The Pennsylvania State University

The Graduate School

College of Earth and Mineral Sciences

INTERACTING WITH MAPS:

THE SCIENCE AND PRACTICE OF CARTOGRAPHIC INTERACTION

A Dissertation in

Geography

by

Robert Emmett Roth

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Doctor of Philosophy

December 2011

The dissertation of Robert Emmett Roth was reviewed and approved* by the following:

Alan M. MacEachren
Professor of Geography
Dissertation Adviser
Chair of Committee

Cynthia A. Brewer
Professor of Geography

Alexander Klippel
Assistant Professor of Geography

Eugene J. Lengerich
Professor of Public Health Sciences

Karl S. Zimmerer
Professor of Geography
Head of the Department of Geography

*Signatures are on file in the Graduate School

Dissertation Abstract:

The current pace of innovation in interactive and web-based mapping is spectacular, and the possibility and pervasiveness of interactivity has transformed the way in which many maps are produced and consumed. Despite this remarkable pace—or perhaps because of it—there have been relatively few efforts to understand how interactive maps should be designed and used. This research directly contributes to this gap, treating the topic of cartographic interaction as a complement to cartographic representation, the traditional topic of inquiry within the field of Cartography. *Cartographic interaction* is described as the dialogue between a human and a map mediated through a computing device. The dissertation seeks to establish a science of cartographic interaction by accomplishing three research goals.

The first research goal of the dissertation is to identify and explore the questions that need to be addressed by a science of cartographic interaction and then to review and synthesize the current state of understanding regarding these questions. Secondary sources from Cartography and related fields were reviewed to understand the current *state of science* regarding cartographic interaction. This review revealed a framework comprising six questions that a science of cartographic interaction must address: (1) *what?*, (2) *why?*, (3) *when?*, (4) *who?*, (5) *where?*, and (6) *how?* The background review on the sixth *how?* question also yielded a new way of conceptualizing and organizing existing taxonomies of cartographic interaction *primitives*—or the basic building blocks that altogether constitute an interaction strategy—based on the stage of interaction. Following the background review, a set of interviews then was completed with 21 participants who use cartographic interaction to support their daily work. The interview study captured the current *state of practice* on cartographic interaction across a number of application domains, generating additional insights into the six questions on cartographic interaction.

The second research goal is to address the important *how?* question by developing a taxonomy of cartographic interaction primitives that is empirically derived. To this end, a pair of card sorting studies were administered with 15 participants who design and develop cartographic interfaces. The pair of studies required each participant to sort a universe of statements, drawn from the reviews on cartographic science and practice, that represented either the objective or operator stage of interaction. The resulting taxonomy of cartographic interaction primitives includes four dimensions, each aligning with a different stage of interaction: (1) *goals* (*procure*, *predict*, and *prescribe*), (2) *operands* (*space-alone*, *attributes-in-space*, and *space-in-time*), (3) *objectives* (*identify*, *compare*, *rank*, *associate*, and *delineate*), and (4) *operators* (enabling operators: *import*, *export*, *save*, *edit*, and *annotate*; work operators: *reexpress*, *arrange*, *sequence*, *resymbolize*, *overlay*, *reproject*, *pan*, *zoom*, *filter*, *search*, *retrieve*, and *calculate*).

Finally, the third and final research goal is to identify prototypically successful and unsuccessful cartographic interaction strategies with a single cartographic interface, initializing a research program for developing a syntactics of cartographic interaction primitives. To this end, a cartographic interface—referred to as *GeoVISTA CrimeViz*—was used as a 'living laboratory' for generating initial insight into the interaction primitive taxonomy. Ten law enforcement personnel from the Harrisburg Bureau of Police completed fifteen user tasks with *GeoVISTA CrimeViz* that are representative of the objective and operand pairings listed in the taxonomy of cartographic interaction primitives. Analysis of the interaction logs by operator allowed for generation of several insights into the syntactics of interaction primitives as well as the development of user *personas*, or chronic user issues in applying the operator primitives.

The research reported here represents a substantial step forward regarding the science of cartographic interaction. However, the there is still much work to be done; the insights generated by the dissertation research offer an initial foundation for structuring future scientific research on cartographic interaction.

Table of Contents:

List of Figures……………………………………………………………………………**vii**
List of Tables…………………………………………………………………………… **ix**
Acknowledgements..………………………………………………………………………… **x**

Chapter One: Introduction………………………………………………………………… **1**
1.1 Twentieth Century Cartographic Science……………………………………………… 1
1.2 Perspectives on Twenty-First Century Cartographic Science………………………… 2
1.3 Cartographic Interaction and the Prototypical Map…………………………………… 3
1.4 Problem Statement: Towards a Science of Cartographic Interaction………………… 5
1.5 Research Goals & Dissertation Structure……………………………………………… 8
1.5.1 Questions for a Science and Practice of Cartographic Interaction………… 8
1.5.2 A Taxonomy of Cartographic Interaction Primitives……………………… 9
1.5.3 Prototypically Successful & Unsuccessful Interaction Strategies………… 10

Chapter Two: Background Review………………………………………………………… **12**
2.1 Questions for a Science of Cartographic Interaction………………………………… 12
2.2 What is Cartographic Interaction?……………………………………………………… 13
2.3 Why Provide Cartographic Interaction?……………………………………………… 16
2.4 When Should Cartographic Interaction Be Provided?………………………………… 20
2.5 Who Should Be Provided Cartographic Interaction?………………………………… 24
2.6 Where Should Cartographic Interaction Be Provided?………………………………30
2.7 Conclusion: Elements of Cartographic Interaction…………………………………… 32

Chapter Three: Cartographic Interaction Taxonomies……………………………………**33**
3.1 How Should Cartographic Interaction be Performed?………………………………… 33
3.2 Stages of Cartographic Interaction……………………………………………………… 34
3.3 Objective-Based Taxonomies…………………………………………………………… 38
3.4 Operator-Based Taxonomies…………………………………………………………… 43
3.5 Operand-Based Taxonomies……………………………………………………………49
3.6 Conclusion: Cartographic Interaction Primitives……………………………………… 55

Chapter Four: Cartographic Interaction Interviews……………………………………… **56**
4.1 An Empirical Approach to Examining Cartographic Interaction Practice…………… 56
4.2 Method: Cartographic Interaction Interviews………………………………………… 57
4.2.1 Review of Ethnographic Methods………………………………………… 57
4.2.2 Participants………………………………………………………………… 58
4.2.3 Materials and Procedure…………………………………………………… 60
4.2.4 Qualitative Data Analysis……………………………………………………61
4.3 Results and Discussion………………………………………………………………… 62
4.3.1 What?……………………………………………………………………… 62
4.3.2 Why?……………………………………………………………………… 67
4.3.3 When?……………………………………………………………………… 70
4.3.4 Who?…………………………………………………………………………71
4.3.5 Where?……………………………………………………………………… 73
4.4 Conclusion: Cartographic Interaction Science versus Practice……………………… 75

Chapter Five: Interaction Primitive Card Sorting……………………………………………… 76
5.1 A Theoretical Framework for a Science of Cartographic Interaction………………… 76
5.2 Method: Card Sorting of Interaction Primitives……………………………………… 77
5.2.1 Review of Methods for Eliciting Cognitive Structures…………………… 77
5.2.2 Participants……………………………………………………………… 78
5.2.3 Materials and Procedure…………………………………………………… 79
5.2.4 Statistical and Visual Analysis…………………………………………… 82
5.3 Results and Discussion: Objectives…………………………………………………… 84
5.3.1 Participant Agreement on Objectives……………………………………… 84
5.3.2 Cartographic Interaction Operand Primitives…………………………… 85
5.3.3 Cartographic Interaction Goals……………………………………………88
5.3.4 Cartographic Interaction Objective Primitives……………………………90
5.4 Results and Discussion: Operators…………………………………………………… 94
5.4.1 Participant Agreement on Operators………………………………………94
5.4.2 Enabling Cartographic Interaction Operators…………………………… 95
5.4.3 Cartographic Interaction Operator Primitives…………………………… 97
5.5 Conclusion: An Evolving Interaction Primitive Taxonomy……………………………103

Chapter Six: Cartographic Interaction Study………………………………………………… 104
6.1 Design and Use Guidelines for Cartographic Interaction……………………………104
6.2 Case Study: Crime Analysis and *GeoVISTA CrimeViz*…………………………… 105
6.2.1 The *GeoVISTA CrimeViz* Cartographic Interface……………………………105
6.2.2 Collaboration with the Harrisburg Bureau of Police……………………… 108
6.3 Method: Cartographic Interaction Study and User Satisfaction Survey……………… 111
6.3.1 Review of Cartographic Interaction Studies…………………………………111
6.3.2 Participants……………………………………………………………… 114
6.3.3 Materials and Procedure…………………………………………………… 115
6.3.4 Interaction Analysis………………………………………………………… 116
6.4 Results and Discussion ……………………………………………………………… 117
6.4.1 Interacting with *GeoVISTA CrimeViz*……………………………………… 117
6.4.2 Prototypically Successful and Unsuccessful Interaction Strategies………… 122
6.5 Conclusion: Towards a Syntactics of Cartographic Interaction Primitives…………… 136

Chapter Seven: Conclusion…………………………………………………………………… 138
7.1 Summary of Contributions…………………………………………………………… 138
7.1.1 Questions for a Science and Practice of Cartographic Interaction………… 138
7.1.2 A Taxonomy of Cartographic Interaction Primitives……………………… 140
7.1.3 Prototypically Successful & Unsuccessful Interaction Strategies………… 142
7.2 Outlook: A Research Agenda for the Science of Cartographic Interaction ……………143
7.2.1 An Evolving Taxonomy of Cartographic Interaction Primitives…………… 143
7.2.2 Towards a Syntactics of Cartographic Interaction Primitives……………… 143
7.2.3 Syntactics and the Cartographic Interaction Context……………………… 144
7.2.4 Integrating Cartographic Representation and Cartographic Interaction…… 145
7.2.5 Integrating Science and Practice…………………………………………… 146
7.3 A Comprehensive View of Twenty-First Century Cartography……………………… 147
7.4 Conclusion: A Parting Note………………………………………………………… 150

Appendix A: Cartographic Interaction Interview Protocol………………………………… 151
A.1 Introduction………………………………………………………………………… 151
A.2 Biographical/Background Survey…………………………………………………… 151
A.3 Work Tasks & Geographic Information…………………………………………… 152

A.4 User Demonstration…… 153
A.5 Debriefing: Reflections on Interactive Map Use…… 154

Appendix B: Objective & Operator Card Sets…… 155
B.1 Objective Cards…… 155
B.2 Operator Cards…… 158

Appendix C: Card Sorting Protocol……163
C.1 Introduction…… 163
C.2 Background…… 163
C.3 Instructions…… 164

Appendix D: Card Sorting Dendograms…… 166
D.1 Objective Dendogram…… 166
D.2 Operator Dendogram…… 168

Appendix E: *GeoVISTA CrimeViz* User Guide…… 172
E.1 Overview of *GeoVISTA CrimeViz*…… 172
E.2 The Map Panel…… 173
E.2.1 Map Navigation and Basemap Style…… 173
E.2.2 Hexagon Overview…… 173
E.2.3 Point Details View…… 174
E.2.4 Map Legend…… 175
E.3 The Data Panel…… 176
E.3.1 Address and ID Unique Search…… 176
E.3.2 UCR Filtering Menus…… 176
E.3.3 Advanced Filtering…… 177
E.3.4 Context Layer Toggles…… 177
E.4 The Temporal Panel…… 178
E.4.1 Histogram…… 178
E.4.2 Animation Controls…… 178
E.4.3 Sequencing Method and Binning Unit…… 178
E.4.4 Linear Temporal Filtering…… 179
E.4.5 Cyclical Temporal Filtering…… 180
E.5 About *GeoVISTA CrimeViz*…… 180

Appendix F: Cartographic Interaction Study Protocol…… 181
F.1 Introduction…… 181
F.2 Demonstration and Opening Exploration…… 181
F.3 Objectives…… 182
F.3.1 *Identify*…… 182
F.3.2 *Compare*…… 182
F.3.3 *Rank*…… 183
F.3.4 *Associate*…… 183
F.3.5 *Delineate*…… 183

Glossary…… 184
References…… 201

List of Figures

Figure 1.1: Cartographic Perspectives……………………………………………………………2
Figure 1.2: The Shifting Conceptualization of the Map…………………………………………4
a. A radial categorization of the analog map
b. A radial categorization of the digital map
Figure 1.3: Growth…………………………………………………………………………………5
Figure 1.4: Cartographic Science under a Growth Perspective……………………………… 6
a. A two dimensional characterization of scientific research in Cartography
b. Topical breadth of the Communication Model
c. Topical breadth of Critical Cartography
d. Topical breadth of Interactive Cartography
e. Topical breadth of Geovisualization
f. Topical breadth of Geovisual Analytics

Figure 2.1: Components of Cartographic Interaction………………………………………… 14
left: User-centered
middle: Technology-centered
right: Interface-centered
Figure 2.2: The Swoopy Diagram……………………………………………………………17
Figure 2.3: Cartography^3……………………………………………………………… 19
Figure 2.4: The Number Scramble Game & the Magic Square Visual Isomorph…………… 23
Figure 2.5: A Pattern-Matching Model for Visual Thinking……………………………………26
Figure 2.6: Interface Complexity versus User Motivation………………………………………30

Figure 3.1: The Stages of Action Model and the Three *O's* of Cartographic Interaction…… 35
Figure 3.2: A Concept Map of Objective-based Primitives…………………………………… 41
Figure 3.3: A Concept Map of Operator-based Primitives…………………………………… 47
Figure 3.4: A Concept Map of Operand-based Primitives…………………………………… 51
Figure 3.5: An Operational Task Typology for Spatiotemporal Visualization……………… 53

Figure 5.1: A Framework for Administering the Card Sorting Method……………………… 81
Figure 5.2: The WebSort Card Sorting Interface……………………………………………… 83
Figure 5.3: Empirically Derived Taxonomy of Cartographic Interaction Primitives…………86
Figure 5.4: Card-by-Card Agreement Matrix for the Objective Card Sorting Study……… 88
Figure 5.5: Card-by-Card Agreement Matrix for the Operator Card Sorting Study……… 96

Figure 6.1: The *GeoVISTA CrimeViz* Cartographic Interface 107
Figure 6.2: A Static Mockup of *GeoVISTA CrimeViz* 110
Figure 6.3: Interaction Logs of *Identify* by *Space-Alone*... 123
Figure 6.4: Interaction Logs of *Identify* by *Attributes-in-Space*................................... 124
Figure 6.5: Interaction Logs of *Identify* by *Space-in-Time*..125
Figure 6.6: Interaction Logs of *Compare* by *Space-Alone*.. 125
Figure 6.7: Interaction Logs of *Compare* by *Attributes-in-Space*.................................. 126
Figure 6.8: Interaction Logs of *Compare* by *Space-in-Time*... 127
Figure 6.9: Interaction Logs of *Rank* by *Space-Alone*.. 128
Figure 6.10: Interaction Logs of *Rank* by *Attributes-in-Space*...................................... 129
Figure 6.11: Interaction Logs of *Rank* by *Space-in-Time*.. 130
Figure 6.12: Interaction Logs of *Associate* by *Space-Alone*... 131
Figure 6.13: Interaction Logs of *Associate* by *Attributes-in-Space*................................ 132
Figure 6.14: Interaction Logs of *Associate* by *Space-in-Time*...................................... 133
Figure 6.15: Interaction Logs of *Delineate* by *Space-Alone*... 134
Figure 6.16: Interaction Logs of *Delineate* by *Attributes-in-Space*................................ 135
Figure 6.17: Interaction Logs of *Delineate* by *Space-in-Time*...................................... 136

Figure 7.1: The Integration of Basic and Applied Research on Cartographic Interaction... 146
Figure 7.2: A Comprehensive View on Twenty-First Century Cartography.................... 148

List of Tables

Table 2.1: The Six Fundamental Questions of a Science of Cartographic Interaction……… 13

Table 3.1: Extant Objective-based Taxonomies of Interaction Primitives…………………… 39
Table 3.2: Extant Operator-based Taxonomies of Interaction Primitives…………………… 44
Table 3.3: Extant Operand-based Taxonomies of Interaction Primitives…………………… 50

Table 4.1: Cartographic Interaction Practice Interview Participants by Domain Area………59
Table 4.2: Participant Balance across Cartographic Interaction Qualities…………………… 59
Table 4.3: Regularity of Using Geographic Info., Static Maps, and Interactive Maps……… 59
Table 4.4: Interactive Maps or Map-based Systems Demonstrated during the Interviews… 61
Table 4.5: Coding Scheme Applied for QDA of the Interviews…………………………………63
Table 4.6: Frequency of Codes Applied for QDA of the Interviews…………………………… 64

Table 5.1: Raw versus Filtered Card Frequencies for the Pair of Card Sorting Studies…… 81
Table 5.2: Definitions and Examples of Each Objective-Operand Primitive Combination… 92

Table 6.1: Regularity of Making and Using Crime Maps……………………………………… 115
Table 6.2: Operator and Operand Primitives Supported by *GeoVISTA CrimeViz*……………119-120
Table 6.3: A Summary of Interactions by Objective and Operand Pairings………………… 121
Table 6.4: A Summary of Interactions by Operator and Operand Pairings………………… 122

Acknowledgements

First and foremost I would like to thank Alan MacEachren. He has been the consummate advisor and mentor throughout my time at Penn State and deserves much of the credit for the quality of the work presented in the dissertation. I attribute much of my own success to the consistent energy Alan has exerted towards first nurturing and then wrangling my ideas.

I also wish to thank my committee members Cindy Brewer, Alex Klippel, and Gene Lengerich for their informative input and careful feedback at the proposal, comprehensive exam, and defense stages of my doctoral progress, as well as for the opportunities they have provided to me on projects outside of the dissertation. In addition to my committee, I wish to thank Mark Harrower, Anthony Robinson, and Andy Woodruff for their influence on my thinking about cartographic interaction and cartographic interface design; the strength of this influence should be apparent in the dissertation.

A project of this size is not without many helping hands; I have enlisted the help of many friends and colleagues during the dissertation research. Kevin Ross has been my partner on the *GeoVISTA CrimeViz* project from its initial inception as a classroom lab exercise and subsequent extension into a small code library, and continues to be a vital member of the *CrimeViz* team, supporting development activities. Benjamin Finch, Wei Luo, Craig McCabe, Ryan Mullins, Scott Pezanowski, and Camilla Robinson also have provided important contributions to the design and development of *GeoVISTA CrimeViz* that deserve noting. Further, Tom Auer and Paulo Raposo assisted with the qualitative data analysis of the cartographic interaction interviews. Finally, the project could not have been completed in a timely fashion without the help of the Penn State GeoVISTA Center and Penn State Geography support staff as a whole, particularly Krista Kahler, Marnie Deibler, and Jessica Watson.

The folks at the Harrisburg Bureau of Police deserve a special acknowledgment, as their interest and hospitality has been unyielding throughout the collaboration. I particularly want to thank Sergeant Deric Moody and Corporal Gabriel Olivera for initiating and organizing the collaboration as well as Larry Eikenberry, Roger Swinehart, and Steve Zimmerman for helping to overcome the technical aspects of the transition.

It is essential to thank my extended network of family and friends, too countless to name, for providing the encouragement and support needed to start a project of this scope and for instilling the drive and work ethic needed to complete such a project. Much love to you all.

Finally, to Aaron Rodgers, Arcade Fire, Arthur Robinson, Irvings of State College, and Meena Pandian: Thank you for the Inspiration!

Chapter One: Introduction
Cartographic Interaction in the Twenty-First Century

Overview:

The first chapter of the dissertation provides an introduction to the overarching goal of this work: establishing a science of cartographic interaction. The chapter begins by reviewing the approaches to twentieth century cartographic science (**Section 1.1**), in particular the traditional focus on cartographic representation, and summarizing the diverging perspectives on twenty-first century cartographic science, which include death, rebirth, and division of the field (**Section 1.2**). A potential cause for the diverging perspectives then is offered—the Digital Revolution and the immediate cartographic interaction that the digital environment affords—and the associated shifting conceptualization of the map is described (**Section 1.3**). Given this review, and taking a fourth perspective of cartographic growth, a problem statement is offered that accepts a fundamental duality between cartographic representation and cartographic interaction (**Section 1.4**). Addressing the under-researched latter component (cartographic interaction), the chapter is concluded by describing the three research goals of the dissertation (**Section 1.5**): (1) identify the key questions that a science of cartographic interaction should answer and compare the existing scope of cartographic interaction science with the needs of cartographic interaction practice, adjusting research expectations accordingly, (2) leverage the reviews of science and practice to derive empirically a taxonomy of interaction primitives, or basic units of cartographic interaction, and (3) use a proof-of-concept cartographic interface to generate empirical insights into the cartographic interaction primitive taxonomy, resulting in an initial set of design and use guidelines for interactive maps and map-based systems.

1.1 Twentieth Century Cartographic Science

Cartography is the art and science of mapmaking and map use.[1] Although stemming from mostly artisan roots, Cartography emerged as a legitimate scientific discipline following the Second World War on the wake of growing interest in empirical map design research and, more broadly, the Quantitative Revolution within Geography. The guiding philosophy during this "Golden Era of Cartography" was ***functional map design***, or the scientific generation of cartographic design guidelines based upon the perceptual and cognitive limits of the intended map user (Robinson, 1952: 3). This approach to cartographic research gave rise to the ***communication model***, which describes the map as a conduit through which a message can be passed from the mapmaker to the map user (Board, 1967, Koláčný, 1969); interruptions in this message transmission were attributed to inappropriate or misleading map symbolization derived by the cartographer's subjective or uninformed design choices. Therefore, it became the mission of academic cartographers to derive empirically a set of map design guidelines that improve the passing of the map message from mapmaker to map user. Many of the map design guidelines generated during this era remain the backbone of the cartographic curriculum today. Reviews of Twentieth Century Cartography can be found in McMaster & McMaster (2002) and Montello (2002).

