Chapter 1

INTRODUCTION

1.1 Introduction

As geographers tackle larger and more complex problems, such as global warming, there has been a shift from studying spatial *patterns* to studying space-time *processes* (Graf and Gober 1992). Change is one of the fundamental elements of these processes. The ability to recognize and track changes in complex physical systems is essential to developing an understanding of how these systems work (Yattaw 1999). Many of today's significant research challenges, such as resource management and environmental monitoring, depend upon integrating change information. One reason that studying geographic change is challenging is the sheer number of interactions that occur within systems and the enormous range of scales over which those interactions take place (i.e., from the molecule to the globe). Representing a static world is challenge enough; representing a dynamic world introduces new challenges for both the map designer and the map reader.

Almost a decade ago Koussoulakou and Kraak (1992, p. 101) noted, "During the nineties important challenges to cartography will be related to mapping spatial data's multi-dimensional and temporal component. From a cartographic point of view it is necessary to look at the implications of the use of animated maps." Animation as a visualization technique has been widely studied and supported in cartography and geovisualization (Monmonier 1990, Slocum and Egbert 1993, Openshaw et al. 1994, Kraak and MacEachren 1994, Edsall et al. 1997). The idea of using a cartographic animation to *map time with time* is intuitive. Animations are "a scale model in both space and time" (Monmonier 1990, p. 40) and as such are potentially powerful tools for depicting change information. However, as a recent research agenda by the ICA Commission on Visualization and Virtual Environments notes (MacEachren and Kraak 2001), progress over the last decade has been sporadic and there remain many unanswered questions regarding the use of animation in geovisualization and the representation of dynamic geographic phenomena more generally. Representing geographic process was one of four major research topics defined by the workshop on *Cognitive Models of Dynamic Geographic Phenomena and Their Representation* organized by Hirtle and MacEachren (1998). The participants noted that no taxonomy of events and processes exists, nor methods to systematically categorize dynamic geographic phenomena as either process or event. Methods for detecting and representing change were discussed, as were the implications of concepts of process on the form of representation. This meeting underscores the fact that GIScientists are still struggling with the basic concept of change, what it is and how to represent it.

This research examines the uses and utility of animation in representing geographic-scale change and proposes usability guidelines and formally tested innovations called *fixed visual benchmarks* (Fixed VBs) and *dynamic visual benchmarks* (Dynamic VBs). An example of a fixed visual benchmark can be seen in Figure 1.1. This research is divided into three major sections: theory, application, and testing (Figure

1.2). An examination of the nature of geographic change and strategies for its representation establishes the theoretical basis for this research. From this, a framework of geographic change is proposed. An in-depth analysis of existing approaches to representing change (within cartography) will yield design and conceptual guidelines for the successful deployment of cartographic animations. This research also addresses criticisms of cartographic animation, proposes solutions to these problems, and more generally argues the utility of map animation in GIScience.

