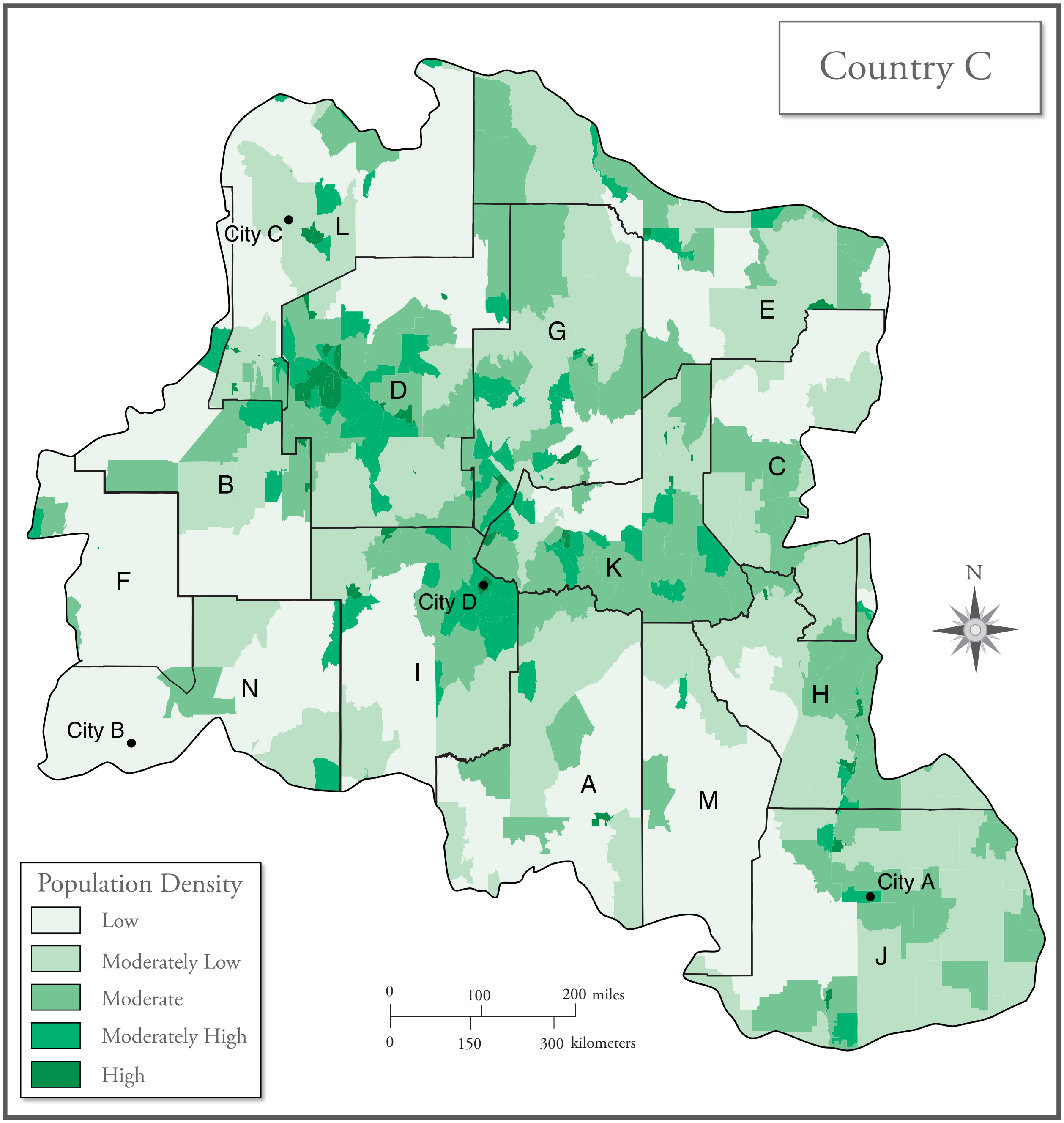
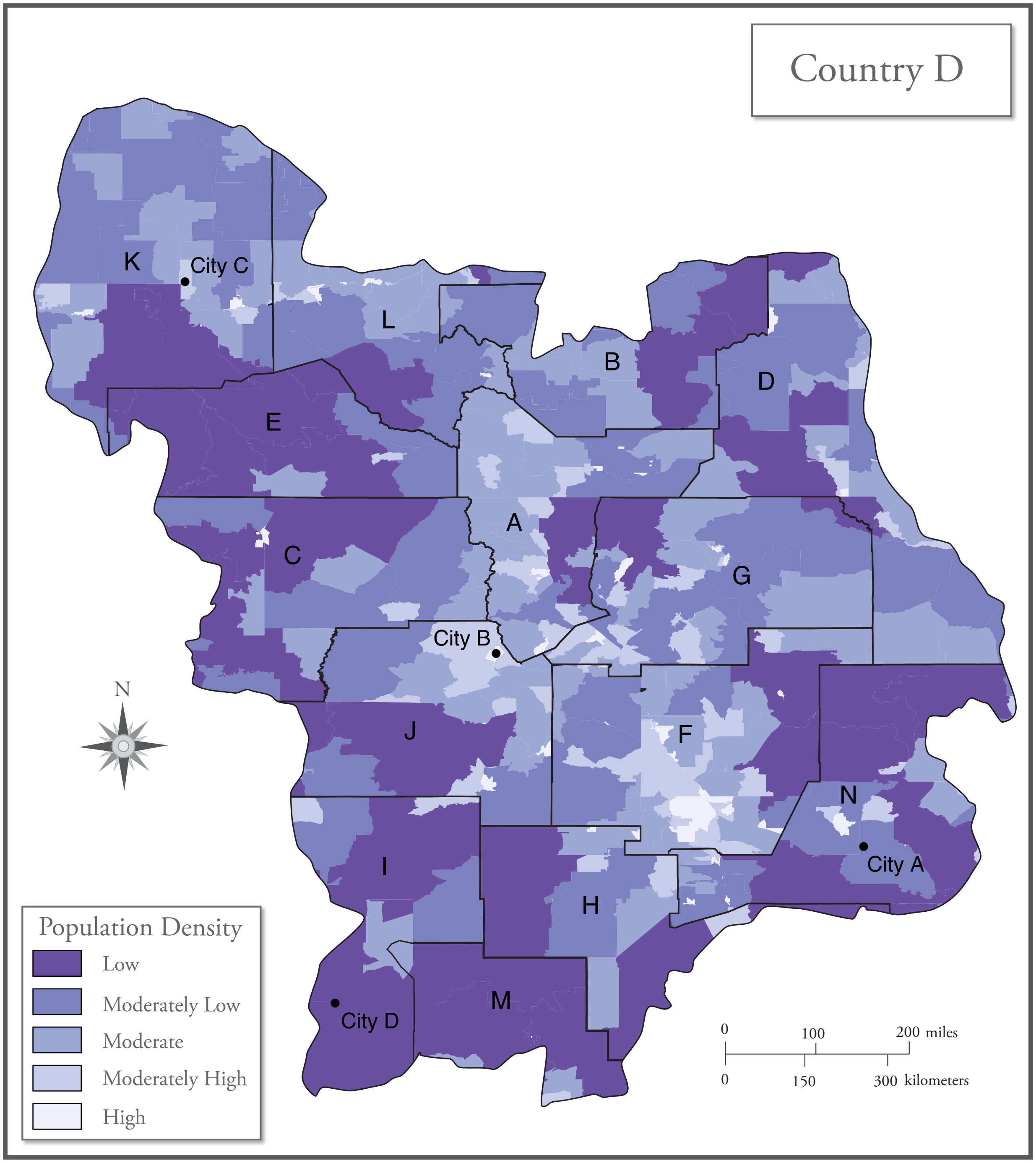
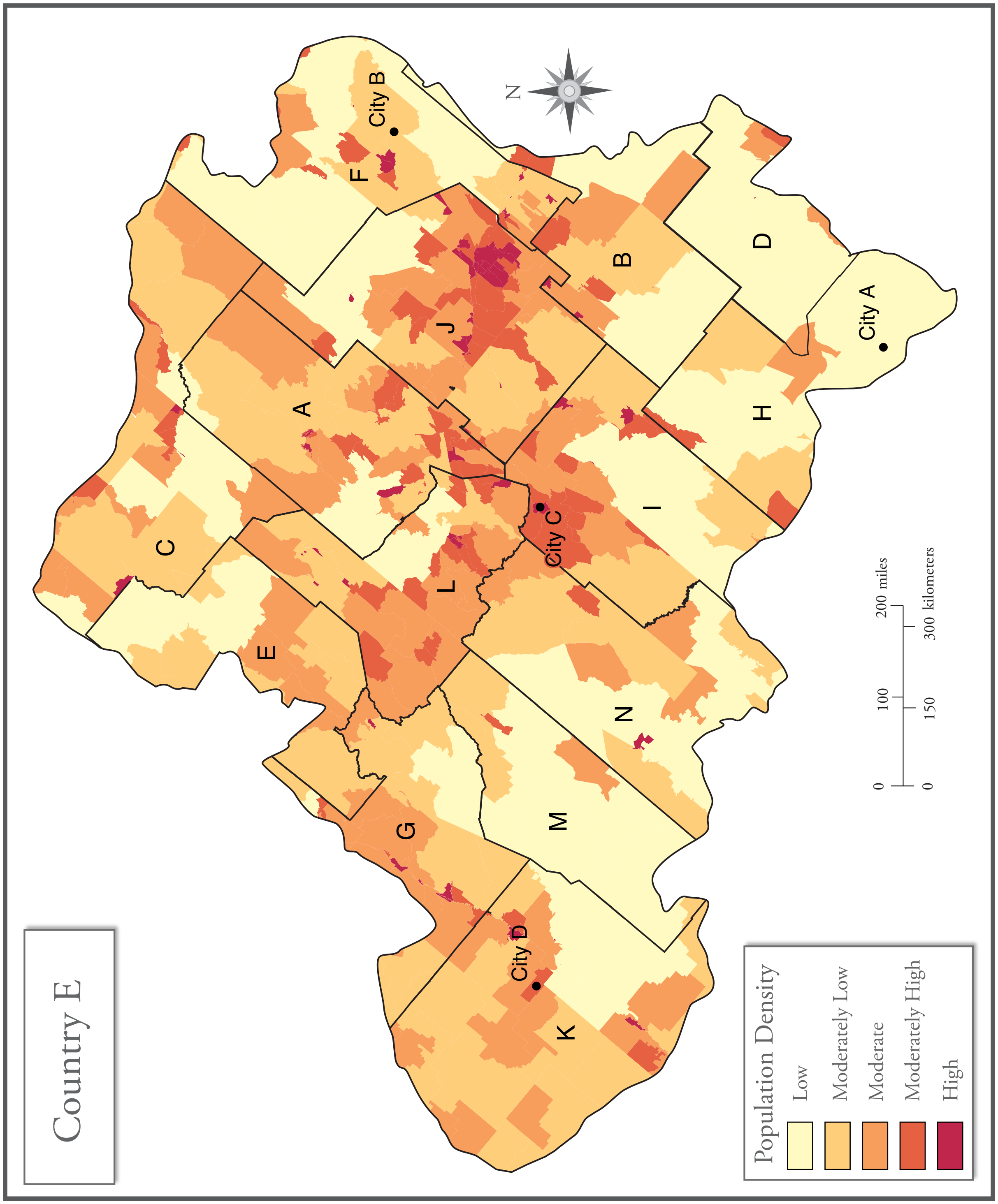
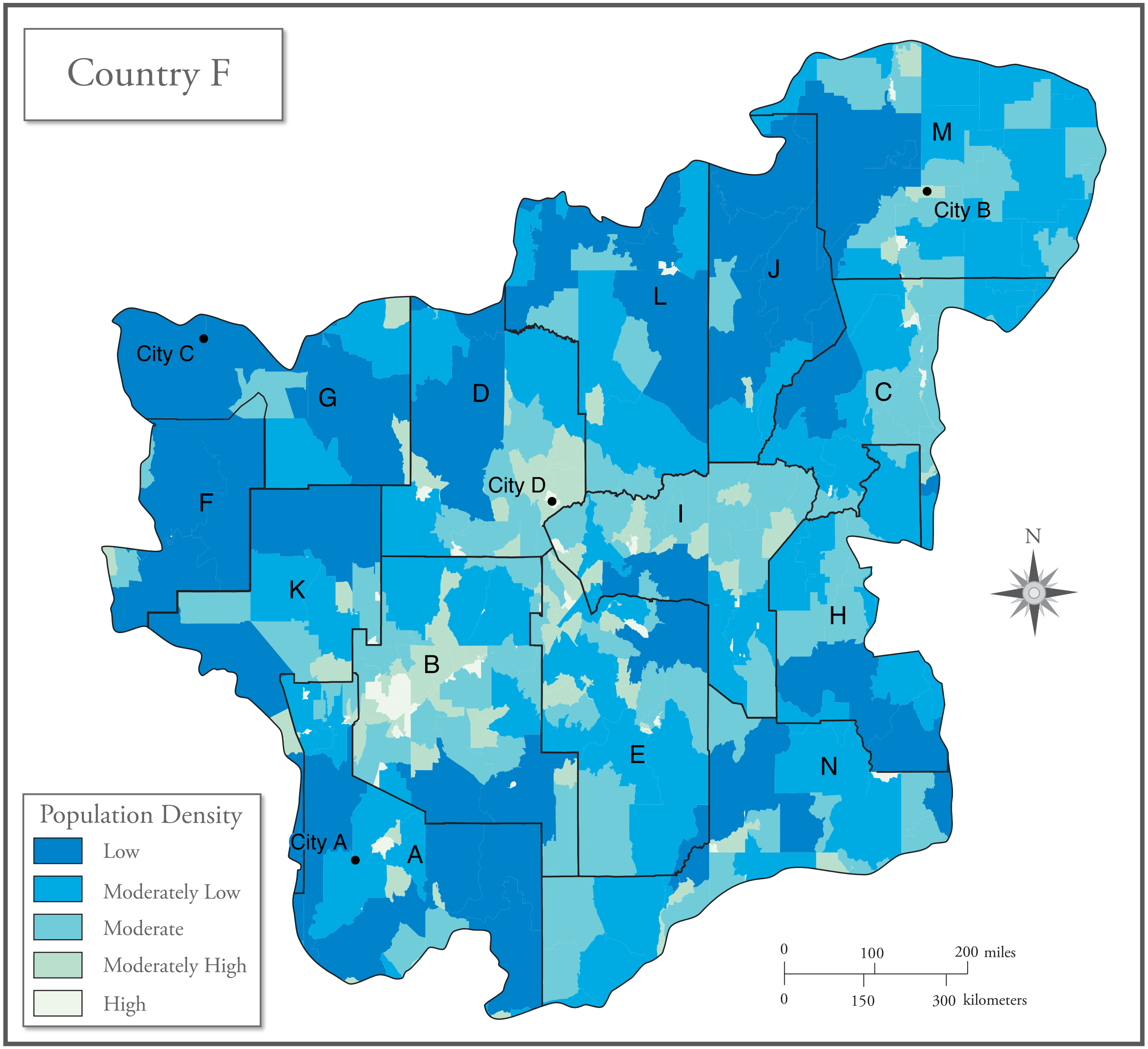
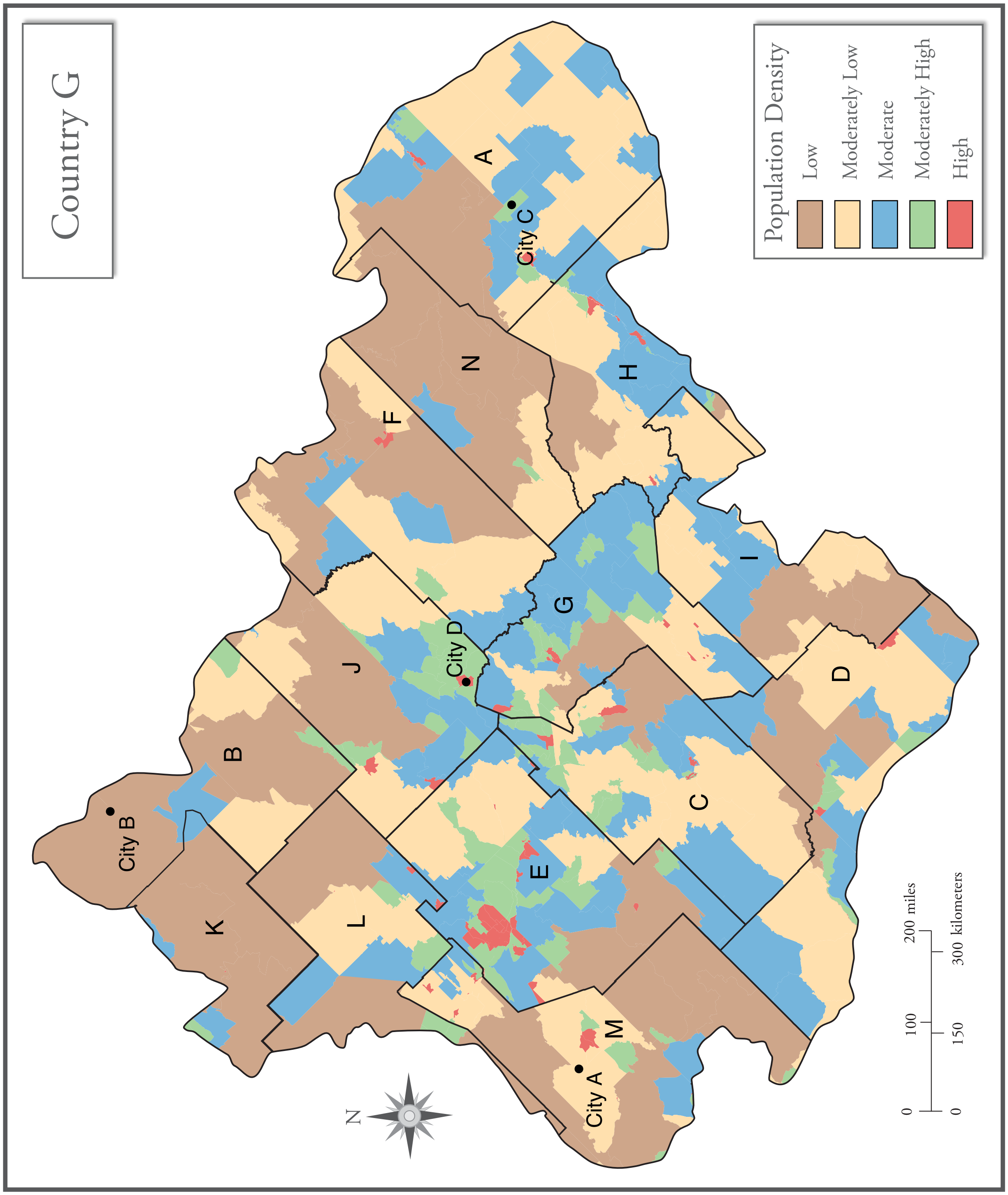
K
City B
J
0
100
200 miles
0
150