Despite a prolonged period of dominance, the communication paradigm drew fire towards the end of the twentieth century from practical/applied (Petchenik, 1983) and critical/social theory (Harley, 1989,

[1] Any single definition of Cartography necessarily will need to necessarily overlook important aspects to provide a terse description. However, this definition is widely accepted as an appropriate synopsis of the field and is how I structure my thinking on the breadth of topics covered by the field.

Wood, 1992) perspectives. Even during the infancy of the communication model, practitioners identified the lack of congruence between the communication model and the way that maps are actually used, rejecting the idea of a predictable map task or an average map user (McCleary, 1975). They argued that the same map can be used to complete a variety of map reading tasks performed under a variety of user motivations and against a variety of user background experiences. Further, critical theorists challenged the assumption of an objective map that openly and truthfully delivers the unbiased message of the mapmaker to the map user; many empiricists identified this issue as well (e.g., Muehrcke, 1974). To the critical theorists, scientific cartographers—through their unyielding attempt to interpret empirical findings as confirmation of the communication model—only acted to sterilize the map of its inherent authorship and subjectivity, concealing alternative messages and reinforced the map's authority.

These arguments, as well as emerging discussions taking place in the areas of exploratory data analysis (EDA) and visualization in scientific computing (ViSC), acted to soften Cartography's pursuit of the optimal map within the framework of the communication model[2] (Monmonier, 1991). As a result, many scholars reframed their work as the science of ***cartographic representation***, underpinning the traditional emphasis on perceptual and cognitive cartographic research with a theory of semiotics (Bertin, 1967|1983, MacEachren, 1995). ***Semiotics***, or the study of sign systems, examines the layered meaning present in a map by examining how a map symbol (i.e., the sign vehicle) comes to represent a real world object (i.e., the referent) through the map user's situated interpretation of the symbol (i.e., the interpretant) (Chandler, 2002). Therefore, the science of cartographic representation still focuses upon how maps (and the graphic symbolization constituting maps) work from a perceptual and cognitive standpoint (i.e., how maps are seen and understood), while also accounting for the map user's situated culture and experiences (i.e., how maps become imbued with meaning).

1.2 Perspectives on Twenty-First Century Cartographic Science

Despite ongoing scientific, applied, and critical work on cartographic representation, many believe that Cartography as an area of scientific inquiry has been and currently is facing an identity crisis. There are three general, competing ***cartographic perspectives*** on this development: Death, Rebirth, and Division (**Figure 1.1**).

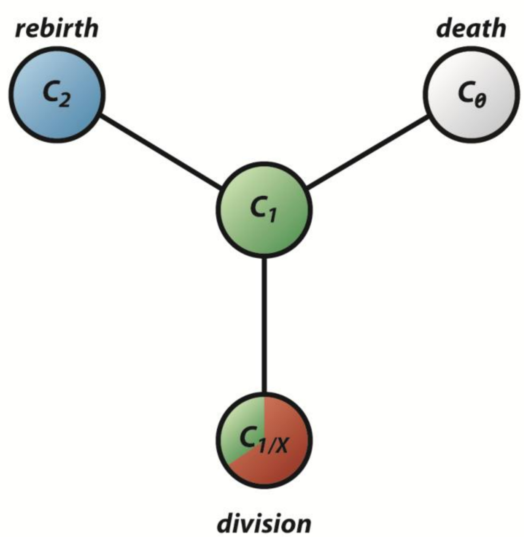


Figure 1.1: Cartographic Perspectives. Competing perspectives on Twenty-First Century Cartography: Death, Rebirth, and Division.

[2] Although no longer the dominant paradigm within Cartography, the communication model remains a useful framework for approaching many questions regarding cartographic representation (e.g., Kostelnick et al., 2008, Robinson et al., 2010, 2011).

The most extreme point of view foresees the ***death*** of academic Cartography, with the science of cartographic representation following thereafter (Wood, 2003a, Koch, 2004). Proponents of this perspective cite the declining number of tenure track professorships in Cartography and the expanding fissure between recommendations produced from cartographic research and what is feasible and appropriate in cartographic practice (for details, see **Chapter 4**). Such a movement represents an un-disciplining of Cartography (Crampton and Krygier, 2006), dissolving the disabling profession of 'cartographer' and returning the capacity to make maps to all spatially-minded people. Under this democratized regime of ***mapmaking***, individuals do not need to be trained in (and thus to follow) the formal guidelines enforced by academic cartographers in order to participate in the act of mapmaking (Rød et al., 2001).

Rather than an ominous death, the second perspective views Cartography as undergoing a ***rebirth*** or reinvention (Wood, 2003b, Turner, 2006).[3] Proponents of this perspective see, and always have seen, Cartography to be a "constantly changing discipline" (Olson, 2004: 4), requiring scientific cartographers to "adapt to the changing role of maps and related graphics in science, and the implications of this change for the theoretical foundations of the field" (MacEachren and Ganter, 1990: 64). New issues of design, technology, authorship, privacy, and interdisciplinarity are expected to emerge as old issues are resolved or discarded. From this perspective, the need for a science of cartographic representation remains, even as the problem context evolves (MacEachren, 1994). As long as the focus of scientific inquiry is upon the map, it remains Cartography.

The final perspective accepts a ***division***, or apportionment, of map-based scientific research across many fields, Cartography only being one of them. This perspective seeks continuity in the reach of cartographic science, continuing to prosper with what has worked over the past half century and leaving new developments to closely related, yet different fields. A division in Cartography may be due to the aggressive encroachment from other disciplines or by the unwillingness of Cartography to extend itself to new opportunities. The former concern is related to the encapsulation of Cartography programs and classes under the heading of GIS or GIScience (Montello, 2002, Sui and Goodchild, 2003), which might act to marginalize important cartographic concepts and research findings as well as to redefine Cartography narrowly as the practice of geospatial information presentation[4] (see **Section 2.3**). The latter concern is related squarely to the contributions of computer scientists, particularly the development and popularization of tile-based, ***slippy*** web mapping services maintained by software firms that, at least initially, received very little input from trained cartographers. The division perspective, therefore, redefines Cartography as the art and science of only particular map designs and only particular map uses.

1.3 Cartographic Interaction and the Prototypical Map

The lack of agreement among these three perspectives perhaps is caused by the shifting conceptualization of the map as a result of the ***Digital Revolution***, a term used to describe the fast-paced innovation of computing technologies in the latter portion of the twentieth century and the associated impact of personal computing on society. The Digital Revolution and the subsequent ***Information Age***, which leverages these digital technologies to make unprecedented volumes of information available and usable, together have prompted changes that are as numerous as they are fundamental to the ways in which maps are produced and consumed (Harrower, 2008). The digital environment allows maps to respond to system-events, which affords the representation of temporal change through cartographic animation (Lobben, 2003, Harrower and Fabrikant, 2008) and the representation of unfolding geographic developments through real-time, data-driven map updates (Boulos and Burden, 2007, Goldsberry, 2007). The digital environment also is paired with a convenient and increasingly ubiquitous dissemination mechanism in the

[3] It is important to note that Wood (2003a) and Wood (2003b) are not the same author, explaining the difference in perspective.
[4] Which effectively would revert Cartography to the communication model in the minds of non-cartographer GIScientists.

Internet (Harrower et al., 1997, Kraak and Brown, 2001). Finally, the digital environment supports context-appropriate ***adaptive cartography***, allowing for cartographic representations and cartographic interfaces that are customized according to use and user context (Reichenbacher, 2003, Friedmannová et al., 2006) and map scale (Brewer and Buttenfield, 2007, Sarjakoski, 2007). Although all of these topics are promising research areas for Twenty-First Century Cartography, Dykes (2005) argues that no single product of the Digital Revolution has had a more transformative impact on the conceptualization, design, and use of maps than the possibility of digital ***cartographic interaction***, defined as the dialogue between a human and a map mediated through a computing device (see **Section 2.2** for a more complete definition).

Figure 1.2 proposes a possible shift in the way in which maps are conceptualized since the Digital Revolution using ***radial categories*.** Such categories have a central prototype (i.e., the first example that comes to mind), with non-prototypical examples bearing family resemblance to the central prototype according to non-arbitrary, motivating characteristics, which often are represented graphically as orthogonal axes (Lakoff, 1987). **Figure 1.2a** illustrates a radial categorization offered by MacEachren (1995: 161) of what may be considered the non-digital, or ***analog***[5] map. The MacEachren radial categorization uses degree of abstraction (image versus diagram) and map scale (atom versus universe) as the motivating characteristics; like most cartographic research in the twentieth century, the focus of these two motivating characteristics is upon cartographic representation. Prototypical maps in the **Figure 1.2a** radial categorization include a planimetric reference map of county roads, an oblique reference map of terrain, and a thematic map of AIDS incidence; none of the almost twenty map examples given in **Figure 1.2a** are explicitly interactive.[6]

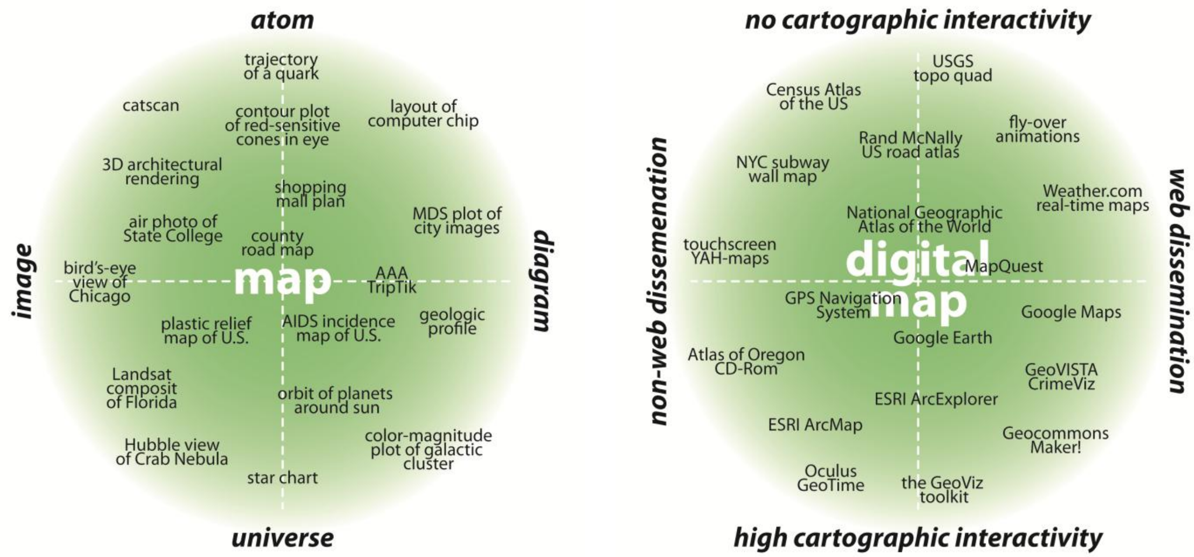


Figure 1.2: The Shifting Conceptualization of the Map as a Result of the Digital Revolution. (a) A radial categorization of the analog map using degree of abstraction and map scale as the motivating characteristics, redrawn from MacEachren (1995: 161). **(b)** A radial categorization of the digital map using web dissemination and cartographic interaction as motivating characteristics.

[5] The term 'analog', while having a specific meaning with regard to electronics, is used here as the complement to 'digital', and primarily refers to non-digital paper or printed maps or non-digital georeferenced photographs. Several of the examples included in the MacEachren (1995: 161) radial categorization were natively digital, but explicitly static (and therefore could have been produced in analog form without any change to their composition).

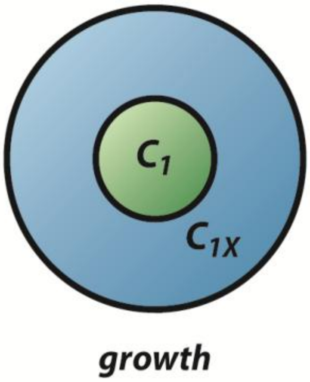
[6] Which is indicative of the mapping technologies available when the MacEachren (1995: 161) figure was created.

Figure 1.2b illustrates a radial categorization of the digital map using motivating characteristics that reflect the impact of the Digital Revolution and Information Age on Cartography.[7] The first axis—web dissemination—describes the degree to which the map (including all of its contents) is delivered using the Internet. The web dissemination continuum ranges through the following overlapping categories: maps available only in print or on CD-ROM, maps that can be downloaded directly from the web but must be used locally as desktop applications, maps that first must be obtained offline but stream in data and system updates from the web, and maps that use the Internet as a platform, allowing for viewing and manipulation within a web browser or on a mobile device. Method of dissemination is important for the radial categorization because it dictates map exposure to and adoption by the general public, which directly influences prototypical examples of the digital map. The second axis—cartographic interaction—describes the number and freedom of available cartographic interactions. The cartographic interaction continuum ranges through the following overlapping categories: static maps with only analog cartographic interactions, natively static maps that are made available digitally, natively digital maps with limited interactivity, highly interactive one-off maps, and desktop map-based systems that offer a robust suite of cartographic interactions for the user-defined maps generated within the systems. Prototypical examples in the **Figure 1.2b** digital map categorization include reference maps for navigation located either in-car (e.g., GPS-based systems) or online (e.g., MapQuest), digital globes (e.g., Google Earth, an example of a map that would be peripheral in **Figure 1.2a** due to the primary depiction's degree of realism), and digitally-native thematic atlases that include both print and digital versions (e.g., National Geographic Atlas of the World). Although many conclusions can be inferred from the **Figure 1.2** comparison, nothing is more evident than the growing centrality of at least a medium degree of cartographic interaction in the conceptualization of the map—it can be expected that cartographic interaction only will become more fundamental as the central prototype continues to shift.

1.4 Problem Statement: Towards a Science of Cartographic Interaction

The ***Cartographic Revolution*** suggested by **Figure 1.2** has been twenty years in the making. With the increased awareness or general adoption of many digital cartographic and location-based technologies, it is possible that we are nearing the terminus of this revolution, rather than being directly in its midst. Unfortunately, and perhaps in part due to the conflicting perspectives portrayed in **Figure 1.1**, cartographic science thus far has failed to keep pace with these rapidly evolving mapping applications and technologies. To reconcile this disconnect, I believe cartographic scientists and practitioners should take a fourth perspective on Twenty-First Century Cartography: ***Growth*** (**Figure 1.3**).

Figure 1.3: Growth. A fourth perspective of Twenty-first Century Cartography suggesting growth of the field to include research on cartographic representation, cartographic interaction, and relationships between the two.



[7] The axes degree of web dissemination and cartographic interaction are best interpreted as two additional motivating characteristics adding to the original MacEachren (1995: 161) schematic. The pairs are separated in **Figure 1.2** for sake of discussion about how the conceptualization of a map may be changing.

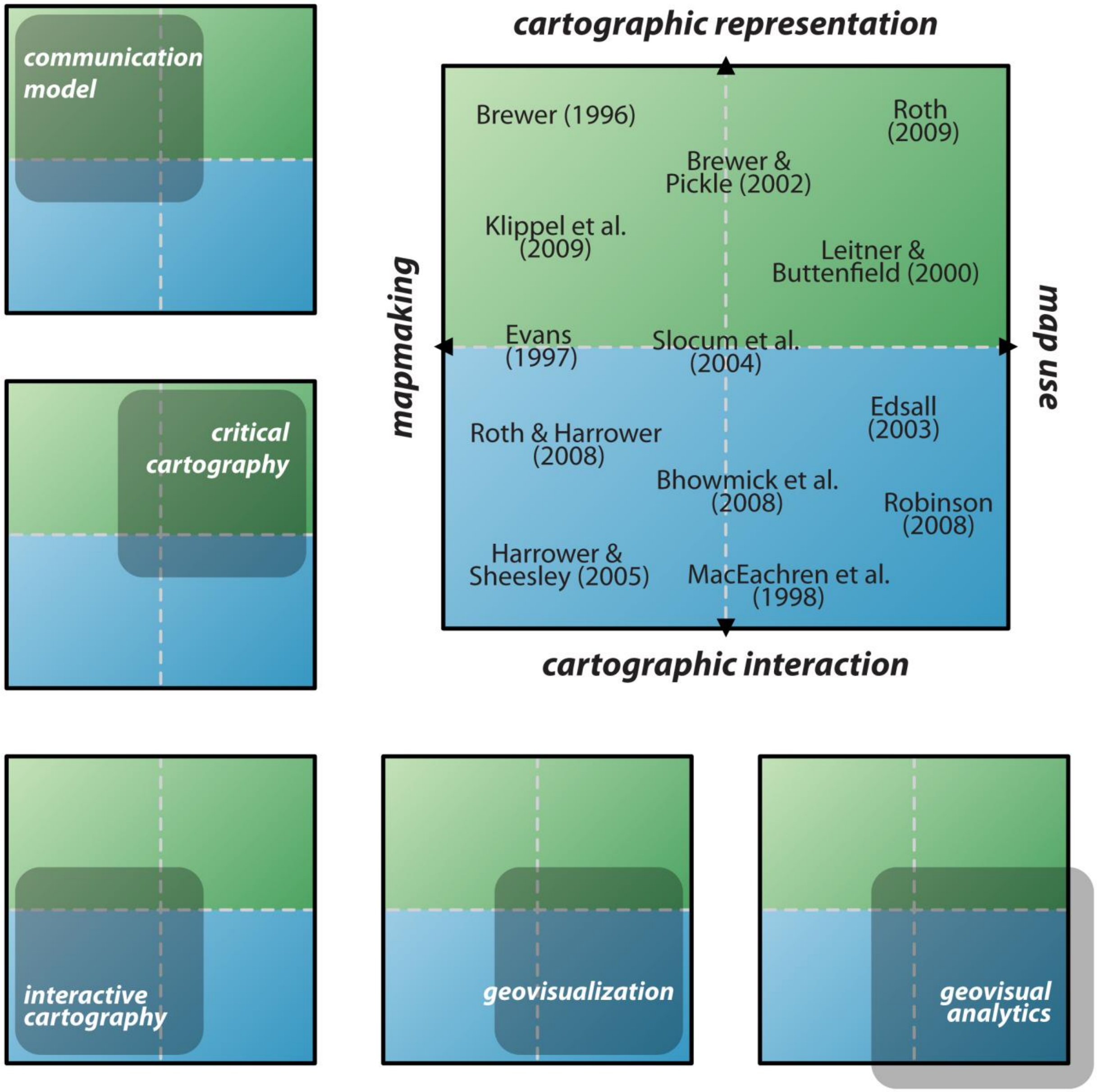


Figure 1.4: Cartographic Science under the Growth Perspective. (**a: right-top**) Most scientific research in Cartography can be characterized along the dimensions of *cartographic representation vs. cartographic interaction* and *mapmaking vs. map use*. The inset drawings suggest the general topical breadth of the cartographic research thrusts of: (**b: left-top**) the Communication Model, (**c: left-middle**) Critical Cartography, (**d: left-bottom**) Interactive Cartography, (**e: middle-bottom**) Geovisualization, and (**f: right-bottom**) Geovisual Analytics.

Cartographic science must expand its reach to provide actionable knowledge about and practical guidelines for the design and use of this new generation of digital maps. Cartographic research also should suggest new opportunities for application of digital cartography, creating a positive feedback loop of expansion and vitality between science and practice. Cartographic growth, however, should not be at the expense of established cartographic research topics. Instead, traditional cartographic questions need to be reevaluated, and readily accepted cartographic guidelines reconsidered, in the context of an interactive, digital environment (Andrienko and Andrienko, 1999a, Koua and Kraak, 2004, Gartner et al., 2007). We need a unifying structure to incorporate the affordances of the Digital Revolution into Cartography without jettisoning the pillars of twentieth century cartographic research. Emerging research topics must be integrated with extant ones.

Figure 1.4a organizes the breadth of research topics covered by this growing Scientific Cartography according to two continua:[8] cartographic representation versus cartographic interaction and mapmaking versus map use. Cartographic research can be focused primarily on cartographic representation, primarily on cartographic interaction, or on the influence each has on the other and their combined synergy. Further, and following the classic distinction in Cartography between mapmaker and map user, cartographic research can examine how the representations or interactions should be designed by cartographers, how these representations and interactions should be employed to support user goals and objectives, or how they should be altered under the increasingly common scenario when the mapmaker is the map user. Representative studies of the various possible combinations of the two categories are listed within the **Figure 1.4a** research space. Modifications of **Figure 1.4a** are provided to show the topical breadth of five important subareas of research within Cartography: the Communication Model (**Figure 1.4b**), Critical Cartography (**Figure 1.4c**), Interactive Cartography (interactive maps for storytelling rather than exploration, e.g., digital atlases, interactive news maps, web-based campus maps, and many map mashups; **Figure 1.4d**), Geovisualization (**Figure 1.4e**), and Geovisual Analytics (**Figure 1.4f**).