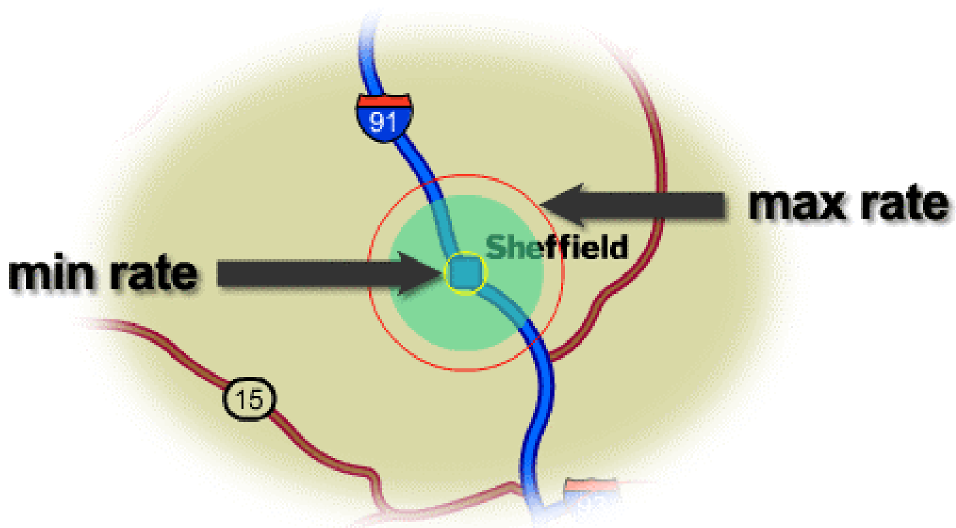

Figure 1.1: Example of fixed benchmarks (red and yellow lines). As the animation plays, the current size of the animated green circle can be compared to the fixed reference circles (i.e., the fixed VBs) to help judge the current data value against the data range.

The applications portion of this research involves building and refining different kinds of animated maps that incorporate visual benchmarks. Working examples of these "enhanced" animated maps will demonstrate potential solutions to common problems in map animation. In particular, visual benchmarks are designed to help users better compare different portions of an animation and visually extract change information. Long and complex animations can easily overwhelm the perceptual and cognitive abilities of users. Visual benchmarks help by shifting some of the cognitive burden from short-term memory to the display itself. Focus groups were successfully used to refine the implementation of the benchmarks and the expert participants in these focus groups were helpful in guiding the development of these maps. Given the lack of design guidelines for the creation of animated maps, the critiques and suggestions that emerged from the focus groups were especially helpful in the early stages of testing and development.

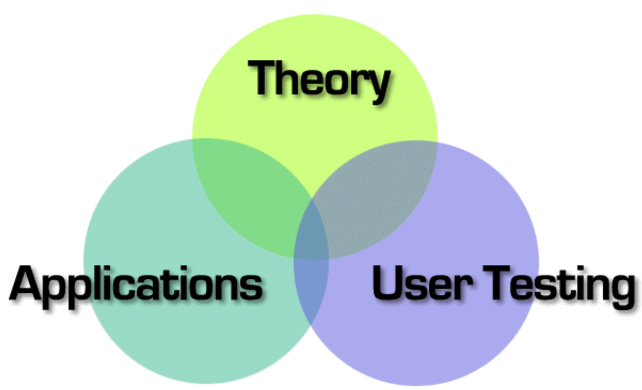

Figure 1.2: Structure of this dissertation. Theory, application, and user testing provide a three-tier framework for this research and are used to design and evaluate the concept of benchmarks on animated maps.

The third component of this dissertation presents the results of formal user testing of visual benchmarks. Enhanced versions of animated isoline maps and animated proportional symbol maps were tested against versions that did not incorporate visual benchmarks in order to determine to what degree benchmarks assist users in understanding geographic change within map animation, and for what kinds of map readings tasks benchmarks were most helpful. Performance was measured as both speed and accuracy in answering multiple-choice questions.

1.2 The Problem to be Addressed

Static maps present all of their information simultaneously; animated maps present information over time. Thus, animated maps have an additional representational axis that can be used to display information. Increasing the running time of an animation increases the total amount of data that can be represented, but at a cost to the user. As the length of the animation increases so too does the difficulty of remembering each frame of the animation. Put another way, although the amount of *data* that can be represented within an animation is virtually unlimited, there is a finite amount of *information* the user can distill from the animation and store in the their short-term visual memory. Overwhelming the map reader with information does more harm than good.

The amount of information stored in short-term memory relates to a basic map-reading task, namely, the ability to construct part-to-part and part-to-whole relationships. Questions such as "How does this December compare to last December?" require that users be able to *remember* the patterns and/or rates of one time period while *looking* at the patterns and/or rates for another time period in order to draw any conclusions. Furthermore, the user may have to synthesize multiple time periods on-the-fly (e.g., all days for a month) in order to answer a question such as "Is December 12th typical of most days in December?" Such tasks involve comparing information stored in short-term memory to information on the screen. Since few of us have a photographic memory, this is a significant mental challenge. But what if some of this cognitive burden of comparing different time periods could be off-loaded to the display itself? What if the user did not have to store a mental picture of different time periods but could compare them directly on the screen itself? It is reasonable to assume that such on-screen comparisons would be more *accurate* and more *detailed*. Such enhancements might make extracting change information from map animation easier and lead to a deeper understanding of the animation as a whole. These goals provide a starting point for this research.