300 kilometers
Population Density
Low
Moderately Low
Moderate
Moderately High
High


Country C
City C
L
D
G
E
B
C
F
K
City D
I
H
N
City B
A
M
City A
J
N
Population Density
Low
Moderately Low
Moderate
Moderately High
High
0
100
200 miles
0
150
300 kilometers


Country D
K
City C
L
B
D
E
A
C
G
City B
J
F
N
City A
I
H
M
City D
N
Population Density
Low
Moderately Low
Moderate
Moderately High
High
0
100
200 miles
0
150
300 kilometers


Country E
Population Density
Low
Moderately Low
Moderate
Moderately High
High
N
0
100
200 miles
0
150
300 kilometers
City A
City B
City C
City D
A
B
C
D
E
F
G
H
I
J
K
L
M
N


Country F
M
City B
J
L
C
G
City C
D
City D
I
F
K
H
N
B
E
City A
A
N
Population Density
Low
Moderately Low
Moderate
Moderately High
High
0 100 200 miles
0 150 300 kilometers


Country G
Population Density
Low
Moderately Low
Moderate
Moderately High
High
City A
City B
City C
City D
A
B
C
D
E
F
G
H
I
J
K
L
M
N
N
0
100
200 miles
0
150
300 kilometers

Ishihara Plates