The research presented in the following chapters elucidates a growth perspective on Cartography based upon the **Figure 1.4** distinction between cartographic representation and cartographic interaction. The former topic encapsulates cartographic research on design for perception and cognition as well as semiotics that together constitute twentieth century cartographic science (**Section 1.1**), while the latter topic emphasizes the primary affordance of the Digital Revolution and digital mapping technologies. Important to the growth perspective on Cartography is the overlap between cartographic representation and cartographic interaction, particularly considering how new research on cartographic interaction may complement, extend, and at times revise extant scientific theories on cartographic representation. Establishing a science of cartographic interaction is not a new concept, with research on interactive maps extending at least to the 1960s (e.g., Pivar et al., 1963, Engelbart and English, 1968). Since the Digital Revolution, scholars in various cartographic subfields repeatedly have identified empirical, systematic examination of the way in which users interact with digital cartographic representations as a key gap in contemporary cartographic research requiring additional attention. Many of these research agendas have come from the cartographic subfield of Geovisualization (MacEachren and Kraak, 1997, Cartwright et al., 2001, MacEachren and Kraak, 2001, MacEachren, 2001), which is logical given its reliance upon high levels of interaction to facilitate open-ended map-based exploration (MacEachren, 1994). Further, the duality of representation (i.e., defined narrowly as graphic rendering) versus interaction (i.e., defined narrowly as graphic manipulation) is largely accepted in the related fields of Exploratory Data Analysis (Buja et al., 1996) and Information Visualization (Yi et al., 2007), so it is logical for Cartography (the study of one type of information graphic) to follow suit. Finally, several of the more recent calls have come from the subfield of Geovisual Analytics; this again is logical given the topical breadth of Geovisual Analytics (**Figure 4e**) and definition as the science of analytical reasoning about geographic

[8] Unlike **Figures 1.2a** and **1.2b**, images in **Figure 1.4** are not a radial categorizations. Instead, images in **Figure 1.4** represent a 2x2 schematization for identifying how existing and future research can be placed in a growing cartographic science.

phenomena and processes facilitated by geovisual interfaces to geocomputational methods (Andrienko et al., 2007). Although not solely speaking to interactions that are cartographic in nature, the most poignant call for a science of interaction is given by Thomas et al. (2005: 76) among their listing of recommendations for developing a science of visual analytics:

> "Recommendation 3.3: Create a new science of interaction to support visual analytics. The grand challenge of interaction is to develop a taxonomy to describe the design space of interaction techniques that supports the science of analytic reasoning. We must characterize this design space and identify under-explored areas that are relevant to visual analytics. Then, R&D should be focused on expanding the repertoire of interaction techniques that can fill those gaps in the design space."

The research goals of this dissertation are three-fold, each aimed towards establishing a science of cartographic interaction following a growth perspective (**Figure 1.3**):

> **Goal #1:** Identify the key questions that a science of cartographic interaction should answer and compare the existing scope of cartographic interaction science with the needs of cartographic interaction practice, adjusting research expectations accordingly.
>
> **Goal #2:** Leverage the reviews of science and practice to derive empirically a taxonomy of ***interaction primitives***, or basic units of cartographic interaction.
>
> **Goal #3:** Use a proof-of-concept cartographic interface to generate empirical insights into the cartographic interaction primitive taxonomy, resulting in an initial set of design and use guidelines for interactive maps and map-based systems.

Each research goal is described in more detail in the following subsection and each is achieved through the remainder of the dissertation chapters.

1.5. Research Goals & Dissertation Structure

1.5.1 Questions for a Science and Practice of Cartographic Interaction

An essential task in establishing a science of cartographic interaction is characterizing its scope. There is a small, yet important set of scholarship on the topic of interaction offered within Cartography that focuses on interactions that are explicitly cartographic in nature. Examples of this theoretical work include DiBiase's (1990) swoopy schematic (**Figure 2.2**), MacEachren's (1994) Cartography^3 (**Figure 2.3**), MacEachren and Ganter's (1990) pattern-matching model for visual thinking (**Figure 2.5**), and the series of manuscripts on cartographic interaction primitives reviewed in **Chapter 3**. This extant research needs to be supplemented and extended by research in the related fields of GIScience, Human-Computer Interaction, Information Visualization, and Visual Analytics, much like Robinson (1952) supplemented extent research within the then emerging field of Cartography with relevant theory from Advertising, Art, Education, and Psychology. Thus, it is the first research goal of the dissertation to identify the fundamental questions that need to be addressed by a science of cartographic interaction, and subsequently to summarize our current answers to these questions.

Importantly, the questions that are asked by a science of cartographic interaction should not be based on existing theory alone (offered both inside and out of Cartography), but additionally should be influenced by the practice of cartographic interaction in order to remain sensitive to and influential on practical concerns. The dynamic nature of the design and use of the twenty-first century maps resulting from the Digital Revolution and associated Information Age presents a challenge to both scholars and practitioners within Cartography. It is conventional wisdom that science outpaces practice, with the significant discoveries occurring in the laboratory and taking years to impact practice. However, this may no longer be the case within Cartography—and other disciplines influenced so heavily by the Digital Revolution and Information Age—given the fast-paced changes currently exhibited in both mapmaking and map use; professionals working in Cartography often are the first to identify and solve emerging problems, at times without their scholarly counterparts ever being aware that these problems existed. Accordingly, scholars and practitioners must share the burden of constant filtering and translation of nascent developments in related (and perhaps unrelated) fields in order to affect positive change within Cartography, all while maintaining a clear and progressive agenda for Cartography itself.

The first research goal was achieved through a pair of complementary background efforts designed to capture and integrate science and practice. A comprehensive review of secondary sources regarding interaction from the fields of Cartography, GIScience, Human-Computer Interaction, Information Visualization, and Visual Analytics first was completed to characterize the current state of science on cartographic interaction. This review resulted in the identification of six broad research questions motivating a science of cartographic interaction (see **Table 2.1**). This review is divided into two dissertation chapters: the first chapter addresses five of these questions (*what?*, *why?*, *when?*, *who?*, and *where?*) that altogether define the context of cartographic interaction while the second chapter addresses the sixth question (*how?*), which is the focus of the second half of the dissertation. These reviews of cartographic interaction science are reported in **Chapter 2** & **Chapter 3** respectively.

A set of semi-structured interviews then was conducted to investigate how the current state of science on cartographic interaction (as formalized in the aforementioned literature review) compares to the current state of practice regarding cartographic interaction. Twenty-one interactive map users were recruited from seven application domains to discuss the way in which cartographic interaction currently supports their work, and limitations thereof. Interview questions were based upon the key gaps in extant scientific research identified in the **Chapter 2** & **Chapter 3** reviews. The cartographic interaction interview study is reported in **Chapter 4**. Together, the review of secondary sources and set of semi-structured interviews provide a contemporary snapshot of the kinds of questions facing the science and practice of cartographic interaction, both answered and unanswered.

1.5.2. A Taxonomy of Cartographic Interaction Primitives

The second goal of the dissertation is to provide insight into one of the identified questions facing a science of cartographic interaction: *how* can users interact with maps. Perhaps the largest breakthrough in the science of cartographic representation was the identification and articulation of the fundamental graphic or ***visual variables*** available to the cartographer when constructing a map (Bertin, 1967|1983, Morrison, 1974, Caivano, 1990, MacEachren, 1992). The visual variables provide a framework for understanding the complete design space of cartographic representation techniques, letting the cartographer know the graphic dimensions that can be manipulated in order to encode information, and, through the formulation of a syntactics, which visual variable should be manipulated depending on the mapping context.

Unlike its representation counterpart, there has yet to be an accepted taxonomy of the fundamental cartographic interaction primitives. This is also true for the related discipline of Information Visualization, which (like Cartography) has "made great strides in the development of a semiology of graphical representation methods, but lacks a framework for studying visualization operations" (Chi and Riedl, 1998: 63). This is not due to a lack of offerings, as demonstrated in the review of extant interaction primitive taxonomies provided in **Chapter 3**. One limitation of extant taxonomies that possibly contributes to their lack of adoption is that most of these taxonomies are not empirically derived.[9] With only several exceptions, extant taxonomies are based solely upon logic and do not integrate empirical

[9]Bertin's (1967|1983) set of visual variables also were not empirically derived, although many of Bertin's claims subsequently were confirmed using empirical evidence.

evidence explicitly. It is a contention of this research that an empirical approach that gathers multiple rounds of evidence, and checks this evidence against current practice, is critical for ensuring that the taxonomy is ecologically valid and broadly applicable.

The second research goal was achieved by a pair of card sorting studies designed to generate an initial taxonomy of cartographic interaction primitives. The background reviews on cartographic interaction science (primarily from **Chapter 3**) and practice (from **Chapter 4**) were combined to generate the universe of example cartographic interaction primitives. Fifteen cartographic interface designers completed a pair of guided sorting tasks in which they were instructed to classify this universe of instances into categories according to similarity. The pair of card sorting studies resulted in an initial taxonomy of cartographic interaction primitives with four dimensions: (1) user goals, (2) user objectives, (3) interaction operators, and (4) interaction operands. The pair of card sorting studies and resulting taxonomy of cartographic interaction primitives are reported in **Chapter 5**. The achievement of the second research goal effectively meets Thomas et al.'s (2005: 76) "grand challenge of interaction" introduced above.

1.5.3. Prototypically Successful and Unsuccessful Cartographic Interaction Strategies

The third and final goal of the dissertation is articulation of prototypically successful and unsuccessful cartographic interaction strategies. Returning to the science of cartographic representation, the visual variable taxonomy was not an important development for Cartography just because it enumerated the various dimensions across which a graphic could be manipulated to encode information. In fact, the taxonomy has been expanded and revised considerably over time and it can be expected that adjustments will continue to be necessary as technology and practice evolves. What makes the visual variable framework important is that it provided a systematic way of varying cartographic representations when empirically examining which representations work the best. The results of these experiments then are used to answer the *how?* question of cartographic representation, introducing a formal ***syntactics*** of the visual variables for assisting cartographers in the selection of representation choices appropriate for the given mapping context.

Once a taxonomy of cartographic interaction primitives is developed, similar experimentation can be administered to compare different sequences of interaction operators—described as competing ***interaction strategies***—that are performed in attempt to achieve a given objective (Edsall, 2003). This investigation then may lead to the generation of cartographic interface design best practices and ultimately the generation of a syntactics of cartographic interaction primitives. Such a syntactical framework allows for the prescription of cartographic interface design and use according to the intended objective, improving the usability and utility of cartographic interfaces and easing the workload of both the interactive mapmaker and interactive map user. However, the development of a syntactics of cartographic interaction that is both reliable across multiple examples of similar mapping contexts and generalizable to all possible mapping contexts requires completion of a comprehensive series of controlled experiments, each varying only a single parameter of the mapping context (e.g., cartographic representation technique, application domain, map user characteristics). Therefore, achieving a syntactics of cartographic interaction primitives is a research goal that is necessarily ongoing—requiring constant revision as new technologies are developed and triangulation as other relevant studies are reported—and is therefore out of the scope of the dissertation. The insights generated to achieve the third research goal serve as a jumping off point for future scientific research on cartographic interaction.

The third research goal was reached through completion of a cartographic interaction study designed to evaluate the initial taxonomy of interaction primitives. The cartographic interaction study leveraged a cartographic interface called *GeoVISTA CrimeViz* as a 'living laboratory' to identify the most effective and efficient application of interaction operators according to the objective and operand context. *GeoVISTA CrimeViz* (http://www.geovista.psu.edu/CrimeViz) is an extensible, web-based geovisualization application that supports exploration, analysis, and sensemaking about criminal activity in space and time and was developed in collaboration with the Harrisburg (Pennsylvania, USA) Bureau of Police following a user-centered design approach. Ten law enforcement personnel at the Harrisburg Bureau of Police participated in a cartographic interaction study using *GeoVISTA CrimeViz*, resulting in a set of prototypically successful and unsuccessful interaction strategies. The cartographic interaction study is reported in **Chapter 6**, following description of the case study with the Harrisburg Bureau of Police. Reflections on the insights generated by the dissertation research and remaining questions for a science of cartographic interaction are provided in **Chapter 7**, the concluding chapter.

Chapter Two: Background Review
Elements of Cartographic Interaction

Overview:

This chapter discusses the fundamental elements of cartographic interaction, outlining the basic questions that a science of cartographic interaction should strive to answer and the associated current state of science responding to each question. The chapter begins by introducing the six fundamental questions of a science of cartographic interaction (**Section 2.1**) first introduced in **Chapter 1**; the five *W's* of cartographic interaction are discussed in the subsequent **Chapter 2** subsections, while the sixth question of *how?* is reserved for **Chapter 3**. The *what?* question is first addressed, providing a definition of cartographic interaction and making an important distinction between cartographic interaction and cartographic interfaces (**Section 2.2**). The *why?* of cartographic interaction then is discussed, first summarizing its importance for visual thinking within the cartographic subfield of Geovisualization and then considering other potential applications (**Section 2.3**). Discussion of the *when?* question centers upon the topics of workload and productivity, particularly focusing upon reasons to constrain the cartographic interaction implemented in a cartographic interface (**Section 2.4**). The *who?* of cartographic interaction addresses variation in the user performing the interaction, including user characteristics such as ability (perceptual, cognitive, and motor skills), expertise, and motivation (**Section 2.5**). A discussion of the *where?* question then is provided, focusing on technological constraints to cartographic interaction associated with input devices, bandwidth size/processing power, and display capabilities (**Section 2.6**). The chapter closes with concluding remarks (**Section 2.7**)

2.1 Questions for a Science of Cartographic Interaction

> One of the major aims of education is to impart an appreciation of what and how much we do not know. It is primarily with this thought in mind that these essays are presented. I am acutely conscious that the reader may be reminded of that unhappy person who tells most of a (supposedly) good story—and then forgets the denouement. For the truth is that the unravelling of many of the mysteries of cartographic design and presentation has not yet been accomplished. Nevertheless, in the hope that the half-told story will excite the curiosity of others to investigate further, these essays are presented without apology, but with the hope that the reader will be understanding enough to maintain constructive attitude—at least towards the subject manner.

It is with this disclaimer that Arthur Robinson (1952: vii) opened his seminal cartographic text *The Look of Maps*. As described in **Chapter 1**, this monograph called for ***functional map design*** informed by the perceptual and cognitive abilities of expected map users and widely is considered as the origin of Twentieth Century Scientific Cartography (Montello, 2002).[10] In the text, Robinson supplemented the few empirical guidelines or design conventions specific to mapmaking with external research from other fields that examine communication, such as Advertising, Art, Education, and Psychology. In doing so, Robinson extrapolated theoretical frameworks and experimental findings to Cartography, rethinking them when necessary to compensate for the cartographic context. This translation generated more questions than answers, a point that Robinson acknowledges in the book's foreword. His effort remained valuable, however, as the questions posed acted to structure a half-century of scientific research on cartographic representation, a collective effort that perhaps culminated in the final installment of Robinson and colleagues' (1995) *Elements of Cartography*.

[10] Although Montello (2002)—and of course Robinson himself in his own volume—identifies important scientific work in Cartography preceding *The Look of Maps*.

Question	***Definition***
What?	the definition of cartographic interaction in the context of cartographic research
Why?	the purpose of cartographic interaction and the value it provides
When?	the times that cartographic interaction positively supports work, and should therefore be provided
Who?	the types of users provided cartographic interaction and the way in which differences across users impacts interface designs and interaction strategies
Where?	the computing device through which cartographic interaction is provided and the limitations or constraints on cartographic interaction imposed by the device
How?	the fundamental cartographic interaction primitives and the design of cartographic interfaces that implement them

Table 1: The six fundamental questions of a science of cartographic interaction.

It is in a similar vein that I embark on reviewing extant research on cartographic interaction. There is a concentrated, and growing, set of research articles examining digital interactions that are explicitly cartographic in nature. In the following review, this set of articles is supplemented by secondary sources on interaction in the disciplines of GIScience, Human-Computer Interaction, Information Visualization, and Visual Analytics. It is likely that these external theoretical frameworks and empirical evidence need to be rethought when applied to Cartography (if they are even relevant at all). Similarly to the approach taken by Robinson (1952), these external works are included in the review to identify the open questions on cartographic interaction that require further investigation.

Science begins with questions. To follow a familiar structure, the background review is organized according to the six categories of descriptive questions common to investigative analysis and reporting (Wang et al., 2008), forming the ***six fundamental questions*** of a science of cartographic interaction (the five *W's* plus *how?*) introduced in **Section 1.5.1**. **Table 2.1** lists and defines each of these questions. The following review provides a synopsis of what we know, and what we need to know, about each question regarding cartographic interaction. The ***five W's*** of cartographic interaction are reviewed in **Chapter 2**, while the sixth question *how?* is handled separately in **Chapter 3**.

2.2 What is Cartographic Interaction?

An important starting point is to define and scope what is meant by cartographic interaction. It can be argued that even the first maps and spatial diagrams etched into the sand or scribbled onto a cave wall were interactive (Peterson, 1998). Using a stick or piece of charcoal, the mapmaker quickly could adjust the design in response to his or her evolving conceptualization of the mapped phenomenon, or in response to an inquisitive cave-peer. Similar arguments have been made for less-ephemeral, paper maps as well (e.g., Bertin, 1967|1983, MacEachren and Ganter, 1990, Wood, 1993, Cartwright et al., 2001, Dodge et al., 2008). The map user can adjust the mapped extent by folding it, bring it nearer to or farther from his or her eyes, annotate it using pens or colored markers, and add pins to identify important locations (Wallace, 2011). Further, categories of map features can be added or removed from the map when decomposed into a set of overlapping transparent sheets, resulting in the common GIS interaction metaphor: the layer stack (McHarg, 1969, Goodchild, 2010).

Undoubtedly, the Digital Revolution has increased the potential for and pervasiveness of cartographic interaction (see **Section 1.3**). The digital environment provides a greater number of ways for manipulating a cartographic representation, with the kinds of interactions provided through the interactive map limited only by the objectives of the map user, the skill set of developer, and the input, processing, and display limits of the hardware (Gahegan, 1999). In the following chapters, the use of ***cartographic interaction*** includes only those interactions between a human and digital map,[11] or more specifically the *dialogue between a human and a map mediated through a computing device* (**Figure 2.1**).

Using Norman's (1988) ***stages of action model***, a cartographic interaction between a human and a digital cartographic representation can be segmented into seven observable steps: (1) forming the goal, (2) forming the intention, (3) specifying an action, (4) executing the action, (5) perceiving the state of the system, (6) interpreting the state of the system, and (7) evaluating the outcome.[12] Each of these steps is essential to the dialogue between the user and the digital map mediated through a computing device, with failures in the accomplishment of each step resulting in an interruption of this cartographic interaction conversation. The ***gulf of execution*** describes the disconnect between the user's objectives and the provided cartographic interaction operators, and roughly relates to interruptions in the first four stages of action. In contrast, the ***gulf of evaluation*** describes the disconnect between what the user expected to accomplish through the cartographic interaction and the interface's representation of the result of the

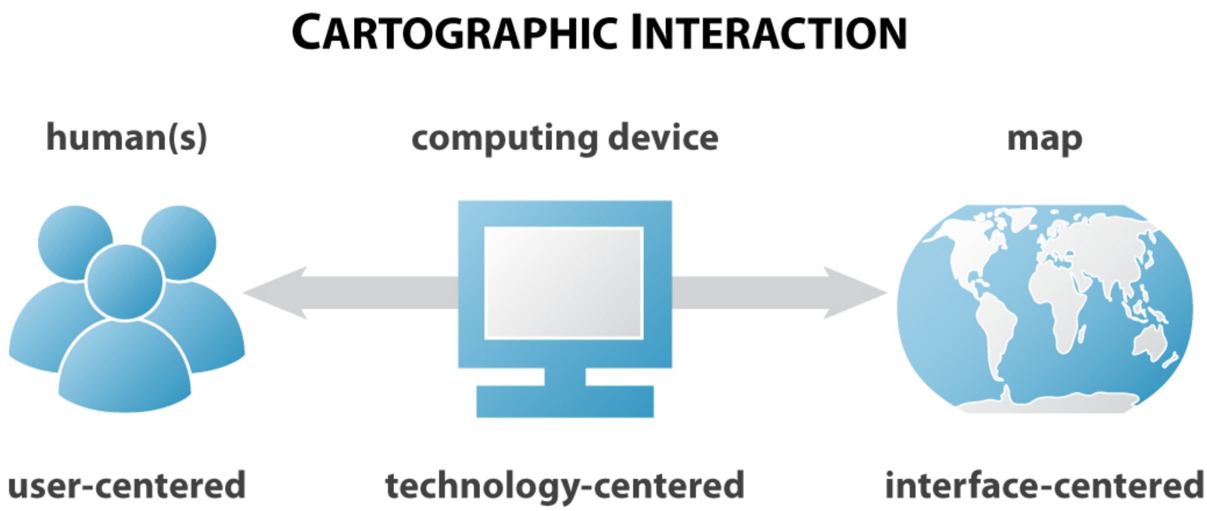


Figure 2.1: Components of Cartographic Interaction. Cartographic interaction is defined as the dialogue between a human and a map mediated through a computing device. This gives rise to three areas of emphasis within a science of cartographic interactive: **(left)** user-centered **(Section 2.5)**, **(middle)** technology-centered **(Section 2.6)**, and **(right)** interface-centered **(Section 2.4)**.

[11] unless otherwise noted

[12] Norman's stages of action model describes how humans interact with any object in the world, analog or digital. The framework has been particularly informative for understanding digital interaction.

cartographic interaction, and roughly relates to interruptions in the final three stages of action. Norman's stages of action model, and the associated gulfs of execution and evaluation, are addressed in more detail in **Section 3.2** when introducing extant interaction taxonomies offered at different stages of action.

Many scholars in Human-Computer Interaction place a limit on the time it takes for the application to respond to the user input in order for it to be considered 'interactive', an issue closely related to the gulf of evaluation. Three limits on response immediacy are recognized in Human-Computer Interaction: (1) 0.1 second for the user to feel as though the system is responding immediately, (2) 1.0 second to avoid interrupting the user's thinking process, and (3) 10 seconds before the user's attention will be diverted to other tasks (Miller, 1968, Nielsen, 1993). Accordingly, recommended response times for high-quality interaction range between one and two seconds (Wardlaw, 2010). Some of these recommendations are constrained by an understanding of human motor skills, as users need to receive visual feedback within one-tenth of a second for optimal hand-eye coordination; therefore, interaction delays of 150 milliseconds may be noticeable (Shneiderman and Plaisant, 2010). According to their Keystroke-Level Model, Card et al. (1980, 1983) recommend that the optimal amount of time to complete an interaction is approximately 0.40 seconds for a keyboard press, approximately 1.16 seconds for a coarse mouse movement, and 0.38 seconds for a fine, honing mouse movement. Any delays beyond these optimal levels, such as those in system response time, affect user productivity (Haunold and Kuhn, 1994). However, immediate response is difficult in the context of voluminous geographic datasets and complex, vector-based cartographic representations. As Haklay and Li (2010: 232) note, "Almost no [geospatial] application is truly interactive and provides a responsive application to the user within two seconds of an operation." Thus, no constraint on response time for a cartographic interaction is imposed *a priori*, but instead will be investigated as a tangential component of the subsequent research.