Cartographers have long known that complex static maps can overwhelm and confuse the perceptual and cognitive abilities of the map-reader. For this reason, choropleth maps are seldom created with more than ten data classes, seven data classes being the often-cited upper limit for good map design. These limits derive from psychology studies performed a half century ago (Miller 1956) that revealed most individuals can cognitively process seven (plus or minus 2) "chunks" of information at once. Does this mean that animated maps should contain no more than seven frames? Clearly not, as people are capable of working with and understanding animations composed of thousands of individual frames, but the question remains: What are the cognitive limits to the complexity of animated maps? In other words, at what point do animated maps become too data-rich for the user? What forms the basic mental chunks of an animated map? How can the size of these chunks be increased? An answer to these questions must consider the *length* of the animation (i.e., running time), the *complexity of the spatial patterns* depicted (i.e., spatial heterogeneity), and the *complexity of the* *patterns of change* (i.e., temporal heterogeneity). The ability to cope with complexity varies among users. Domain experts such as geologists, can successfully utilize maps with 30 or more data classes. Hence, any guidelines for animated maps will have to consider both use and user.

Animated maps are typically less than a minute in duration. They are more analogous to television commercials than feature-length films. One practical reason for this is that animated maps are expensive to make, requiring many hours of work for every second of the animation. Another reason is that animated maps are temporal abstractions. As condensed forms of knowledge, animated maps are intentionally scaled-down representations of the world.

The data sets that geographers use continue to grow in our information-rich digital world. For example, climatologists have amassed daily data for over 100 years, and remote-sensing analysts must contend with terrabytes of continuous satellite feed per day. As Gahegan (1996 and 2000) notes, tools and techniques that allow users to handle massive data sets are increasingly necessary. Within the context of cartographic animation, there will be situations where a short animation is insufficient for the mapping task at hand (e.g., daily climate data). Although many authors have championed the use of animation in cartography, some are beginning to recognize that traditional animation is inadequate for many map reading tasks: "Pure animation is insufficient for supporting exploratory analysis of time-referred data" (Andrienko et al. 2000, p. 220). So how can we help the map reader cope with longer and more complex animations? More specifically, what visual techniques can help users remember previous (or important) moments in the animation and visually compare them *in real-time* to other frames in the animation?

1.3 Visual Benchmarks

Visual benchmarks are proposed as a solution to the questions and issues raised above. ***Fixed Visual Benchmarks (Fixed VBs)*** are static reference points within the animation. They can represent the extremes of the data set, the starting/ending point of the animation, or a critical value (e.g., 32˚F isoline) that can be superimposed into the animation. They serve as a visually embedded data legend against which all other frames of the animation can be compared. Visual benchmarks can be turned on or off as needed.

Dynamic Visual Benchmarks (Dynamic VBs) are continuously changing reference points within the animation. In their simplest form, the "ghost image" of the last (or next) frame would be superimposed on top of the current frame. The temporal distance between the current frame and the Dynamic VB image, however, can be adjusted. For example, in an animated dot map of hourly traffic accidents the Dynamic VB image could be 24 frames ahead (i.e., same time, next day). Dynamic benchmarks are designed to help users answer the question *how does the current state of the phenomenon compare to what is about to happen or what has just happened?*

There are two kinds of dynamic VBs: those that represent a single time period (e.g., one hour later) and those that represent multiple time periods (e.g., a moving average). It is possible to embed multiple Dynamic VBs within the animation. One approach is to fade these reference images proportionally to their temporal distance from the current frame. A more computationally intensive solution is to average the values, or create a temporally weighted average, around the current frame. An example would be an animation of daily isobars with the average of the two-week period around that day superimposed into the animation. This way a climatologist could watch the actual values and the moving average simultaneously.