It is necessary to distinguish cartographic interaction from ***cartographic interfaces***, or the digital tools through which the cartographic interaction occurs (Nielsen, 1993, Haklay and Tobón, 2003); as illustrated in **Figure 2.1**, the cartographic interface is but one part of a complete cartographic interaction experience. Cartographic interfaces include both one-off interactive maps built around a single geographic information set as well as complex map-based systems that possibly include several or many non-cartographic components, as both provide cartographic interaction. Scholars in the fields of Human-Computer Interaction and Usability Engineering characterize interfaces according to three properties: (1) the cartographic interaction it supports (as defined above), (2) its interface style, and (3) its interface design. The ***interface style*** describes the way in which user input is submitted to the software to perform the cartographic interaction, and includes: (1) ***direct manipulation*** (pointing at the map or custom interface widget to manipulate it), (2) ***menu selection*** (selecting items from a list), (3) ***form fill-in*** (keying in text to indicate the parameters of desired action), (4) ***command language*** (use of a simplified syntax to indicate a series of desired actions), and (5) ***natural language*** (use of spoken language to submit a question or command) (Shneiderman and Plaisant, 2010). In contrast, the ***interface design*** describes the graphics, sounds, haptics, etc., that constitute the interface widget and its feedback mechanism, producing its 'look and feel' (Cooper and Reimann, 2003). The success of cartographic interfaces is evaluated in terms of their ***utility*** (i.e., usefulness for completing the user's desired set of tasks) and ***usability*** (i.e., the ease of using the system to complete the desired set of tasks) (Grinstein et al., 2003, Fuhrmann et al., 2005). Cartographic interactions and cartographic interfaces are inextricably related; digital cartographic interaction cannot occur without implementing some sort of cartographic interface,[13] and the utility and usability of the cartographic interface is determined by the kind and quality of cartographic interactions provided through it. Yet, a science of interaction, cartographic or otherwise, must begin with fundamental cartographic interaction primitives themselves and not the user interfaces that implement these interaction

[13] Here considering the notion of a 'cartographic interface' to be any interface that allows you to manipulate the map display, not necessarily a map display that doubles as a direct manipulation interface.

primitives (Beaudouin-Lafon, 2004). Most existing scientific research on the topics within Cartography, however, examines cartographic interfaces and not cartographic interactions.

Many questions on the fundamental nature of cartographic interaction and the conceptualization of cartographic interfaces remain. For instance, the radial categorization shown in **Figure 1.2b** includes both desktop mapping and GIS software; do the developers or users of these tools agree that such applications are cartographic interfaces, and, if so, does considering them as cartographic interfaces influence the way in which they are designed or the way in which the provided cartographic interactions are initiated to complete user tasks? **Figure 1.2b** also includes Web 2.0 technologies (O'Reilly, 2007), such as web mapping services (e.g., Google Maps, MapQuest) and ***map mashups*** that combine geographic information feeds and web mapping services using their application programming interfaces (APIs) (e.g., Roth and Ross, 2009). This even includes tools that help users create interactive map mashups with these web mapping services, such as the NeoGeography service provided by GeoCommons (Harrower et al., 2008); are these interactive maps? What about applications that coordinate interaction across multiple information views, the map being only one of them (Roberts, 2008)? Does simply labeling an application an 'interactive map' or 'cartographic interface' change the cognitive schema (see **Section 2.3**) evoked during its use, as with the positive influence of using the term 'map' instead 'diagram' (Kealy and Webb, 1995, MacEachren, 1995). Further understanding also is needed about the influence of analog cartographic interactions (e.g., interactions that can be completed with hand drawn or paper maps) on the way in which users understand and apply cartographic interactions (e.g., Robinson, 2008b). How does the advent of digital paper and augmented paper maps alter our conceptualization of cartographic interaction (McGee et al., 2000)? To what degree should designers explore new classes of cartographic interactions that have no physical parallel (Cartwright, 1999)? Finally, are users aware of the distinction between cartographic interaction and cartographic interfaces made above, and, if made aware, do their interaction strategies change? All of these questions, and many others, concerning the *what?* of cartographic interaction require additional scientific research.

2.3 Why Provide Cartographic Interaction?

Once cartographic interaction is defined, it then is important to address why it should be provided. In **Chapter 1**, a strong argument was presented that academic cartographers should give equal treatment in their research to both cartographic representation and cartographic interaction, establishing a science of cartographic interaction in the process. However, not every map needs to be interactive. Thus, it is necessary to examine the value that is added by providing cartographic interaction, which then aids in determining when cartographic interaction should be provided (**Section 2.3**).

A map can be considered an externalization of the mapmaker's knowledge about the mapped phenomenon (MacEachren, 2005, Tomaszewski and MacEachren, 2006). Beginning with the context of analog mapping, the map is a closed artifact of the mapmaker's interpretation that can be used as a vehicle to send an intended message to the map user; the map is a one-shot chance for relaying an intended point about the represented phenomenon. This approach to Cartography is described in **Section 1.1** as the communication model (see **Figure 1.4b**). As noted, communication of a message from mapmaker to map user is rarely perfect; the mapmaker can imbue the cartographic representation with multiple layers of meaning—multiple abstractions or interpretations of their internal knowledge about the mapped phenomenon—and the map user will apply their unique set of experiences, perspectives, and skills to extract different meanings from the cartographic representation (MacEachren, 1995). Whether successful or not, the goal of this communication process is the transfer of a known set of geographic insights from mapmaker to map user.

Maps need not be closed artifacts of a mapmaker's knowledge. The framework of ***distributed cognition*** supposes that externalizations, with maps being a visual form of such, can act as an extension of cognition

(Hollan et al., 2000). Visual externalizations allow individuals to offload cognitive processing onto information graphics, using perceptual (seeing-that), cognitive (reasoning-why), and motor (interacting-with) processes to reintegrate the external knowledge into existing internal schema (MacEachren and Ganter, 1990); additional details on this process are provided in **Section 2.5**. Here, the map is not just an external representation of internalized knowledge, but a complement to it in the overall act of knowledge construction (Scaife and Rogers, 1996). In this respect, the externalization serves as a memory aid for declarative, procedural, and configurational knowledge (Chen et al., 2008), as well as a ***visual isomorph*** (i.e., a representation of equivalent information in a different visual structure) for examining the problem from a different, perhaps more informative perspective (Hanrahan, 2009). In other words, maps literally allow people to *think visually* to the end of generating new, previously unknown insight (Arnheim, 1969).

DiBiase (1990) compares visual thinking and visual communication, as related to the mission of science, in his often reproduced ***swoopy diagram***[14] (**Figure 2.2**). Drawing from research in exploratory data analysis (Tukey, 1980), four stages of science are identified: (1) ***exploration*** (examining the data from multiple perspectives to identify research questions and to generate research hypotheses), (2) ***confirmation*** (formally testing hypotheses to answer research questions, the goal of most statistics prior to Tukey's work), (3) ***synthesis*** (summarizing and integrating insights generated from multiple iterations of the exploration and confirmation stages to triangulate a final solution to the research questions; this stage was an addition of DiBiase's to EDA), and (4) ***presentation*** (communicating the uncovered solution to a wider audience). One possible interpretation of the 'swoop' in the diagram is the number of unique

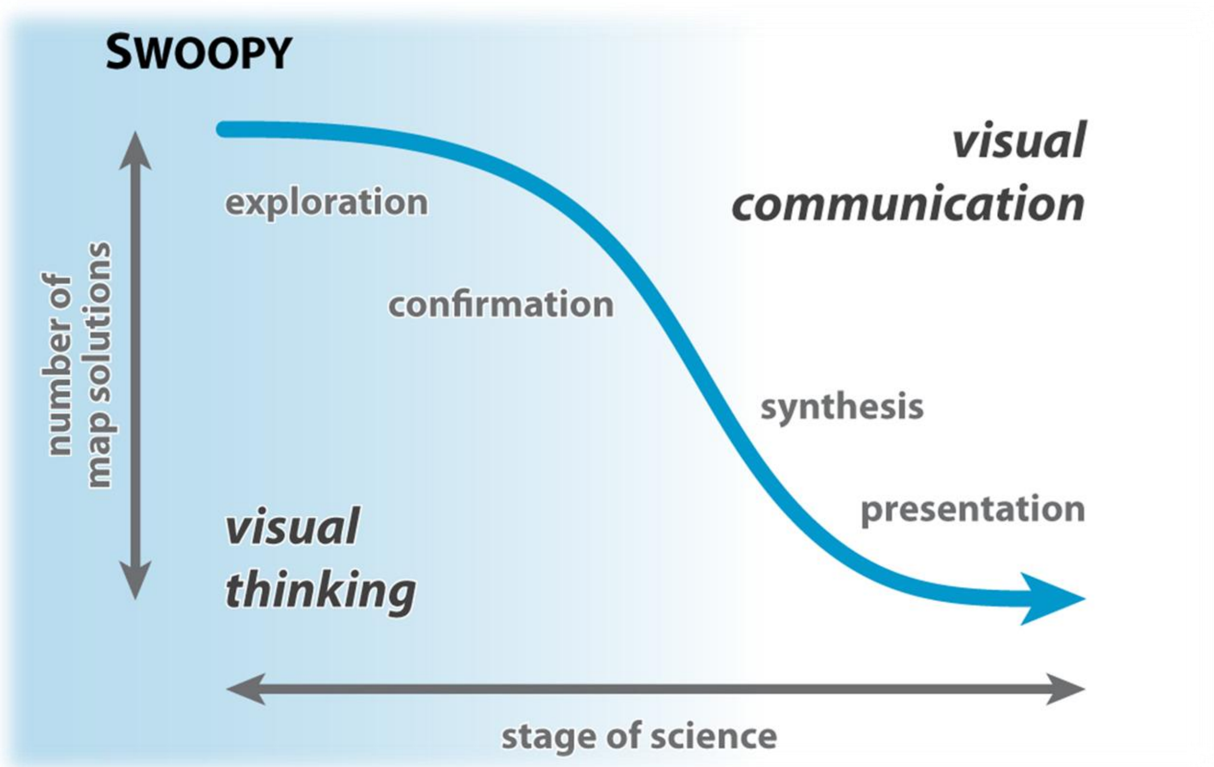


Figure 2.2: The Swoopy Diagram. In the early, exploratory stage of science, scientists require numerous different map solutions to promote visual thinking and prompt new research hypotheses. It is not until the later, presentation stage that a single, optimal solution is needed for visual communication. Image redrawn, reinterpreted, and annotated from DiBiase (1990: 3).

[14] The name 'swoopy' was coined by John Krygier and was not used in print until the web edition of the DiBiase (1990) article was released.

cartographic representations needed at each stage, ranging from perhaps an infinite number at the exploration stage (i.e., visual thinking) to a single, optimal representation during presentation (i.e., visual communication).

MacEachren (1994) used the swoopy diagram, and the notion of visual thinking, as the input for one of the more important cartographic frameworks currently in place: Cartography^3 (Figure 2.3). ***Cartography^3*** summarizes all possible map uses according to three axes: (1) revealing unknown insights versus presenting known ones,[15] (2) private map use versus public map use,[16] and (3) high versus low human-map interaction. Through the center of the cube runs the swoopy schematic, illustrating the change from visual thinking (i.e., infinite possible views) to visual communication (i.e., one optimal view). The bottom, forward-most corner (revealing unknowns, private map use, and high human-map interaction) of Cartography^3 has come to represent the cartographic subfield of ***Geovisualization*** (Figure 1.4e).

Importantly, the Cartography^3 schematic prescribes the way in which visual thinking is best supported: through high levels of human-map interaction. Map-enabled visual thinking begins with the cartographic representation (i.e., what is seen), and static maps have and likely always will be an important component of visual thinking. However, in order to generate the multitude of cartographic representation variants needed to support visual thinking, digital cartographic interaction is essential (MacEachren and Ganter, 1990). As MacEachren and Monmonier (1992: 197) write, the digital environment "allows visual thinking/map interaction to proceed in real time with cartographic displays presented as quickly as an analyst can think of the need for them." Such exploration of numerous, user-defined, and ephemeral cartographic representations reveals anomalies, patterns, and trends in the dataset that were previously unknown, leading to the generation of ***geographic insights***, or any new understanding about the true nature of the studied geographic phenomenon or process. Thus, the basic premise of visual thinking is that "insight is formed through interaction" (Roberts, 2008: 26). It is the promise of visual thinking in a digital age that requires the establishment a science of cartographic interaction.

Yet many questions remain concerning why cartographic interaction should be provided to support the generation of new insights during the scientific stage of exploration. A pressing issue requiring additional research is the poor formalization of the concept of insight, which has resulted in few empirically derived interaction strategies or interface design guidelines for facilitating the generation of new insight. Several useful structures for understanding insight come from the field of ***Visual Analytics***, defined as the use of visual interfaces to computation methods in support of visual-enabled human reasoning (i.e., visual thinking) and decision making (Thomas et al., 2005). Prompted by an empirical study by Saraiya et al. (2004), North (2006) describes insight as varying across five measurable characteristics: (1) complex (insights involve investigating a voluminous dataset in subtle and integrative ways), (2) deep (insights require time and evidence accumulation to be robust), (3) qualitative (insights often are inexact and uncertain, and also may have multiple levels of resolution), (4) unexpected (insights are considered more valuable when they reveal the unexpected), and (5) relevant (insights are couched within the domain of analysis and may not generalize to other domains). In a reaction to the North essay, Chang and colleagues (2009) offer a distinction of insight at a higher conceptual level. They distinguish between insight as small bits of knowledge that build upon existing knowledge (e.g., the insights transmitted through visual communication from mapmaker to map user) and insight as spontaneous new cognitive structures, or ***schema***, which explain patterns in new and existing bits of knowledge; the authors describe the difference as ***knowledge-based insight*** and ***spontaneous insight*** respectively. Chang et al. argue that the successful application of visual analytics must support generation of both types of insights.

---

[15] This axis was updated to "knowledge construction" versus "information sharing" in MacEachren et al. (2004).

[16] The private/public distinction in Cartography^3 perhaps is dissolved in the context of distributed cognition, where externalized map artifacts can be used for very public visual thinking (i.e., geocollaboration) to the end of generating collective knowledge and facilitating group reasoning (MacEachren 2005). The terminology was updated to "specialist user" versus "public user" in MacEachren et al. (2004).

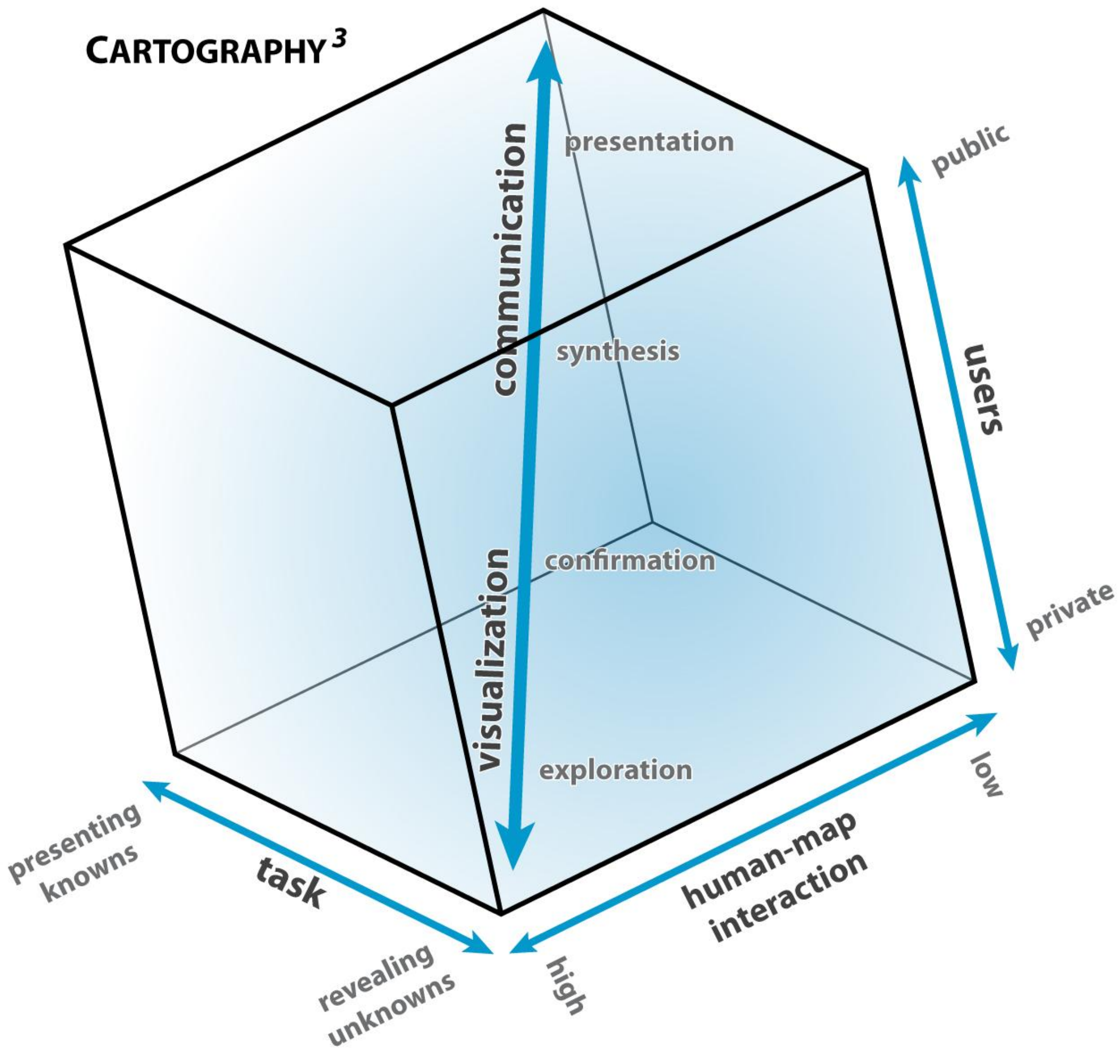


Figure 2.3: Cartography[3]. Visual thinking is best supported through high levels of human-map interaction. Image redrawn from MacEachren (1994: 6).

It is quite likely that cartographic interaction, and the visual thinking it supports, has value beyond the exploratory stage of science. As Dix and Ellis (1998: 3) suggest, "virtually any existing static representation can be made more powerful by adding interactivity." Cartographic interaction is a method for overcoming the tradeoffs inherent to any given form of cartographic representation, and the design decisions embedded therein. Returning to the swoopy diagram (**Figure 2.2**), multiple scholars have suggested the utility of cartographic interaction for confirming both empirical and model-based analyses (DiBiase, 1990, Bhowmick et al., 2008), for synthesizing analytical results into coherent arguments (Robinson, 2008a), and for presenting results to academic and public communities (MacEachren et al., 2008, Roth and Harrower, 2008). The latter category is related to the extent of ***Interactive Cartography*** outlined in **Figure 1.4d** and includes interactive maps focused on storytelling, such as digital atlases, interactive news maps, web-based campus maps, and a large proportion of map mashups. In these situations, does the purpose of cartographic interaction remain visual thinking and insight generation, or does cartographic interaction provide something entirely different? Is cartographic interaction even appropriate for these other stages of the scientific workflow? Additional questions arise when considering cartographic interaction for purposes other than support of the mission of science, as many cartographic interaction techniques developed to enable science now are applied commonly to support practical goals in a variety of domains.[17] For example, applications of Geovisual Analytics (**Figure 1.4f**) support somewhat different goals than those of Exploratory Geovisualization, particularly when used for science. Geovisual Analytics is concerned with the process of ***sensemaking***, or the collection, exploration, evaluation, and presentation of evidence that supports or refutes a set of competing hypotheses about the nature of and solution to a problem, often to the end of making an informed decision about the proper course of action (Pirolli and Card, 2005). Does cartographic interaction serve a different purpose when implemented in such sensemaking tools or other spatial decision support systems? Finally, does cartographic interaction support efforts in Critical Cartography (**Figure 1.4c**), such as public participatory GIS, and if so, in what ways does its purpose change (Schuurman, 2006)?

A final issue regarding the *why?* of cartographic interaction deals with a fundamental cartographic concern: the uncertainties that are inherent to all geographic information and therefore the cartographic representations of this information (Couclelis, 2003). The process of externalizing geographic knowledge into a single cartographic representation for the purpose of communication necessarily requires the mapmaker to abstract their mental model of reality, which itself is already an abstraction of reality. In completing this process, the mapmaker omits information from the page that may be needed for a comprehensive understanding of the geographic phenomenon or process for the sake of clarity. This is the ***cartographic problematic***: when abstracting reality (and one's knowledge of reality) to make a cartographic representation understandable and useful, uncertainty is introduced into the cartographic representation (Pickles, 2004, Roth, 2009b). A comprehensive discussion on the ways in which uncertainty enters into cartographic representations is provided by MacEachren et al. (2005b). The important point is that one potential way to overcome the cartographic problematic—and perhaps even to operationalize the numerous uncertainties inherent to cartographic representations for informed decision making—is through cartographic interaction (Paradis and Beard, 1994, Howard and MacEachren, 1996). Thus, cartographic interaction can be employed to provide the map user with a more complete understanding of the mapped geographic phenomenon, rather than to reveal unknown insights about the geographic phenomenon through exploration; it is unclear if the difference in these goals is significant enough to require different cartographic interface designs and cartographic interaction strategies.

2.4 When Should Cartographic Interaction Be Provided?

The **Section 2.3** discussion indicates that cartographic interaction adds a great degree of value for Exploratory Geovisualization, and perhaps beyond. Going a step further, it is necessary to examine if cartographic interaction always adds this value to a static cartographic representation, or if its utility is conditional in some way. In other words, is the addition of cartographic interaction always a wholesale good? When should cartographic interaction be provided, and, when cartographic interaction should be provided, *how much* control should the user be given?

The Cartography^3 schematic (**Figure 2.3**) represents cartographic interaction as a continuum from low to high. The more numerous and substantive the possible manipulations to the cartographic representation, the better, at least in the context of Exploratory Geovisualization (MacEachren, 1994). This perspective on cartographic interaction has led to the development of many coordinated multi-view ***toolkits*** that allow users to access a variety of cartographic representations and cartographic interactions, and to combine them in any way they see fit (e.g., Takatsuka and Gahegan, 2002, Weaver, 2004, Chen, 2006, Hardisty and Robinson, 2011). An extensible, component-based approach to cartographic interface development is valuable because it allows for the integration of novel interaction techniques as they are conceived. This

[17] This development is of course encouraging. However, the pervasiveness of this transition requires examination of cartographic interaction outside of the swoopy (**Figure 2.2**) and Cartography^3 (**Figure 2.3**) frameworks.

approach—and the ever-expanding toolkits that result—implicitly subscribes to the notion that more functionality is better, and that the system should be designed to include more functionality when available. Following this logic, the answer to the question of *when?* may be *always!*

While it is likely that increasing the level of interactivity improves the utility of a broadly-purposed application, there is growing evidence that interaction may act to inhibit the completion of some tasks. This is true not only of the number of interactions implemented in a system, but also of the degrees of freedom available for performing each interaction (i.e., how ***free*** the interaction is) (Harrower and Sheesley, 2005); the term ***interface complexity*** is used to describe the combination of the number of cartographic interactions implemented in a cartographic interface and the freedom in performing each provided interaction. Much of the criticism of complex interfaces comes from research on interface workload and worker productivity (Card et al., 1980, Hart and Staveland, 1988). Free interaction allows users to perform alternative sequences of cartographic interactions, or competing interaction strategies (Edsall, 2003), to complete a task. Supporting a large number of interaction strategy variants may produce a type of interface error described by Zapf et al. (1992) as ***inefficiency***,[18] a situation in which the user is presented with flexibility in the way in which a task can be completed, but chooses a suboptimal approach. Much of the early work on this topic was motivated by the ***productivity paradox***, a critique on the immense investment in computing technology in the workplace during the early stages of the Digital Revolution, because, at the time, the investment had led to only marginal increases in workers' productivity (Landauer, 1995, Haklay and Nivala, 2010); as Robert Solow (1987: 36) famously wrote, "You can see the computer age everywhere but in the productivity statistics." As a result, researchers and developers began to investigate the ways in which free interaction could be constrained in order to optimize interaction workflows (i.e., permit only a small set of possible interaction strategies) and increase productivity. There are at least four empirical studies that indicate a need for cartographic interaction ***constraint***, or a reduction to the number of cartographic interactions and/or the degree of freedom available for performing each cartographic interaction; each is summarized in the following.

Davies (1998) describes a participant observation study first reported by Davies and Medyckyj-Scott (1996) in which GIS analysts working in a range of application domains were videotaped while completing their daily work. In the updated work, a new coding scheme was developed for qualitative data analysis using Whitefield et al.'s (1993) distinction between work and enabling actions; ***work (inter)actions*** include those interactions that accomplish the desired goal, while ***enabling (inter)actions*** include those interactions required to prepare for, or clean up from, work actions. From a productivity perspective, it can be assumed that enabling interactions should be eliminated where possible and that interaction strategies consisting primarily of work interactions should be promoted. The coding scheme used in the study includes four codes: (1) work interactions, (2) general enabling interactions (open file, save, export, etc.), (3) enabling interactions (panning, zooming, changing the mode of the mouse hand, etc.) and (4) goal acquisition interactions (i.e., reading documents describing what needs to be accomplished). No participant spent more than 30% of their time on actual work interactions with the GIS, with most participants spending approximately 10-20% of their time performing work interactions. The remainder of the video time was allocated evenly for the performance of enabling and general enabling interactions. No participant spent more than 5% of their time on goal acquisition, indicating the participants' familiarity with their own work tasks (i.e., user expertise—see **Section 2.5** for details). Regarding the potential need to constrain free interaction, there was a large amount of variation in the participants' interaction strategies, even for simple interactions such as a point query.

[18] This term is somewhat confusing in the context of usability engineering, as it differs from Nielsen's (1993) concept of efficiency, a component of usability.

Keehner et al. (2008) describe a set of three controlled experiments requiring participants to draw the shape of a two-dimensional cross section produced by splitting a three-dimensional shape with a plane.[19] One of the experiments featured a yolked design between the static and interactive test conditions to control for the representations shown to participants between the testing groups; one group of participants were presented with an interactive representation of the three-dimensional object and intersecting plane that could be rotated to change the viewing perspective, while a second group of participants were shown a non-interactive video recording of the interactions of the first group (with a matched pairs design, so that no participant in the second group saw the same animation). Completion of the task was facilitated by navigating to the optimal visual isomorph, which was the view showing the intersecting plane at nadir for the experimental task. Advantages of interactivity that were found in an initial, non-yolked experiment were no longer found in the yolked experiment design, suggesting that interaction is only helpful when it leads to presentation of task-critical information (i.e., the optimal visual isomorph). For visual tasks with known solutions, provision of interaction may lead users to create unrelated or misleading views of the information. This conclusion was supported further by a final experiment in which participants given a non-interactive representation showing only the most task-relevant information outperformed participants given an interactive representation. The combined interpretation of these results led the authors to make their titular declaration that "What matters is what you see, not whether you interact" (Keehner et al., 2008: 1099). It is important to note that, as with the study completed by Davies (1998), the authors observed a large amount of variation in interaction strategies for the interactive condition in all experiments; in the final study, the subset of participants in the interactive condition that quickly identified the proper interaction strategy preformed as well as participants given the ideal, non-interactive representation.

Jones et al. (2009) describe an informal 'workshop' study in which a small team of targeted end users of a suburban profiling application were videotaped during an initial session with the system. Unlike the Davies (1998) and Keehner et al. (2008) studies, design of the suburban profiling application was informed by the tenets of Exploratory Geovisualization, with the goal of the application identified as insight generation and knowledge construction about unknown patterns and trends in social activity in the London area suburbs. The authors introduce their work by advocating for cartographic interface constraint within Geovisualization, arguing that Philbruck's (1953) ***simplicity principle*** (i.e., design parsimony or an economy of design) should apply to the design of cartographic interactions as well as cartographic representations; they describe this as a 'less-is-more approach' to cartographic interface design, after Buxton (2001). Following this perspective, cartographic interaction was limited to toggling among a series of preprocessed, static maps known by the developers to contain tasks-relevant information. The authors were particularly averse to including unrestricted ***map browsing*** (i.e., panning and zooming) functionality in their application and instead constrained navigation to explicit specification of individual suburban centers (i.e., panning from one extent to the other via menu selection). Relating this constraint to the above productivity discussion, map browsing may be considered an enabling interaction made necessary when the screen real-estate allocated to the map is prohibitively small to match the extent of the mapped phenomena (Haklay and Zafiri, 2008). The less-is-more approach was considered successful, as the video recording revealed that participants were 'on task' (i.e., discussing patterns in the maps) for 71% of the time. It is important to caution about the broader generalizability of these results given the ***discount interface evaluation*** approach taken, which recruits a small set of study participants to the end of quickly and cheaply improving a single product (Nielsen, 1993). Jones et al. did not use the video recording to break down the amount of time on task into work versus enabling interactions, as in the Davies study, making it inappropriate to compare the time percentages reported in the two studies.

[19] Keehner et al. (2008) also review extant studies in the cognitive science literature on performance using static versus interactive displays of spatial information, with these studies yielding contradictory results about the value added by interaction. As with their own study, the reviewed studies are not explicitly cartographic, but use spatial representations similar to maps.

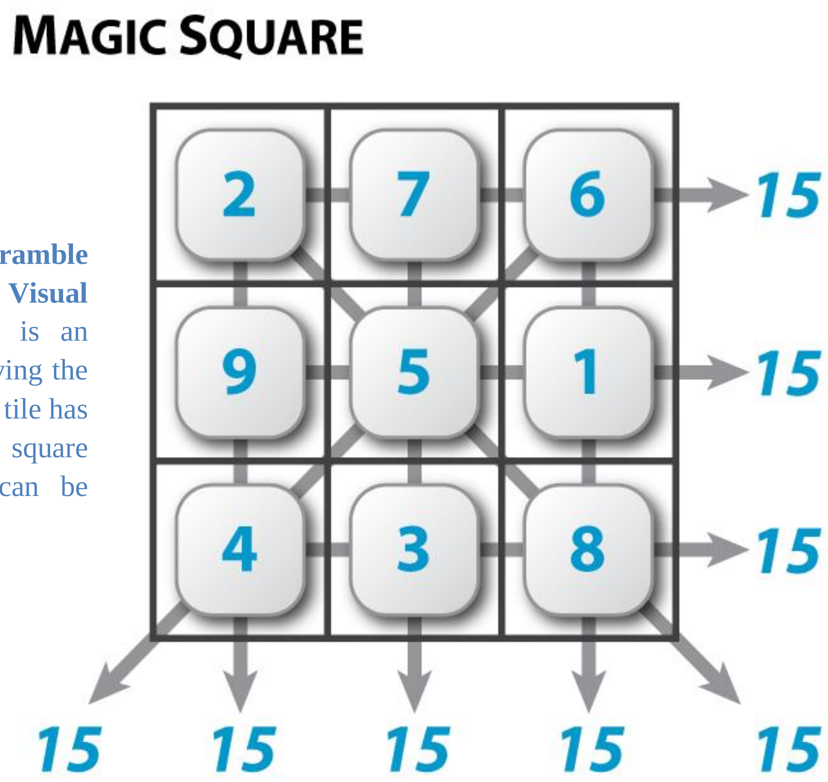


Figure 2.4: The Number Scramble Game & the Magic Square Visual Isomorph. The magic square is an optimal visual isomorph for solving the Number Scramble game. Once a tile has been selected, the magic square prescribes which other tiles can be taken to produce a sum of 15.

Most recently, Dou et al. (2010) examined the importance of interaction constraint in a controlled problem solving experiment. Problem solving was evaluated in the context of a simple card game, called the Number Scramble, in which two players alternate in drawing from a set of nine cards marked ace (i.e., one) through nine, with the goal of obtaining three cards that add up to fifteen. The Number Scramble problem is simplified greatly once identifying the optimal visual isomorph, a three-by-three spatial arrangement of the numbers called the ***magic square*** (**Figure 2.4**). The experiment was conducted in four steps: (1) a pre-test during which participants played six times against a computer programmed to make optimal card selections, (2) a strategizing session during which participants were allowed to interact with a set of materials, (3) an externalizing session during which participants could create a representation they felt would help them play the game, and (4) a post-test during which participants played the computer an additional six times. Importantly, participants were grouped into one of five conditions during the strategizing session according to the materials they were presented, which impacted the freedom in externalizing the problem and interacting with competing solutions: (1) pen and paper, (2) multiple sets of cards, (3) a single set of cards, (4) a single set of cards and a boundary the size of a three-by-three grid, and (5) no interaction (i.e., participants had to consider the problem in their head); these conditions varied from free interaction, through increasing levels of constrained interaction, to no interaction. The authors report that interaction constraint had a significant positive impact on the likelihood of identifying the optimal visual isomorph and on performance in the Number Scramble game; however, constraint on interaction impeded response time (i.e., it took longer for participants in the most constrained groupings to respond), a finding that surprised the authors. These results lead the authors to conclude that "complete freedom of interaction may make problem-solving more difficult" (Dou et al., 2010: 7).

This set of studies indicates that provision of increased levels of cartographic interaction may not always add value to the cartographic representation. It even may be appropriate to state that cartographic interaction should be constrained whenever possible to prevent users from employing suboptimal or unhelpful interaction strategies. But, it is necessary to consider if these results are relevant to the exploration stage of science (**Figure 2.2**), and thus to the design of geovisualization tools, for which interaction is considered "paramount" in order to support visual thinking (MacEachren and Ganter, 1990: 74). Selection of the requisite set of cartographic interactions must be informed directly by knowledge about the users of the interface and their objectives (Robinson et al., 2005); the more clearly defined the tasks, the more constrained the provided cartographic interaction should be, as indicated by the above summary of research. Geovisualization tools, however, are designed to support tasks that are loosely-defined, open-ended, and highly iterative, with the size of the solution space for these tasks approaching the infinite as the complexity of the problem grows (Gahegan, 1999). Further, it is not possible to identify one, optimal interaction strategy to generate one, optimal visual isomorph, as the goal of geovisualization is to reveal insights that are unknown (i.e., to complete analytical work that has never before been done) and to generate a large number of competing hypotheses (i.e., to perform a number of variations of the same task as creatively as possible, rather than to complete the task once as quickly and accurately as possible). The very delineation between work and enabling interactions blurs when considering exploration, and it may be that interactions traditionally considered as enabling are essential for visual thinking and thus are important for supporting exploration (Norman, 1984). Thus, to respond to Keehner et al. (2008), while it definitely matters what you see, you may not know what you need to see until you begin to interact. Additional research is needed to define the notion of work and productivity in the context of open exploration and to determine the degree to which cartographic interaction can be constrained before stifling visual thinking.

2.5 Who Should Be Provided Cartographic Interaction?

As indicated in **Figure 2.1**, cartographic interaction should be conceptualized as a two-way conversation between a human and a map made possible by a computing device (Peterson, 1998, Cartwright, 1999, Beaudouin-Lafon, 2004, Yi et al., 2007). Such a perspective makes the user fundamental to completion of a cartographic interaction. It therefore is equally important to consider the user performing the cartographic interactions as it is to consider the cartographic interface providing the cartographic interactions. In other words, to what degree does the quality of the cartographic interaction depend upon the individual to whom it is provided?

Individual users vary greatly in the cartographic interaction strategies they apply to complete a given task (Marsh and Dykes, 2008). The discussion presented in **Section 2.4** attributes this variation primarily to the cartographic interface component of the interaction conversation. Under this map-centered or, in the context of Interactive Cartography, ***interface-centered perspective*** (**Figure 2.1: right**) of cartographic interaction, the primary way to improve use of an interactive map or map-based system is to constrain the available interactions, thus preventing suboptimal interaction strategies. This design philosophy became known as ***Taylorism*** after its earliest proponent Frederick Winslow Taylor (Kelly, 1982), and, when applied to the design of digital interfaces, forces all users to perform the same, 'best' interaction strategy in order to achieve an objective (Albrecht and Davies, 2010). Taylorism remains central to research and development on workflow optimization (Aalst, 1998, Stohr and Zhao, 2001) and has been applied in the context of scientific workflows, or the "analytical pipeline" from data to knowledge (Ludäscher et al., 2006); Roth et al. (2009) provides an overview on how research on scientific workflows relates to cartographic interaction and the usability and utility of cartographic interfaces.

Even when interaction is constrained considerably, as prescribed by Taylorism, a large amount of difference still is observed in cartographic interaction strategies across users (as indicated in the above examples from Davies, 1998, and Keehner et al., 2008). Much of this variation in performance may be explained by individual user differences (Slocum et al., 2001). Understanding the characteristics of the targeted set of end users falls in line with a ***user-centered perspective*** of cartographic interaction (**Figure 2.1: right**), which attempts to improve cartographic interaction by designing for anticipated user differences. Accounting for the variation across users during design and development aligns with the concepts of designing for interaction ***flexibility***, or the ability to achieve the same user objective using multiple interaction strategies (Cooper and Reimann, 2003, Roth and Harrower, 2008), as well as supporting ***universal usability***, or the design of interfaces that work for a diverse range of users (Cartwright et al., 2001, Plaisant, 2004).

Returning to the discussion of the productivity paradox introduced in **Section 2.4**, Landauer (1995) attributes much of the loss in productivity during the early stages of the Digital Revolution to the widespread subscription to Taylorism, and the associated lack of engagement with the characteristics and needs of end users when planning design. The very notion of Taylorism may be described as an attempt to standardize users by standardizing the way in which they can complete their work, with interaction constraint and interaction flexibility locked in opposition with each other. Landauer suggests a user-centered approach as a potential solution to the productivity paradox, with user-centered interfaces yielding positive gains in productivity, even if no two users discover and apply the same interaction strategy to complete the same task. It then follows that interaction constraint and interaction flexibility may not be opposing forces with regard to productivity, but rather need to be considered simultaneously in order to arrive at a useful and usable cartographic interface. Therefore, the degree to which the provided cartographic interaction can be constrained is a function of how well the user task can be defined and how homogenous the user group is expected to be; understanding of both conditions requires early and active input from targeted end users through a user-centered design process. To this end, user characteristics, and their influence on the presented cartographic interactions, are summarized in the remainder of the section, and include differences across ability, expertise, and motivation, among others.

The primary user characteristic of concern under the communication model (**Figure 1.4b**) of Cartography is ***ability***, or the mental and physical limitations of the user. Influenced by the Quantitative Revolution in Geography, and the broader positivist model of science, researchers subscribing to the communication paradigm used knowledge of the perceptual and cognitive abilities of humans to establish metrics for a benchmark or ***average user***, which then could be used to prescribe optimal cartographic representations (McCleary, 1975); Flannery's (1971) famous study on the systematic underestimation of circular proportional symbols, and the associated power function he offered for perceptual scaling of proportional circles, is one example in many. Returning the discussion to cartographic interaction, it can be argued that the possibility of cartographic interaction reduces the necessity of studying map user perception and cognition, as the cartographic representation is no longer a one-shot chance at delivering an intended message. It allows users to (inter)act like themselves, rather than to conform to the qualities of the average user. There is a growing body of research and development falling under the heading of ***Adaptive Cartography*** that is concerned with allowing users to customize the mapping system (i.e., the cartographic representations and interactions) according to their abilities and preferences, in addition to allowing the computing device to customize the system according to changes in the mapping context (Reichenbacher, 2003).

It is likely that the introduction of cartographic interaction instead poses new challenges in designing for human ability (Slocum et al., 2001), perhaps with a greater emphasis on cognition than in the past given the focus on visual thinking (MacEachren et al., 1992). The emergence of Visual Analytics, and it's emphasis on the support of human reasoning, is one indication of the growing importance of designing for human cognition (Thomas et al., 2005). Following user-centered design, the emphasis of perceptual and cognitive cartographic research is much less on prescribing design rules for an average map user and more about producing customized solutions across the variation in users; research on mapping for the visually impaired (e.g., Lobben, 2005) and color-vision deficient (e.g., Olson and Brewer, 1997) are two examples of such a change in focus related to cartographic representation. In addition to perception and cognition, cartographic interaction also requires consideration of physical abilities, such as motor skills, and the combination of physical and perceptual/cognitive abilities, such as hand eye coordination

(Beaudouin-Lafon, 2004). ***Fitt's law*** (1954), a predictive model of the time it takes the average user to point to a screen object, provides initial insight about how the design of interactive maps (e.g., the layout of interface widgets, the size of interactive map symbols) may be influenced by knowledge about motor skills. Questions concerning human motor skills expand when considering digital cartographic interactions not provided through personal computers, such as mobile devices and immersive/augmented technologies.

MacEachren and Ganter (1990) provide an overarching, guiding framework for investigating the impact of user ability on cartographic representation and cartographic interaction, integrating perception, cognition, and motor skills. The authors propose a ***pattern-matching model*** of visual thinking (**Figure 2.5**), a model later extended by MacEachren (1995) under the heading of feature-identification. The model includes two main stages: a blended perceptual-cognitive stage of ***seeing-that***, or recognizing previously known patterns and noticing unexpected ones, and a primarily cognitive stage of ***reasoning-why***, or evaluating the viewed patterns and integrating them into existing knowledge schema. Importantly, seeing-that and reasoning-why are mediated by a stage of action, or ***interacting-with***, which is primarily conducted in one's head when given a single, static cartographic representation. This mental action can be offloaded onto the cartographic representation through the provision of cartographic interaction (Scaife and Rogers, 1996), making visual thinking a highly iterative process composed of seeing the cartographic representation (perception), interacting with the cartographic representation to change it (motor skills), and thinking about the newly created cartographic representation (cognition). These three abilities essential to visual thinking are applied iteratively to generate new insight about the mapped phenomenon, and variation across users in each of these abilities ultimately may produce different sets of insights. Interactive maps and map-based systems designed based on principles of visual perception from the field

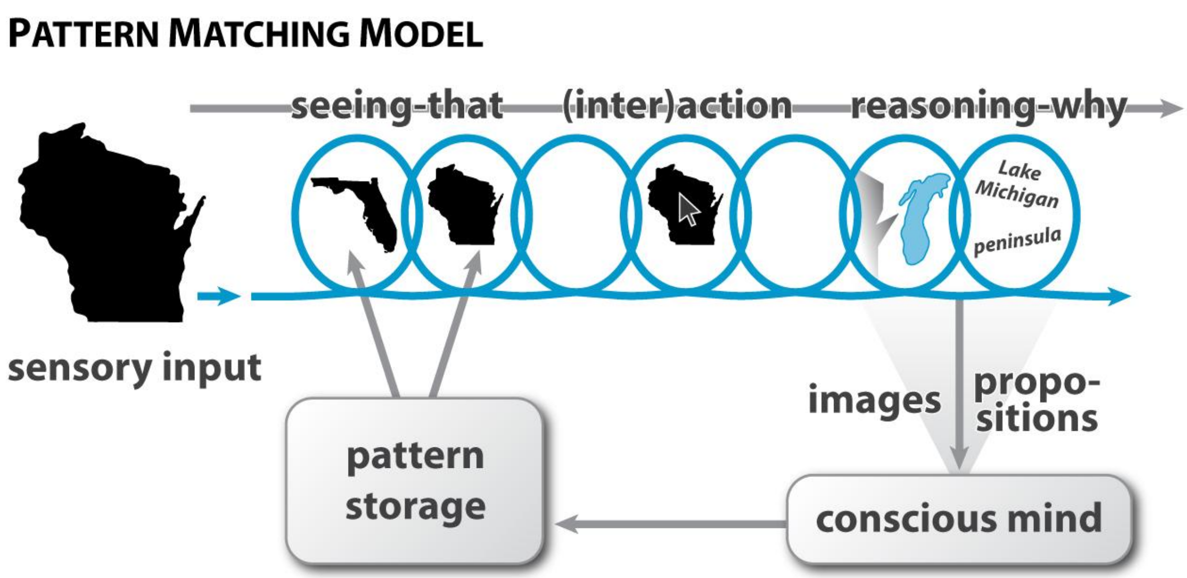


Figure 2.5: A Pattern-Matching Model for Visual Thinking. The pattern matching model considers visualization as a process in which sensory input iteratively is compared against and integrated with existing knowledge schema. Visual thinking is best supported through high levels of human-map interaction. The model identifies three user abilities important to visual thinking: perception (sensory input and seeing-that), motor skills (interacting-with), and cognition (reasoning-why). Image modified from MacEachren and Ganter (1990: 70).

of Psychology, qualitative formalisms of geographic concepts from the study of Spatial Cognition, and limitations of human motor skills from the field of Ergonomics have been termed ***sapient interfaces*** (Klippel and Hardisty, 2008). Yet, research on the impact of variation in perceptual and cognitive abilities on cartographic interaction remains in its infancy, with few studies including pre-tests to measure individual abilities and therefore stratifying results across individual abilities.