Benchmarking is a special form of bivariate mapping. Traditional bivariate maps juxtapose two data variables on the same map to allow users to search for spatial correlations and co-occurrences. With benchmarking the second "variable" is the *same* variable but at a *different point in time*. It is believed that such a mapping technique will allow users to search for temporal correlations and co-occurrences. Preliminary indications for success of the visual juxtaposition of two or more data sets come from Howard and MacEachren (1995) who built *RViz*, a prototype visualization system designed to allow users to compare actual data values with reliability measures of those data values simultaneously in an animated map. Similar bi-variate animated mapping systems have been implemented successfully by Fauerbach et al. (1996), Evans (1997), and bi-temporal animated mapping has been explored by Blok et al. (1999).

1.4 How Animation Can Contribute

Geovisualization is concerned fundamentally with leveraging the pattern-recognition and information-extracting abilities of the eye-brain system and giving the user the tools to "see" and explore complex data sets in the hopes of discovering new insights (MacEachren 1995). In the early stages of research, geovisualization can be used to form hypotheses about the behavior of complex geographic systems especially when formal (i.e., testable) hypotheses about those systems are lacking (MacEachren et al. 1992, Hearnshaw and Unwin 1994, Gahegan et al. 2001). Later in the research process, geovisualization may be used to confirm, synthesize, and ultimately present ideas and information (DiBiase et al. 1992). The use of animated maps runs the spectrum of map use from exploration (e.g., exploratory tools for scientists) to communication (e.g., presenting facts to a wide audience with an animated weather loop). Thus, visualization is potentially helpful in all stages of the knowledge construction process. "A picture is often cited to be worth a thousand words and, for some (but not all) tasks, it is clear that a visual presentation—such as a map or photograph—is dramatically easier to use than is a textual description or a spoken report" (Shneiderman 1996, p. 336). Preliminary research has shown that animation can reveal subtle space-time patterns that are not evident in static representations, even to expert users who are highly familiar with the data (MacEachren et al. 1998).

Both Dorling and Openshaw (1992) and DiBiase et al. (1992) have demonstrated how map animation can be used to generate new insights into geographic processes that had been previously unrecognized using either static maps or statistical analysis. Animated maps are appealing because we live in an animated world. As Morrison et al. (2000) note, there is a strong *conceptual congruence* between dynamic phenomena and dynamic representations of those phenomena.

The basic visual elements of cartography are often insufficient for the task of representing change because they are primarily spatial and static and thus do not adequately support questions of—or foster hypothesis about—geographic *behaviors* or *processes*. Because animated maps can explicitly incorporate time they are potentially better suited to this task. Making animated maps interactive further extends their utility and allows the reader to "go into the map" and change the map to suit their needs. In the forward to *Interactive and Animated Cartography* Monmonier extols: "In rescuing both makers and users of maps from the straitjacket of ossified single-map solutions, interactive mapping promises a cartographic revolution as sweeping in its effects as the replacement of copyists by printers in the late fifteenth and early sixteenth centuries" (Peterson 1995, p. ix). Although the "promises" of this revolution have been slow to marterialize, there is justifiable enthusiasm for animated and interactive mapping systems.

1.5 Goals of the Dissertation

The goals of this research are to extend animation theory in cartography and geovisualization and to develop and test visual aids called benchmarks for the comparison of change information. The research objectives within these goals are to:

- Develop a conceptual framework of change with which to structure a discussion on how to visually represent the nature of change in animated maps. Provide an in-depth overview of kinds of geographic change and cartographic strategies for the representation of change in animated displays.

- Incorporate Fixed VBs and Dynamic VBs into multiple working examples including animated proportional symbol maps and isoline maps.

- Refine the implementations of Fixed VBs and Dynamic VBs with focus groups involving cartography and visualization experts.

- Determine whether Fixed VBs and Dynamic VBs significantly impact the abilities of map readers to construct a more accurate understanding of change information or to construct that information more quickly. This will be tested through controlled task-based experiments. This work builds on a strong cartographic tradition in cognitive-perceptual testing and previous successes in my own research.

The research undertaken for this dissertation compliments research underway elsewhere. The report "Cognitive Models of Dynamic Geographic Phenomena and Their Representations: Report of a Specialist Meeting," produced under the auspices of the Varenius Project (Hirtle and MacEachren 1998), outlines the top research issues in the fields of cartography and representation (related to dynamic phenomena and representation) and establishes a broad research agenda. This report, sponsored by the National Center for Geographic Information and Analysis (NCGIA), focuses on the significant problem of how to bridge the gap between the way people think about dynamic geographic phenomena and how we represent those phenomena on maps. Considerable attention in both the NCGIA Report and this doctoral research is directed toward successful strategies for representing dynamic and complex geographic phenomena.

The work undertaken here is part of this larger effort directed toward representing dynamic geographic phenomena. For example, a broad research agenda for cartography is presented by MacEachren (1995) based on a representational paradigm, which emphasizes the role of cognitive representations in mapping and the role of cartographic representations as prompts to knowledge creation and representation (in cognitive forms, or in further maps). Many of the ideas contained within this dissertation grew out of the research agenda outlined by The International Cartographic Association (ICA) Commission on Visualization and Virtual Environments (MacEachren and Kraak 2001). As a front-runner in cartographic research efforts, the Commission is charged with identifying and addressing the core research problems associated with extending cartographic methods into an increasingly dynamic technological environment.

1.6 Expected Results and Significance

This research contributes to cartography, and more generally to the problem of representing a dynamic world, in three areas: theory, implementation, and user-testing. As various authors have noted, tools that allow map readers to cope with longer and more complex animated sequences are needed (Blok et al. 1999, Andrienko et al. 2000). This work provides usable design solutions to the basic problem of overwhelming the visual and cognitive abilities of map readers with complicated animated map sequences. The utility of the visual benchmarks has been validated with the results from the formal user testing undertaking for this dissertation.

Given the fundamental and important nature of change in geographic, earth science, and other research, the limited body of theory on how to visually represent geographic change is surprising. This work contributes to this body of theory by (1) developing a conceptual framework of geographic-scale change, (2) outlining issues in the design of effective animated maps, (3) proposing how to systematically characterize the difficulty of specific visual change-recognition tasks, and (4) discussing the inherent strengths and weaknesses associated with various animated map types. Better representations as well as better decisions based on these representations will result from expanding knowledge of the nature of change and how to detect and display change with animated maps. In short, this work helps users of geospatial data to better represent change using map animation.

I have previously developed and formally evaluated innovative temporal controls in map animation (Harrower et al. 2000). This dissertation research further extends techniques for map animation and continues in the tradition of testing new visualization tools with users in order to determine what impact, if any, these tools have on different kinds of map reading tasks. Given the limited body of research that deals with map animation, the work presented in this dissertation is expected to result in advances in the design and implementation of animated maps.

1.7 Structure of the Dissertation

The structure of the remainder of this dissertation is as follows. Chapter 2 is a look at the larger theoretical context of this research with specific attention to outlining concepts of change, time, and the representation of process. Chapter 3 is a history of the *production* of animated maps and Chapter 4 is a history of the academic *study* of animated maps. In Chapter 3, a new framework is proposed for identifying the critical historical, technological, and social developments in the history of making animated maps. Chapter 4 contains a comprehensive review and distillation of relevant literature on animated maps. Chapter 5 describes the concept of visual benchmarks, the alternatives to benchmarks, and the rationale for their use. Chapter 6 is a look at the design and implementation of visual benchmarks incorporated into animated isoline maps and animated proportional symbol maps. The results of the focus group session are also presented in Chpater 6. Chapter 7 is the methodology chapter and introduces the experimental design behind the formal task-based user testing. Chapter 8 presents the results of this testing. Chapter 9 provides a summary of this work and directions for future research efforts.