Spatial ability is one aspect of user ability that has received attention in the GIScience literature. ***Spatial ability*** is defined as the practical skills needed to think geographically (Golledge, 1992). Spatial ability, while considered primarily a characteristic of cognition, also is connected to physical (e.g., equilibrium and balance) and perceptual abilities (e.g., depth perception). It currently is unclear how differences in spatial ability impact cartographic interaction strategies, and therefore the design of cartographic interfaces. On one hand, spatially able users are more likely to understand and make use of interface designs based upon metaphors of real-world spatial interactions (Davies et al., 2010). On the other hand, spatially unable users are less likely to be able to hold complex spatial concepts in their head, and therefore may be more dependent upon externalizing their spatial thinking in a cartographic representation through cartographic interaction (Downs et al., 2006). Further, spatially unable users more easily may get lost when navigating an interactive map, requiring additional orientation cues in the cartographic representation and additional map browsing interactions to navigate the representation (Vincente and Williges, 1988, Harrower and Sheesley, 2005). Spatial ability, like many aspects of perception, cognition, and motor skills, also may be dependent upon other user characteristics, such as age, gender, and culture. For instance, Montello et al. (1999) found that, overall, men performed better on tasks requiring rotation of objects while women performed better on tasks requiring recall of exact locations of objects; such findings may impact the design and use of cartographic interfaces for map browsing and searching/filtering. Importantly, the Keehner et al. (2008) study summarized in **Section 2.4** did not find that differences in spatial ability predict differences in cartographic interaction strategies.

A second, and arguably equally influential, user trait on cartographic interaction is ***expertise***, a characteristic of the user that emphasizes the importance of learned knowledge and skills to enhance and append one's innate abilities. The characteristic of user expertise is implicit to the Cartography[3] (**Figure 2.3**) distinction between public (i.e., novice) and private (i.e., expert/specialist), with a recommendation that experts be provided with a higher level of cartographic interaction in support of free exploration, and therefore a greater amount of flexibility in preferred interaction strategies (MacEachren, 1994, MacEachren et al., 2004). Expertise is a multifaceted concept and is best conceptualized as a set of continua that vary from novice to expert, rather than a single binary with two discrete states. Definitions of expertise in the context of cartographic representation include the amount of formal education or training on making and/or using cartographic representations (Evans, 1997), the amount of experience one has making and/or using cartographic representations (Kobus et al., 2001, Hope and Hunter, 2007), and the self-reported degree of familiarity or comprehension with cartographic representation generally (Aerts et al., 2003). Further, there are various kinds of expertise that may be relevant to cartographic interaction, including general map reading, use of computing devices, and knowledge of important domain concepts or analytical methods (Roth, 2008, Roth, 2009a).

McGuinness and colleagues (1992, 1994) provide important early work on the impact of expertise on cartographic interaction. Nine experts and nine novices participated in a think aloud study in which they were asked to verbalize their thoughts as they completed a pair of open-ended exploratory tasks with a cartographic interface built in ArcInfo. Expertise was defined as the amount of education/training in the use of GIS and there was no significant difference in measured spatial ability between the expert and novice group. Drawing from work on expertise in cognitive science (Chase and Simon, 1973, Egan and Schwartz, 1979, Lesgold, 1984), the authors expected experts to demonstrate a superior pattern-matching ability (**Figure 2.5**) due to their more refined knowledge schema employed during the interactive exploration.[20] The understanding developed by advanced training facilitates the reasoning-why stage, enabling experts to identify optimal interaction strategies and to generate more informative cartographic representations during the iterative process of visual thinking. In other words, the authors proposed that the cognitive abilities needed for visual thinking are less innate (e.g., what could be measured by an IQ test) and more learned, dependent upon the user's expertise. Interestingly, experts did not exhibit significant differences in the quantitative interaction metrics collected during the experiment, such as time to complete tasks or number of maps plotted. Analysis of the verbal externalizations, however, revealed that the experts were engaging with the system at a higher level, as predicted, and leveraged interaction strategies that more fully explored the available geographic information; together, these differences led the experts to generate a deeper and more complex set of insights from the system, as found in a content analysis of the participants' summary write-up.

There have been few subsequent controlled experiments examining the impact of expertise on cartographic interaction, with most of the reported studies instead measuring expertise conducted in the context of Usability Engineering, with the goal of improving a single cartographic interface (e.g., Harrower et al., 2000, Kessler, 2000, Slocum et al., 2004). Because of the small amount of subsequent research, many of the research questions about expertise identified by McGuinness (1994: 186) remain open:

> Why is expertise important? It may seem an obvious prediction to make that experts are likely to be better than novices at a given task—they know more. But does this difference always affect performance? If not, when does it? When experts view or interact with a single display or a sequence of displays, do they extract the same information as novices do? Do they follow the same solution steps as novices or less experienced people? In terms of cognitive organization, we can ask whether the experts' mental representation of the task and their solution processes are similar to those of novices. Additional questions centre on the development and training of expertise. How is expertise acquired? Through what stages does it proceed? How does education and training impact on its development? Can support aids and tools affect how expertise is exercised?

There is a growing body of research in Cartography examining interaction strategies to bridge the expert-novice divide. One strategy is provision of a ***multi-layered interface*** (Kang et al., 2003), a solution first suggested for cartographic interfaces by Monmonier and Gluck (1994). Multi-layered interfaces exhibit a ***cascading information-to-interface ratio***, in which each increased level supplies the user with additional cartographic interactions, and thus the possibility to create additional cartographic representations, without increasing the amount of underlying information available for representation (Roth and Harrower, 2008); a common example is inclusion of a 'regular' versus 'expert' mode within an application. An alternative strategy for bridging the expert-novice divide is to provide users with process-oriented training or help materials, essentially improving the cartographic interaction by improving the user's knowledge of interactive maps or domain concepts (Roth et al., 2009). A third solution to the expert-novice divide is development of an ***intelligent visualization,*** or an expert system that leverages the cartographic and domain knowledge that otherwise may be available only as training and help materials to present context-appropriate representation and interaction solutions (Andrienko and Andrienko, 1999b, Andrienko and Andrienko, 2001). A final, related solution to the tradeoff is provision of a ***map brewer***, or a cartographic design support system that recommends a subset of appropriate cartographic representation or interaction design solutions based upon expert knowledge, allowing the user then to select their preferred choice from the subset (Brewer, 2003, Harrower and Brewer, 2003). Intelligent visualizations and map brewers are particularly useful in the context of the Democratization of Cartography (Rød et al., 2001, Wood, 2003b) and NeoGeography (Turner, 2006), as the map user is also the mapmaker and may not have the necessary expertise to make informative mashups that appropriately combine cartographic representations and cartographic interactions.

[20] It is important to note that the expert participants did not have more refined knowledge schema concerning the mapped phenomena. The users did not have domain expertise in the two case studies used in the exploratory tasks.

While user ability and expertise clearly are important to cartographic interaction, and should be considered throughout the design of a cartographic interface, high levels of ability or expertise are not always necessary for successful cartographic interaction, even with unconstrained cartographic interfaces that implement many cartographic interactions with a large amount of interaction freedom. A third user characteristic that needs to be considered is user ***motivation***, or the desire one has to use the cartographic interface either out of necessity (i.e., to complete a work task) or out of interest (e.g., curiosity, entertainment, popularity, recommendation) (Greif, 1991). Motivation differs from expertise in that users with low levels of motivation are not necessarily incapable of using a robust suite of cartographic interactions, they simply do not wish to do so (Roth and Harrower, 2008). Conversely, users with high levels of motivation, but lacking expertise, may take the time to acquire the necessary levels of expertise through training and help documents, or even formal education.

Motivation, when high, is a user characteristic that plays to the advantage of cartographic interface designers and developers, as it inspires users to overcome barriers to using a system. User motivation therefore should be cultivated whenever possible, which includes strategies for increasing motivation to begin use of a cartographic interface (e.g., offering incentives, demonstrating utility through real world examples) and increasing motivation to continue use of an application (e.g., rewarding positive interaction strategies, offering easy ways to correct mistakes) (Nielsen, 1994). Many of these tenets fall in line with increasing user satisfaction and are contingent upon the aesthetics of the graphical user interface implementing the cartographic interactions (i.e., the application's look and feel). In contrast, low levels of user motivation work against cartographic interface designers and developers, as individuals with no need or no interest in using a tool are unlikely to take the time to learn complex interfaces, even if they easily can do so because of past experience or training. Therefore, successful cartographic interaction may be contingent upon the relationship between interface complexity and user motivation, not user expertise (Harrower, 2002, Roth and Harrower, 2008); **Figure 2.7** illustrates this suggested relationship. User motivation has important implications for both the engineering of unique cartographic interfaces and the scientific investigation of cartographic interaction, as discussed in **Chapter 6**.

Finally, the prior discussion in **Section 2.5** assumes that the user is working alone, but how does the nature of cartographic interaction change when multiple users are interacting with the system? There is a growing body of work within Cartography, falling under the subfield of ***Geocollaboration***, that is focused upon the design and use of cartographic interfaces that support cooperative and collaborative activities (MacEachren, 2000). This subfield draws upon relevant research from the field of Computer Supported Cooperative Work (CSCW), adopting two basic distinctions to inform the design of collaborative tools: (1) same-time (synchronous) versus different-time (asynchronous) collaboration and (2) same-place (face-to-face) versus different-place (distributed) collaboration (Ellis et al., 1991). Each time-place combination requires unique solutions to support the particular collaboration context (see Haklay, 2010, for examples), and therefore likely requires different cartographic interaction solutions. Further, MacEachren (2005) describes three ways in which a map supports group work: (1) the use of the cartographic representation as the object of collaboration, (2) the use of the cartographic representation to support dialogue, and (3) the use of cartographic representation to support coordinated activity. Does the purpose of the cartographic interaction provided to manipulate the map change according to these different types of collaboration? If so, how do the cartographic interaction strategies and cartographic interface designs also change? Discussion of collaborative work is related to the possibility of ***role-based interaction***, or interface customization based on the user's role on the collaborative team (i.e., the tasks that he or she has been assigned to accomplish) (Wang et al., 2001, Convertino et al., 2005), which identifies the importance to compensate for variation in not only user ability, expertise, and motivation, but also user responsibilities. The research reported in the dissertation focuses upon single user cartographic interactions, but cartographic interaction in multi-user systems remains an important research topic requiring additional attention.

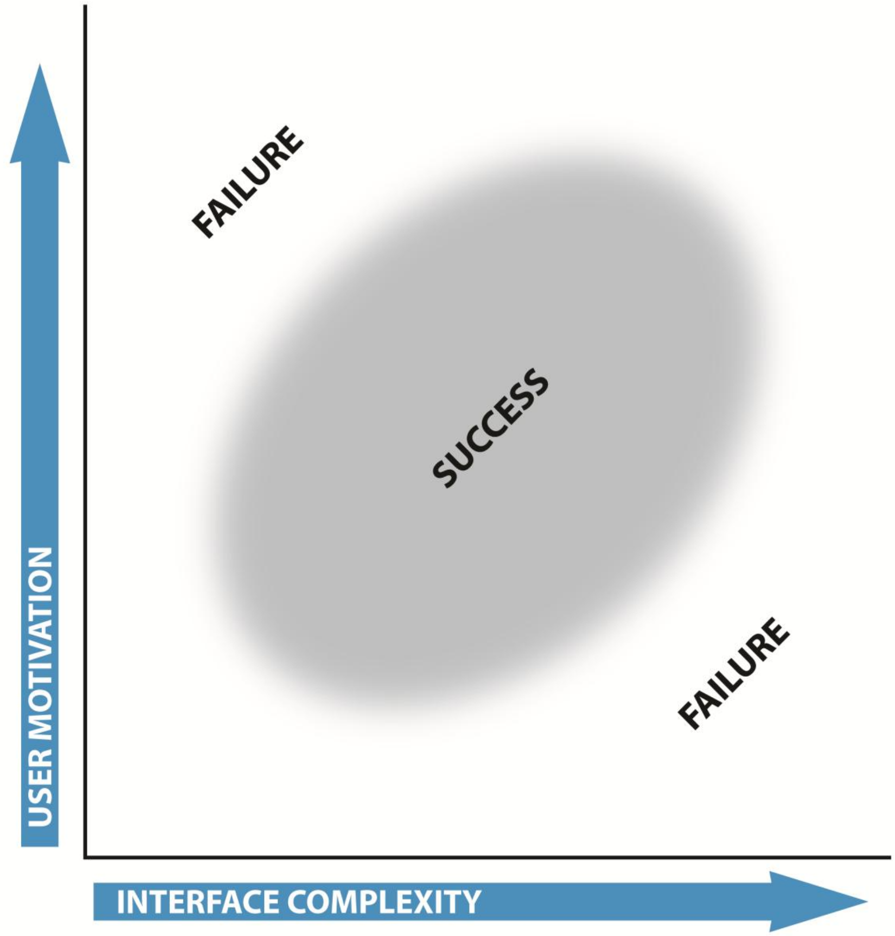


Figure 2.6: Interface Complexity versus User Motivation. The success of cartographic interaction is contingent upon the relationship between interface complexity and user motivation. Image modified from Roth and Harrower (2008: 59).

2.6 Where Should Cartographic Interaction Be Provided?

Cartography has become truly ubiquitous due to the similar ubiquity of computing technologies resulting from the Digital Revolution (Gartner et al., 2007). A digital, interactive map can be provided through any device that has some sort of user input function, some sort of display function, and a processor that can translate user inputs to the display. Therefore, a final influence on the appropriate type and amount of cartographic interaction is the platform on which the cartographic interaction is implemented. In other words, to what degree does the computing device impact cartographic interaction and how should cartographic interactions be altered based on where they are implemented?

The previous subsections accentuate that cartographic interaction is bounded by the map user performing the interaction (**Section 2.5**) and the cartographic interface providing the interaction (**Section 2.4**); emphasis on one component over the other is referred to as a user-centered perspective (**Figure 2.1: left**) versus an interface-centered perspective (**Figure 2.1: right**) of cartographic interaction respectively.

There is a third component necessary to cartographic interaction: the computing device through which the user and the map communicate. Emphasis on the vehicle through which the cartographic interaction is provided may be described as a ***technology-centered perspective*** (**Figure 2.1: middle**) and encompasses issues related to the device's input capabilities, bandwidth size/processing power, and display capabilities. Designers and developers working professionally in Interactive Cartography and Geovisualization likely spend a majority of their time engaging with the technology component of cartographic interaction, with much less time allocated to thinking through the targeted user's characteristics and needs as well as the conceptual design of the user interface. The focus on technology is appropriate from an applied perspective, as practitioners need to engage closely with the technology *de jour* to develop customized mapping solutions that provide the requisite set of cartographic interactions. A technology-centered view is less appropriate when considering the science of cartographic interaction, as it often leads to a scholastic *cul-de-sac* by which scholarly contributions exhibit an abbreviated shelf-life and offer little opportunity for extension. Technology is certain to evolve, and the ultimate objective of scientific cartographers is to establish theories, frameworks, and guidelines that are broadly applicable across technologies and that remain useful even after a set of technologies fades from use (Olson, 2004). The principles of cartographic interaction should persist, even if the cartographic interface solutions providing these interactions must vary across platforms.[21]

Yet the computing device through which the interaction is provided is not without its influence on cartographic interaction. The underlying technology influences the interaction strategies performed to achieve a user objective. For example, screen resolution and screen size have been identified as components of the display capability that influence map browsing interaction strategies, with use on coarser screens requiring additional zooming and smaller screens requiring additional panning (Haklay and Zafiri, 2008). Therefore, technology can be considered a third constraint on interaction. Major advances in technology also may act to influence, or even inspire, new research lines within Interactive Cartography and Geovisualization. One such example is the recent research prominence of mobile mapping and ***location-based services***, or those that leverage GPS technology to update the cartographic representation with information that is tailored to the user's current location (Brimicombe, 2008). Although technology is continuing to improve, mapping on mobile devices presents a situation in which cartographic interaction is provided under extreme input, processing, and display constraints. Research on the design of location-based services, and associated mobile map displays, draws upon user characteristics, such as spatial cognition (Klippel et al., 2005), and novel interaction styles (Burigat and Chittaro, 2008) alike, showing the interconnectedness of the three components of cartographic interaction illustrated in **Figure 2.1**. Thus, important technological concerns are considered here, although more briefly than the other four *W's* given the goal of a science of cartographic interaction to generate technology-independent findings. As noted above, technological concerns that influence cartographic interaction fall into three primary groups: (1) input capabilities, (2) bandwidth size and processing power, and (3) display capabilities; each is considered in the following.

Most personal computers provide two primary input devices: the keyboard (for the entry of long text strings or learned keyboard shortcuts) and the mouse (for point-and-click operations). Although keying in text is a basic low-level interaction, much of the HCI research on user input is focused on pointing devices that allow rapid selection of pre-defined widgets in a graphical-user interface (GUI) or direct manipulation of the visual representation itself. While the mouse generally outperforms alternatives in 2D environments (Mithal and Douglas, 1996), other options like the directional pad, graphics tablet, joystick, touchpad, touch point, and trackball are often provided, particularly for laptop computers (Shneiderman

[21]There currently is a lively debate over the use of proprietary Flash-/Flex-based applications and open JavaScript/html5 applications. Young scholars reviewing this dissertation a decade or more from composition are likely to be unfamiliar with this debate, an indication of the trivial nature of technology-centered problems to the development of a science of cartographic interaction. The underlying principles of cartographic interaction used to inform the design of these applications should remain consistent, and should be transferrable from one technological solution to another.

and Plaisant, 2010). Touch screens and multi-touch screens are a particularly interesting solution for pointing, as they unite the input with the display to produce a more congruent metaphor to real-world interaction (White, 2009). These seem particularly useful for handheld mobile devices, where an external pointing device is impractical, and geocollaborative work, where many people need to be interacting with the same cartographic representation at once. Finally, research also has been completed on multi-modal interfaces that allow text entry and pointing through voice commands, wearable devices, and device-less gesturing (MacEachren et al., 2005a).

Bandwidth and processing are considered as a single issue because together they determine the speed at which interaction occurs. As discussed in **Section 2.2**, cartographic interaction should affect instantaneous changes to the display to support fluid visual thinking (Dykes, 2005). Gahegan (1999: 290) refers to this as the "need for speed" and notes that delays in cartographic interaction can be caused by lags in processing the data calculations or transformations and rendering the output onscreen. Many consider this a technology issue that will be solved once bandwidth and processing capabilities are improved. However, advances in disk storage space are outpacing those in bandwidth and processing (Shneiderman and Plaisant, 2010), resulting in a possible catch-22 where the state-of-art in bandwidth/processing always will struggle to handle the largest available geospatial datasets. Thus, new strategies are needed to scale existing cartographic interactions and interfaces to the increasingly voluminous geographic datasets (Thomas et al., 2005).

The final technological concern for cartographic interaction is the display capability, a technological aspect that is of fundamental importance to digital cartographic representations. The visual display enables cartographic interaction by providing ***affordances*** (i.e., signals to the user about how to interact with the interface) and ***feedback*** (i.e., signals to the user about what happened as a result of the interaction) (Norman, 1988). Harrower et al. (1997) identified three varying display characteristics that change from screen to screen and that therefore affect cartographic representation and interaction: (1) screen resolution, (2) screen size, and (3) color depth. Characteristics that can be added to this listing include (4) luminance capability, (5) refresh rate, (6) expected viewing distance, (7) display continuity (in the case of multiple screens linked together in display walls), (8) lighting conditions, and (9) portability. All of these characteristics influence the amount and type of affordances and feedback provided to support cartographic interaction.

2.7 Conclusion: Elements of Cartographic Interaction

The topics discussed in this chapter cover the five *W's* (*what?*, *why?*, *when?*, *who?*, and *where?*) that should be addressed by a science of cartographic interaction. The *what?* and the *why?* questions establish the meaning of cartographic interaction and present a case for its scientific investigation within Cartography. The *when?*, *who?*, and *where?* questions examine the three components of cartographic interaction included in **Figure 2.1** that act to constrain interaction: (1) the map/interface, (2) the user, and (3) the computing technology. It is hoped that the previous review on these topics provides a useful snapshot of our current understanding of cartographic interaction, and in doing so establishes the scope of a science of cartographic interaction. More importantly, this review on cartographic interaction—much like Robinson's (1952) review on cartographic representation—reveals that we have many more open questions than firm answers and suggests areas of further research to ensure that science of cartographic interaction keeps pace with practice. The literature review is continued in **Chapter 3**, in which the important *how?* question of cartographic interaction is addressed. Existing conceptualizations of cartographic interaction are summarized and organized in a first attempt to identify the basic building blocks, or primitives, of cartographic interaction.

Chapter Three: Cartographic Interaction Taxonomies
The *How?* of Cartographic Interaction

Overview:

This chapter continues the background review started in **Chapter 2** by addressing the *how?* question of cartographic interaction. The purpose of this chapter is to identify the various ways in which past scholars have segmented cartographic interaction into sub-components or interaction primitives. These primitives then can be reassembled as competing interaction strategies (i.e., how users can interact) and evaluated empirically to identify optimal ways of achieving user objectives (i.e., how users should interact), to the end of designing better cartographic interfaces. The chapter begins with an introduction to the *how?* question of cartographic interaction, focusing on the need first to identify and articulate a taxonomy of cartographic interaction primitives that can be varied in controlled experiments (**Section 3.1**). To elucidate the *how?* question and cartographic interaction primitives, Norman's (1988) stage of action model is introduced and described (**Section 3.2**). The remainder of **Chapter 3** reviews extant interaction primitive taxonomies that loosely align with three of these stages (i.e., the three *O*'s of interaction): (1) taxonomies offered at the objective stage (**Section 3.3**), (2) taxonomies offered at the operator stage (**Section 3.4**), and (3) taxonomies offered at the operand stage (**Section 3.5**). Interaction primitives identified in the former two sets of extant taxonomies are included in the **Chapter 5** card sorting studies to supplement the primary information collected from the semi-structured interview study reported in **Chapter 4**. The chapter closes with concluding remarks (**Section 3.6**)

3.1 How Should Cartographic Interaction Be Performed?

The five *W's* of cartographic interaction outlined in **Chapter 2** provide the context of use for any interactive map or map-based system. After identifying these constraints, it is then time to move to the important *how?* question, as it is this question that prescribes the design and employment of cartographic interaction. As introduced in **Section 1.5.2**, perhaps the largest break-through in the science of cartographic representation was identification and articulation of the ***visual variables***—or the fundamental dimensions across which a representation can be varied to convey information—available to the cartographer when constructing a map. This is especially influential for visual cartographic representation (Bertin, 1967|1983, Morrison, 1974, Caivano, 1990, MacEachren, 1992), but is equally important for animated (DiBiase et al., 1992), haptic (Griffin, 2002), and sonic (Krygier, 1994) cartographic representation as well. These taxonomical frameworks provide a systematic way of varying cartographic representations when empirically examining which representations work the best. These findings then are used to answer the *how?* question of cartographic representation, assisting cartographers in the selection of representation choices appropriate for the specific mapping context.

The majority of existing research on the *how?* question of cartographic interaction has been specific to the evaluation of a single cartographic interface design,[22] or several competing interface designs, to the end of improving a single map application implementing a specific set of cartographic interactions, rather than improving the understanding of cartographic interactions generally. Although such an approach may provide useful insights for designers and developers undertaking projects similar to the map application

[22] The parallel in a science of cartographic representation would the investigation of single map, rather than all variations in a class of maps (or all maps together).

evaluated in the study, the generalizability of these findings to all interactive mapping contexts is unclear. To generate broadly applicable results, cartographic scientists must design experiments to evaluate cartographic interactions, rather than cartographic interfaces. One way to do this is to identify the fundamental kinds or types of cartographic interactions that altogether constitute an interaction session and then vary the combination of these ***interaction primitives*** in a series of controlled experiments to identify prototypically successful cartographic interaction strategies. For cartographic interfaces that provide numerous cartographic interactions, a taxonomy of cartographic interaction primitives acts as a logical coding scheme for unitizing and interpreting the interaction log produced during the interaction session.

Investigation of interaction primitives is important for a science of cartographic interaction (as with visual variables to the science of cartographic representation) to ensure that the design rules and guidelines derived from empirical evidence are generalizable beyond specific cartographic interface designs and technological capabilities (Cartwright, 1999). Such investigation also is important when identifying the appropriate amount of interaction freedom (**Section 2.4**), as it is essential to have an understanding of the complete cartographic interaction design space before knowing how to best select from that space to constrain the interaction (Bowman et al., 2002). As introduced in **Chapter 1**, development of a taxonomy of fundamental interaction primitives is considered to be the "grand challenge" of a science of interaction by the related field of Visual Analytics (Thomas et al., 2005). As Chi and Reidl (1998: 63) note, "Information visualization has made great strides in the development of a semiology of graphical representation methods, but lacks a framework for studying visualization operations," a sentiment that also is true in Cartography. Although no single taxonomy has been universally adopted within Cartography, there are a large number of taxonomies proposed in the GIScience, Human-Computer Interaction, and Information Visualization literature, with the proposals exhibiting only a limited degree of overlap. **Section 3.2** introduces a framework for compartmentalizing cartographic interaction into a sequence of stages that is useful for organizing extant taxonomies of interaction primitives; taxonomies offered at a subset of these stages then are summarized in the remainder of the chapter.

3.2 Stages of Cartographic Interaction

Identification and articulation of cartographic interaction primitives must be considered within the formal definition of cartographic interaction. As introduced in **Section 2.2**, ***cartographic interaction*** is best conceptualized as a conversation between a user and a map mediated through a computing device (**Figure 2.1**). While the overall interaction session is freeform and highly iterative—like a conversation between two humans—it is possible to unitize the session into a string of individual ***interaction exchanges***, or unique question and answer sequences completed during the cartographic interaction conversation. These individual exchanges then can be combined into logical blocks of conversation, or unique ***interaction strategies***, with competing solutions compared against one another to identify ***prototypically successful interaction strategies*** and thus to answer the important *how?* question of interaction (Edsall, 2003).

Norman's (1988) stages of action model provides a useful framework for identifying possible interaction primitives within this two-way conversation metaphor, replacing the abstract question and answer sequence constituting an exchange with a more concrete execution and evaluation sequence. In the model, Norman (1988) further decomposes an individual exchange in the overall interaction conversation into a sequence of seven observable steps, or ***stages of (inter)action***.[23] **Figure 3.1** shows these seven stages in relation to the **Figure 2.1** definition of cartographic interaction. Stages include:

[23] As stated in **Section 2.2**, Norman's stages of action model describes how humans interact with any object in the world, analog or digital. The remainder of the discussion on the stages of action model assumes the interactions are inherently digital.

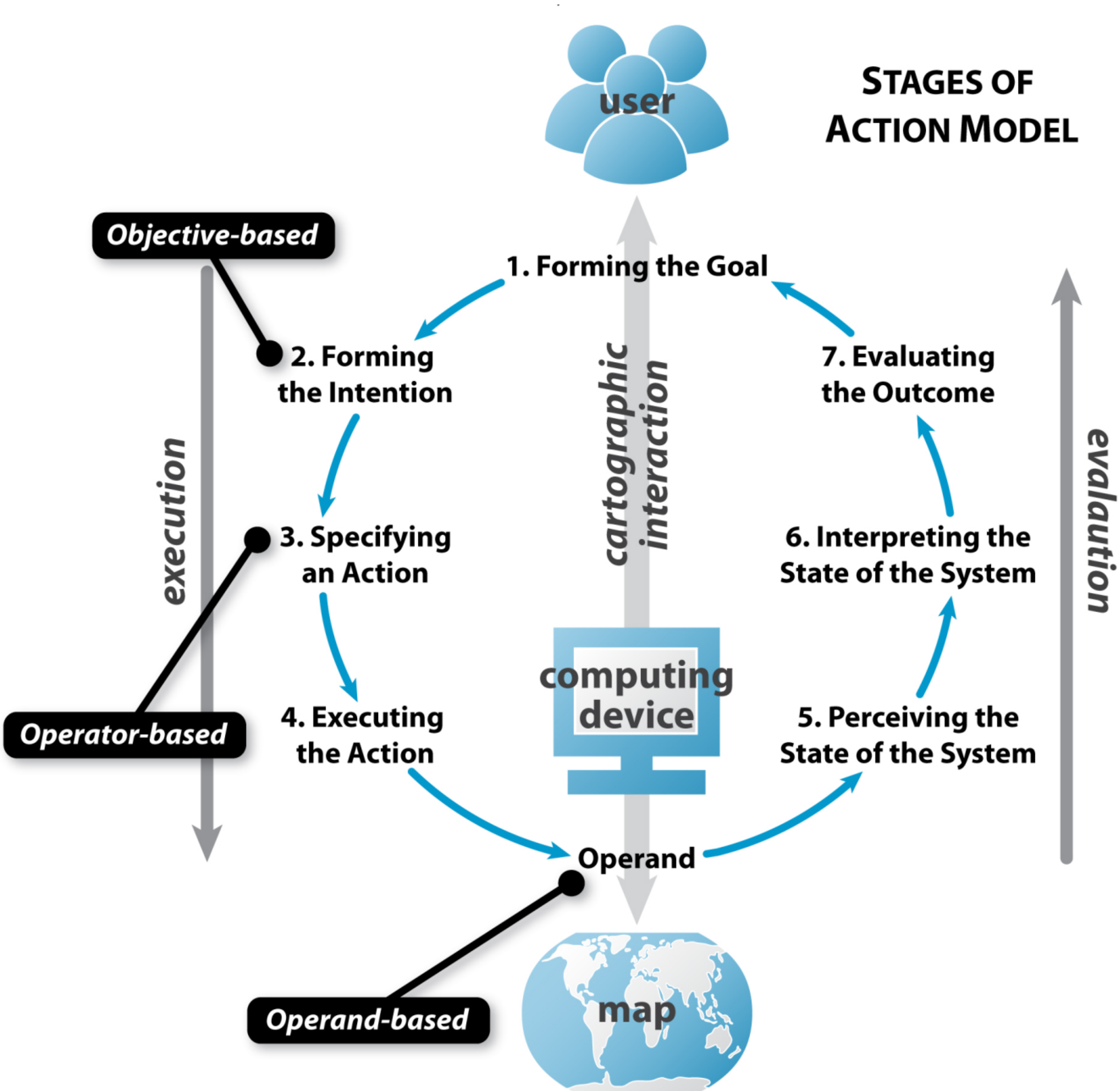


Figure 3.1: The Stages of Action Model and the Three *O's* of Cartographic Interaction. Norman (1988) decomposes a single execution-evaluation exchange into a sequence of seven stages. While a taxonomy of interaction primitives could be offered at all of these stages, there are three common approaches: (1) objective-based (at the stage of forming the intention), (2) operator-based (at the stage of specifying an action), and (3) operand-based (at the nexus of execution and evaluation, between the stages of executing an action and perceiving the state of the system). **Figure 3.1** is placed in relation to the definition of cartographic interaction offered in **Figure 2.1.**

(1) ***Forming the Goal***: The ***goal*** is what the user is trying to achieve and often is poorly defined and domain specific. In the context of cartographic interaction, goals motivate the use of geographic information and cartographic interfaces. Goals relate to the purpose of cartographic interaction, as reviewed when discussing the *why?* question in **Section 2.3**; for instance, a user may have one of four goals when employing interactive maps to support science: exploration, confirmation/analysis, synthesis, and presentation (**Figure 2.2**). Depending on the complexity of the work being completed, and how well past interactions achieved the goal, the goal itself may remain static throughout the interaction session, and therefore be the same at each exchange.

(2) ***Forming the Intention***: The intention, referred to here as the ***objective***, describes the task that the user wishes to complete during the exchange. Objectives are formalized at an increased level of precision from the broader goals and can be conceptualized as a statement of what the user wants to do with the cartographic interface. Objectives therefore form the cognitive user input into the cartographic interaction (see **Section 3.5**). The objective often is identified from past interaction sequences in the overall session, particularly in the context of Exploratory Geovisualization where the user may not have an objective in mind when beginning the interaction session (but does have a goal in mind: exploration).

(3) ***Specifying an Action***: Specification of the action describes the translation from the user's objective formed in the prior stage to the functions provided by the cartographic interface that are perceived by the user to support this objective. These functions, which can be distilled into generic classes of ***operators***, or the actions provided through cartographic interfaces that allow for interactive change to the map display. The user becomes aware of the available operators through ***affordances*** built into the cartographic interface that indicate what the system can do and how it should be used. As noted in **Section 2.2**, operators rely upon one of five ***interface styles*** (direct manipulation, menu selection, form fill-in, command language, and natural language), but are more abstract than the interface styles that implement them, as the same operator can be implemented using any of the five basic interface styles. Gould (1993) describes the difference between objectives and operators as an "abstract worlds" perspective versus a "data manipulation" perspective.

(4) ***Executing the Action***: Once the user identifies a possible operator for achieving the objective, he or she must execute that operator. ***Execution*** represents the 'doing' component of the interaction exchange, or the physical human input required to manipulate the provided cartographic interface. Most of the aforementioned interface styles require application of human motor skills to manipulate a physical input device (even most map-based systems using speech-recognition are multi-modal and include motor movements such as pointing); **Section 2.6** provides an overview of different input devices available for executing an operator. Computing devices provide the necessary logic to convert basic user inputs (i.e., raw input) into meaningful information that can be ingested by the application for manipulation of the display (i.e., semantic input), offloading this potentially additional stage of action from the user and onto the machine.

(5) ***Perceiving the State of the System***: The operator, once executed, manipulates the recipient of the operator in some way, changing the system state. The operator recipient, or ***operand***, describes the digital/virtual object with which the user is interacting either directly (through direct manipulation interface styles) or indirectly (through the other four interface styles) (Ward and Yang, 2003). In the context of interactions explicitly cartographic, the operand is a digital map (or a component thereof) or isomorphic views linked to the digital map. The operand is essential for completion of all seven stages of action, given the two-way conversation between user and map. However, the operand is particularly important directly

following execution, as it is a primary way to provide ***feedback*** to the user, or signals about what happened as a result of the executed operator. It is through the provision of feedback about changes made to the operand that the map interface participates in the interaction conversation. Executing the Action (**Figure 3.1, #4**) and Perceiving the State of the System (**Figure 3.1, #5**) are the stages that emphasize the computing device through which the digital interaction is made possible (**Figure 2.1**).

(6) ***Interpreting the State of the System***: Once the updated operand is perceived, the user then must make sense of the update. One way to understand this stage[24] is completion of the objective formulated in the second stage of action; once a new cartographic representation—or additional information about that cartographic representation—has been requested, it should be used to carry out the identified user objective. If the revised system state properly reflects application of the desired operator, completion of the objective may lead to the generation of new insight. In the context of the MacEachren and Ganter (1990) pattern-matching model, Perceiving the State of the System (**Figure 3.1, #5**) is similar to 'seeing-that', while Interpreting the State of the System (**Figure 3.1, #6**) is similar to 'reasoning-why'.

(7) ***Evaluating the Outcome***: The final evaluation compares the result of the operator with the expected or desired result. This includes both a critical evaluation of the validity of generated insights ("does this seem right?") and a meta-evaluation to determine if the overarching goal has been accomplished through generation of these insights ("do I have my answer?"). Following this evaluation, the user may initialize a new interaction exchange, restarting the seven stage sequence.

Norman (1988) warns of two general kinds of failures in communication between users and an interface during an individual interaction exchange, described as ***gulfs***: (1) the gulf of execution and (2) the gulf of evaluation. In the context of cartographic interaction, the ***gulf of execution*** describes the divide between the user's goals and objectives that motivated them to use the cartographic interface and the available operators (or those perceived by the user to be available) and input devices provided to manipulate the map display in support of those goals and objectives; in other words, the gulf of execution describes a situation in which the user is uncertain what to do with a cartographic interface, or certain of what to do with it, but uncertain of how to do it. The gulf of execution generally refers to interruptions in the first four stages of action. Overcoming the gulf of execution requires an understanding of the user's needs and intentions during cartographic interface design and development as well as the inclusion of strong affordances within the system that indicate its functionality to the user. Conversely, the ***gulf of evaluation*** describes the divide between the result that the user expected to receive after executing a given cartographic interaction and the result that actually is perceived and interpreted by the user based on the cartographic interface response to the executed interaction; in other words, the gulf of evaluation describes a situation in which the user is uncertain what they did with a cartographic interface or uncertain of what the resulting change means. The gulf of evaluation generally refers to interruptions in the final three stages of action. Overcoming the gulf of evaluation requires a prompt and informative feedback mechanism in the cartographic interface (e.g., a modified cartographic representation, a results table, a dialog or error message). Investigation of the individual stages that constitute a single interaction exchange is important for identifying successful interaction strategies and diagnosing unsuccessful ones, as commonly repeated or particularly critical incidents of the gulfs of execution and evaluation together may lead to a breakdown in the overall cartographic interaction conversation.

Norman's (1988) stages of action model also is useful for organizing extant taxonomical frameworks of interaction primitives. It may be possible to construct a comprehensive listing of all available options at

---

[24] That goes beyond Norman's description, which implies that Interpreting the System State (**Figure 3.1, #6**) and Evaluating the Outcome (**Figure 3.1, #7**) are restricted to the system feedback only.

each stage of interaction, producing a seven-dimensional[25] taxonomy of interaction primitives. Most extant taxonomical frameworks of interaction primitives, however, align loosely with one of three components of the stages of action model, producing three recommended approaches to parsing exchanges into interaction primitives: (1) an objective-based approach, (2) an operator-based approach, and (3) an operand-based approach. These three approaches are together described here as the ***three O's*** of cartographic interaction. **Figure 3.1** is annotated to indicate the locations of the three approaches within the stages of action model. Extant objective-based, operator-based, and operand-based taxonomies of interaction primitives are defined and reviewed in **Section 3.3**, **Section 3.4**, and **Section 3.5** respectively, although several taxonomies include interaction primitives from multiple stages of interaction. Each section includes a table summary of extant taxonomies offered at the identified stage as well as a concept map showing the relationships of extant taxonomies and the relative frequencies of interaction primitives. Only a minimal attempt was made to disambiguate the terms in each concept map figure (e.g., changing pre-fixes or suffixes, dividing conflated terms into two primitives) in order to provide an unfiltered view of the terminology currently in use; areas of overlap or confusion instead are discussed in the following sections. Italics are used in the following summary to differentiate terms used to describe an interaction primitive from regular uses of the same terms.

3.3 Objective-Based Taxonomies

Objective-based approaches compartmentalize interaction at the Forming the Intention (**Figure 3.1, #2**) stage of action, emphasizing the kinds of tasks the user may wish to complete with the cartographic interface. Objective-based taxonomies often are described as task ontologies; the development of functional task ontologies has been identified as a key research need for Geovisualization specifically (e.g., Fabrikant, 2001, Andrienko et al., 2003) as well as GIScience more broadly (e.g., Goodchild, 1988, Albrecht, 1997). **Table 3.1** summarizes extant object-based taxonomies from the domains of Cartography, GIScience, Human-Computer Interaction, Information Visualization, and Visual Analytics, which include: Wehrend and colleagues (1990, 1993), Zhou and Feiner (1998), Blok (1999), MacEachren et al. (1999), Crampton (2002), Andrienko et al. (2003), Amar et al. (2005), and Yi et al. (2007). The **Figure 3.2** concept map indicates the similarities and differences across objective-based taxonomies and the relative frequencies of each interaction primitive.

It is possible to segment the **Figure 3.2** concept map into three general subsections based on their overlap, delineated in the figure by dashed lines. At the top of the graphic, there are a concentrated set of equivalent objectives-based taxonomies that include only the primitives *identify* and *compare*: Wehrend and Lewis's (1993) 'operations', Blok et al.'s (1999) 'exploratory tasks', and Andrienko et al.'s (2003) 'cognitive operations' (see **Section 3.4** for additional details about the Andrienko et al. operational task taxonomy). *Identify* and *compare* are the only two primitives included in a majority of objective-based taxonomies. The definitions of *identify* and *compare* are largely consistent across taxonomies; *identify* describes the examination of a single map object,[26] while *compare* extends *identify* to consider similarities and differences across multiple map objects. The MacEachren et al. (1999) 'meta-operations' also are included in this subsection of the **Figure 3.2** concept map, but extends the two-part objective-based taxonomies with the primitive *interpret*; drawing from previous work on map reading in Cartography by Muehrcke (1986), MacEachren et al. (1999) define *interpret* as determining the relationship of an identified feature to a real-world entity. Feature interpretation is important when considering a triadic model of ***semiotics*** (see **Section 1.1**), with the interpretant mediating the sign-vehicle and the referent, and thus is fundamental to map use (**Figure 1.4a, right**).

[25]Or, if the operand is included as its own stage, as suggested by **Figure 3.1**, an eight-dimensional taxonomy of interaction primitives.

[26] The term 'object' is used here generically to span across Bertin's (1967|1983) levels of map reading, ranging from identification and comparison of individual map elements through identification and comparison of broad patterns.

Author(s)	*Title*	*Objectives*
Wehrend & Lewis (1990)	Operations	(1) identify, (2) compare
Wehrend (1993)	Visualization Goals	(1) identify, (2) locate, (3) distinguish, (4) categorize, (5) cluster, (6) rank, (7), compare, (8) associate, (9) correlate
Zhou & Feiner (1998)	Visual Tasks	(1) associate, (2) background, (3) categorize, (4) cluster, (5) compare, (6) correlate, (7) distinguish, (8) emphasize, (9) generalize, (10) identify, (11) locate, (12) rank, (13) reveal, (14) switch, and (15) encode.
Blok et al. (1999)	Exploratory Tasks	(1) identify, (2) compare
MacEachren et al. (1999)	Meta-Operations	(1) identify, (2) compare, (3) interpret
Crampton (2002)	Interactivity Tasks	(1) examine, (2) compare, (3) (re)order/(re)sort, (4) extract/suppress, (5) cause/effect
Andrienko et al. (2003)	Cognitive Operations	(1) identify, (2) compare
Amar et al. (2005)	Analytic Tasks	(1) retrieve value, (2) filter, (3) compute derived value, (4) find extremum, (5) sort, (6) determine range, (7) characterize distribution, (8) find anomalies, (9) cluster, (10) correlate
Yi et al. (2007)	User Intents	(1) select, (2) explore, (3) reconfigure, (4) encode, (5) abstract/elaborate, (6) filter, (7) connect

Table 3.1: Extant Objective-based Taxonomies of Interaction Primitives

The second subsection in the concept map, located in the middle of **Figure 3.2**, includes two objective-based taxonomies that greatly extend the simpler frameworks that include only *identify* and *compare*: Wehrend's (1993) 'visualization goals', and Zhou and Feiner's (1998) 'visual tasks'. Wehrend (1993) proposes nine 'visualization goals', defined as actions that a user would like to perform on his or her data. Visualization goals include: (1) *identify* (establish the characteristics by which an object is distinctly recognizable), (2) *locate* (determine the position of an object in absolute or relative terms), (3) *distinguish* (recognize one object as different from another or group of others), (4) *categorize* (place objects into a set of divisions for organization), (5) *cluster* (join objects into groups based on similar characteristics—this task differs from *categorize* in that clustering creates the groups as the objects are placed in them, rather than using an *a priori* set of intervals), (6) *rank* (give an object an order or position with respect to other objects of the same type), (7) *compare* (notice similarities and differences between/among objects when they have no explicit ranking), (8) *associate* (link or join two or more objects in a relationship), and (9) *correlate* (establish a direct connection between/among objects). There are two characteristics of the Wehrend's (1993) taxonomy worth noting. First, Wehrend chooses to separate *locate* from *identify*; *locate* is a task that is clearly spatial, but is not found in any of the objective-based taxonomies within the cartographic literature. Using this distinction, the *identify* primitive narrowly focuses upon the attributes of a map feature that already has, or needs to be, *located* on the map. Albrecht (1997) describes this difference as *thematic search* versus *spatial search* in the context of GIS operators.[27] Second, Wehrend

[27] The use of the term 'interaction operator' is slightly different than its use in GIS to describe a computational calculation or transformation applied to a spatial dataset (e.g., Goodchild 1988; Albrecht 1997). Like GIS operators, cartographic interaction

includes a large number of primitives that go beyond *compare* to organize individual data elements at different strengths; examples that may be considered special cases of *compare* include *associate*, *categorize*, *cluster*, *correlate*, *distinguish*, and *rank*.

Zhou and Feiner (1998) directly extend Wehrend's (1993) taxonomy to generate a total of 15 'visual tasks', defined as abstract visualization techniques that can be accomplished through a set of low-level operations. Added primitives include: (10) *background*, (11) *emphasize*, (12) *reveal*, (14) *switch*, and (15) *encode*; definitions are not offered for the added six primitives. One addition made by Zhou and Feiner is organization of the taxonomy around the objective's visual accomplishment and visual implication**.** The ***visual accomplishment*** describes the change to the operand, provided to the user through feedback, as a result of completing an objective. Given this focus on manipulation to the operand—a concept more commonly evoked in operator-based approaches (**Section 3.4**)—each of Zhou and Feiner's additions possibly can be interpreted as operators instead of objectives; again, specific definitions are not offered to allow for confirmation of this interpretation. In contrast, the ***visual implication*** describes the new objectives that can be achieved after first completing a given objective, indicating a conditioning that may occur when considering multiple interaction exchanges together, or multiple loops through the stages of action model (**Figure 3.1**).

The final subsection located along the outer rim of the **Figure 3.2** concept map includes largely unprecedented or orthogonal offerings that exhibit minimal overlap with taxonomies in the other two **Figure 3.2** subsections, or with each other. These taxonomies include Crampton's (2002) 'five interactivity tasks', Amar et al.'s (2005) 'analytic tasks', and Yi et al.'s (2007) 'user intents'. One explanation for this disconnect is that at least one interaction primitive (and often more) in each of the remaining objective-based taxonomies is better understood as an operator. Despite this blending of objectives and operators, the Crampton, Amar et al., and Yi et al. taxonomies are considered objective-based because of the scholars' overall focus on user tasks or intentions, rather than interfaces. Each remaining objective-based taxonomy is treated separately in the following due to the divergence in their approaches.

Crampton (2002) offers five 'interactivity tasks', defined as the kinds of actions users conduct with a geovisualization. Interactivity tasks include: (1) *examine* (looking at and inspecting a feature), (2) *compare* (examining two or more displays at once) (3) *(re)order/(re)sort* (examining the data in addition to performing a direct manipulation on it), (4) *extract/suppress* (highlighting and filtering), and (5) *cause/effect* (linking views to identify the strength and nature of a relationship across representations). This taxonomy is important because it is organized across a characteristic of the user objectives: their level of ***sophistication***, or amount and complexity of the subsequent operators required to complete the objective. Sophistication increases in an ordinal manner across the five objectives, from *examine* to *cause/effect*. The least sophisticated primitives are those also found in the simpler objective-based taxonomies (e.g., Wehrend and Lewis, 1990, Blok et al., 1999, Andrienko et al., 2003), including the common *compare* as well as *examine*, a primitive that overlaps with *identify*. The objectives at an intermediate level of sophistication are confused with operators, describing manipulations to the operand such as a request for a visual isomorph (*(re)order/(re)sort*) or a request to show a subset of features (*extract/suppress*). Although *(re)order* and *(re)sort* conceptually are similar to Wehrend's *rank* and *categorize* respectively—and thus may be representative of objectives—the definition of *(re)order/(re)sort* provided by Crampton focuses specifically on manipulation to the view through a cartographic interface. The most sophisticated objective primitive, *cause/effect*, describes a specific case of *compare* in which the goal is to establish a one-way temporal relationship between compared items. As

---

operators describe a class of functionality that manipulate; however, cartographic interaction operators describe a visual manipulation to a map-centered display (whether manipulating the underlying data or not).

described above, Wehrend's (1993) objective-based taxonomy also includes additional discrimination within the *compare* primitive, although does not include *cause/effect*.

Amar et al. (2005) list 10 'analytic tasks' in the context of information visualization. These scholars take an ***analytic primacy*** perspective, focusing on how visualization tools support user needs (i.e., objectives) taxonomies. The opposite perspective, ***representation primacy***, focuses on the information representations and the ways to manipulate them (i.e., the operands and operators). This taxonomy is interesting because it is empirically derived, unlike all previously mentioned objective-based taxonomies (and most extant taxonomies of interaction primitives generally). Amar et al. asked college students in an Information Visualization course to generate a listing of possible tasks that could be accomplished with a sample dataset using commercial visualization tools. These tasks then were grouped using the affinity diagramming method (see **Section 5.2.1** for details). The 10 analytic tasks identified include: (1) *retrieve value* (find attributes about an identified data case), (2) *filter* (find cases whose attributes meet a set of conditions), (3) *compute derived value* (calculate an aggregate representation for a set of cases), (4) *find*

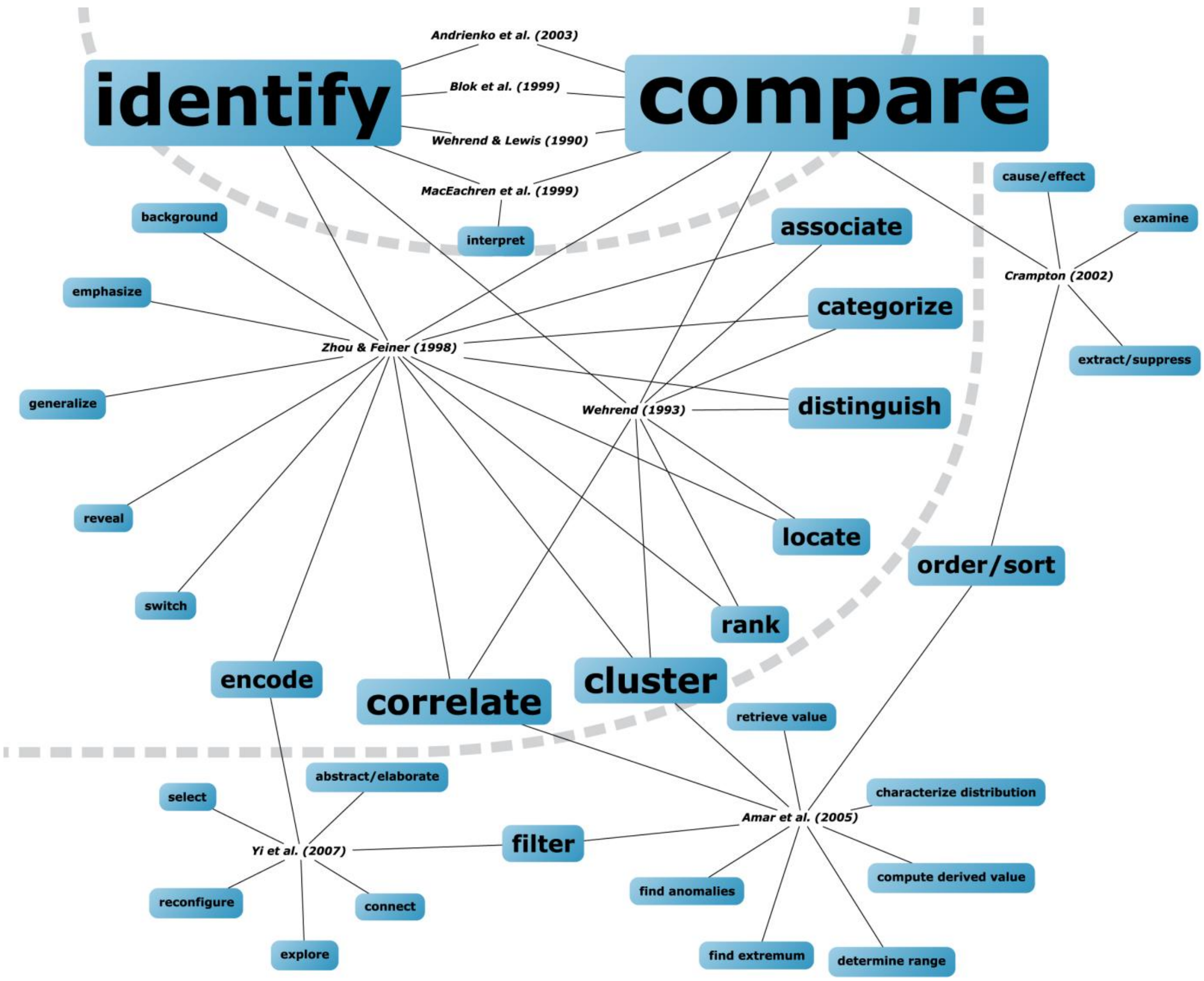


Figure 3.2: A Concept Map of Objective-based Primitives. The concept map shows the relationships among extant objective-based taxonomies and the relative frequency of the included interaction primitives. The objective-based concept map can be segmented into three subsections based on relations: **(top)** A concentrated set of simple taxonomies that include the primitives *identify* and *compare*; **(middle)** Two taxonomies that expand upon the *compare* primitive; **(outer rim)** Unprecedented or orthogonal taxonomies that have minimal overlap with others.

extremum (identify cases with extreme values), (5) *sort* (rank cases according to a numeric attribute), (6) *determine range* (find the span of attributes for a set of cases), (7) *characterize distribution* (produce statistics that characterize the distribution of a set of cases), (8) *find anomalies* (identify cases that do not match a given relationship or expectation), (9) *cluster* (group cases based on similar attributes), and (10) *correlate* (identify relationships across cases by their attributes). Interestingly, *identify* and *compare* are not listed and instead are replaced with more specific terminology common to statistics, such as *compute derived value*, *find anomalies*, *find extremum*, and *retrieve value* for the *identify* primitive and *characterize distribution*, *cluster*, *correlate*, *determine range*, and *sort* for the *compare* primitive. This replacement perhaps is appropriate if a more detail delineation within *identify* and *compare* is possible and/or necessary; other objective-based taxonomies that include both the generic *identify* and *compare* primitives, along with special cases of these primitives, insufficiently redefine what is meant by *identify and compare*, resulting in an objective-based taxonomy that is not mutually exclusive. Finally, the primitive *filter* is included in the Amar et al. and subsequent Yi et al. (2007) taxonomies, but aligns more closely with operator-based taxonomies (see **Section 3.4**).

Yi et al. (2007) identify seven 'user intents' (i.e., objectives) that drive the application of interaction techniques (i.e., operators). Like Amar et al. (2005), Yi et al. use an affinity diagramming approach to develop the taxonomy, although on secondary sources rather than empirical evidence. Their review included 59 papers and 51 visualization systems, producing a collected total of 331 interaction techniques. Techniques are grouped by seven user intents: (1) *select* (mark a case of interest), (2) *explore* (display a different subset of cases), (3) *reconfigure* (change the arrangement of cases), (4) *encode* (change the method of representing the data), (5) *abstract/elaborate* (show the data in more or less detail), (6) *filter* (show cases that satisfy a set of conditions), and (7) *connect* (highlight associated or related items). An eighth, catch-all category is added for system interactions like undo/redo and change variable assignment/configuration. When examining the definitions alone, it is possible that all primitives within this objective-based taxonomy are better considered as generic descriptions or characteristics of operators. Most operator-based taxonomies within Cartography collapse what Yi et al. call *explore* and *filter* into a single operator primitive, using only the term *filter* and instead reserving the term *explore* for use as an overarching goal, not an objective (**Figure 2.2**). Yi et al. do not include *identify*, with *select* representing the conceptually most similar included primitive (i.e., a combination of the *identify* objective with an operator that then marks the identified map feature). Interestingly, Yi et al. explicitly reject inclusion of *compare*, the most pervasive objective primitive, arguing that it is a higher level goal that builds upon other interaction primitives. Thus, they do not agree with Crampton's (2002) notion of sophistication, instead arguing for a taxonomy of primitives that are at the same semantic level of meaning, or same level of sophistication.

In summary, extant objective-based taxonomies of interaction primitives exhibit the following characteristics:

- The *identify* and *compare* primitives are the most commonly included across the reviewed objective-based taxonomies (Wehrend and Lewis, 1990, Wehrend, 1993, Zhou and Feiner, 1998, Blok et al., 1999, MacEachren et al., 1999, Andrienko et al., 2003);

- The more complex objective-based taxonomies discriminate within the *compare* primitive commonly (Wehrend, 1993, Zhou and Feiner, 1998, Crampton, 2002, Amar et al., 2005) and less frequently within the *identify* primitive (Amar et al., 2005);

- Of those taxonomies that do discriminate within the *identify* and *compare* primitives, only Amar et al. (2005) removes the broader *identify* and *compare* to ensure that the objective-based taxonomy is mutually exclusive;

- Several scholars organize the primitives into categories (e.g., visual accomplishments & implications from Zhou and Feiner, 1998) or across a continuum (e.g., level of sophistication from Crampton, 2002), while others explicitly argue against inclusion of operators at different semantic levels of meaning (Yi et al., 2007);

- The distinction between objectives and operators described in **Section 3.2** has not been considered by many authors, resulting in several taxonomies offered at an intermediate stage or a blending of the two stages (Zhou and Feiner, 1998, Crampton, 2002, Amar et al., 2005, Yi et al., 2007).

Before concluding the summary on objective-based taxonomies, it is important to note that there are a considerable number of purpose-driven objective-based taxonomies in the Human-Computer Interaction and Usability Engineering literature that are specific to a single application domain and include highly detailed descriptions of the primitives.[28] Construction of these customized objective-based taxonomies is part of the task analysis, or ***work domain analysis***, step in design and development of a cartographic interface (Robinson et al., 2005). The work domain analysis is the initial step in a ***user-centered design*** approach and describes the initial contact with the targeted end users to identify their key met and unmet needs, and therefore to establish the requirements of the cartographic interface. This stage of the user-centered workflow can be streamlined with a broadly applicable and generally accepted objective-based taxonomy in place *a priori* (i.e., the goal of the reviewed taxonomies in this section), as the designers and developers simply can work through the objective primitives to determine which need to be supported, identify specific examples of each included objective primitive, and brainstorm potential operators that support the identified objectives. One such example within Cartography is presented by Auer (2009), who describes a robust 'task typology' of spatiotemporal dynamic map reading tasks specific to the study of bird distribution and migration patterns; his final, purpose-driven objective-based taxonomy was constructed through the integration of the existing objective-based taxonomies from Wehrend (1993), Blok (2000), and Andrienko et al. (2003) and user input from a focus group session with expert ornithologists.

3.4 Operator-Based Taxonomies

Operator-based approaches compartmentalize interaction at the Specifying the Action (**Figure 3.1, #3**) stage, focusing upon the cartographic interfaces that make manipulation of the representation possible. At this stage of action, the user identifies the operator he or she believes will support the objective, but does not execute the operator itself using available input devices. The cartographic interface designer must ensure that the provided set of operators completely supports the user's objectives and that the user is aware of the available operators through strong affordances; as described in **Section 3.2**, the mismatch between user objectives and available or perceived interface operators is referred to as the gulf of execution (Norman, 1988). **Table 3.2** summarizes extant operator-based taxonomies, which include: Becker and Cleveland (1987), Shepherd (1995), Buja et al. (1996), Chuah and Roth (1996), Shneiderman (1996), Dykes (1997), Dix and Ellis (1998), MacEachren et al. (1999), Masters and Edsall (2000), Keim (2002), Ward and Yang (2003), and Edsall et al. (2008). The **Figure 3.3** concept map indicates the similarities and differences across operator-based taxonomies and the relative frequencies of each interaction primitive.

---

[28] So much so that it is perhaps inappropriate to consider them as 'primitives', although they are the lowest-level component of the taxonomy.

Unlike the concept maps in **Figure 3.2** and **Figure 3.4**, the **Figure 3.3** concept map cannot be segmented easily into subsections of similar structures because of a much greater amount of lexical variation across the operator-based taxonomies. These taxonomies commonly employ the same term to refer to different operators or employ different terms that refer to the same operator. This results in a complex concept map with only several primitives common to multiple operator-based taxonomies and many primitives found in only one or two taxonomies. The **Figure 3.3** concept map instead is segmented according to the frequency of primitives. The following review is organized according to this delineation, first treating the small subset of primitives common to a large portion of the operator-based taxonomies (*brushing*, *focusing*, and *linking*), but often used in a contradicting or inappropriate manner, and then treating the

Author(s)	***Title***	***Operators***
Becker & Cleveland (1987)	Brushing Operations	(1) highlight, (2) shadow highlight, (3) delete, (4) label
Shepherd (1995)	Observer-related Behavior	(1) observer motion, (2) object rotation, (3) dynamic comparison, (4) dynamic re-expression, (5) brushing
Buja et al. (1996)	Interactive View Manipulations	(1) focusing, (2) linking, (3) arranging views
Chuah & Roth (1996)	Basic Visualization Interaction Operators	(1) encode data (graphic), (2) set-graphical-value (graphic), (3) manipulate objects (graphic), (4) create (set), (5) delete (set), (6) summarize (set), (7) join (set), (8) add (data), (9) delete (data), (10) summarize (data), (11) join (data)
Shneiderman (1996)	Tasks	(1) overview, (2) zoom, (3) filter, (4) details-on-demand, (5) relate, (6) history, (7) extract
Dykes (1997)	Observer-related Behavior	(1) observer motion, (2) object rotation, (3) dynamic comparison, (4) dynamic re-expression, (5) brushing
Dix & Ellis (1998)	Kinds of Interaction	(1) highlight and focus, (2) accessing extra information, (3) overview and context, (4) same representation-changing parameters, (5) same data-changing representation, (6) linking representations
MacEachren et al. (1999)	Interaction Forms	(1) assignment, (2) brushing, (3) focusing, (4) colormap manipulation, (5) viewpoint manipulation, (6) sequencing
Masters & Edsall (2000)	Interaction Modes	(1) assignment, (2) brushing, (3) focusing, (4) colormap manipulation, (5) viewpoint manipulation, (6) sequencing
Keim (2002)	Interaction & Distortion Techniques	(1) dynamic projection, (2) filtering, (3) zooming, (4) distortion, (5) linking and brushing
Ward & Yang (2003)	Interaction Operators	(1) navigation, (2) selection, (3) distortion
Edsall et al. (2008)	Interaction Forms	(1) zooming, (2) panning/re-centering, (3) re-projecting, (4) accessing exact data, (5) focusing, (6) altering representation type, (7) altering symbolization, (8) posing queries, (9) toggling visibility, (10) brushing and linking, (11) conditioning

Table 3.2: Extant Operator-based Taxonomies of Interaction Primitives

menagerie of remaining primitives that together exhibit several common themes (e.g., operators that manipulate the symbolization in the cartographic representation, operators that manipulate the user's viewpoint on the cartographic representation, and enabling operators)

The central subsection of the **Figure 3.3** concept map includes three primitives found in a large portion of the reviewed objective-based taxonomies: *brushing*, *focusing*, and *linking*. *Brushing*, one of the earliest digital interaction operators offered in the exploratory data analysis literature, is the only primitive common to a majority of the reviewed objective-based taxonomies. Becker and Cleveland (1987) describe *brushing* as a highly interactive technique for directly selecting groups of data items in a display, making it one of the few offered operator primitives that can be implemented by a single interface style: direct manipulation. While several scholars suggest that brushing is possible through other interface styles, these alternatives are not considered because they either require direct manipulation of linked interface widgets (which acts as either *brushing* of that widget or *filtering* of a linked control) (Ward, 1997) or are non-interactive (Monmonier, 1989). Becker and Cleveland identify four 'brushing operations': (1) *highlight* (brushing changes the representation of the selected items; this operator is further delimited by Robinson, 2006), (2) *shadow highlight* (brushing changes the unselected items), (3) *delete* (brushing deletes the selected items), and (4) *label* (brushing retrieves the labels for selected items). Thus, under the Becker and Cleveland conceptualization, brushing is an enabling interaction that indicates the map elements (i.e., the operands) to receive some additional treatment (i.e., a second operator).

It perhaps is this dual-step nature of *brushing* that has caused confusion in subsequent uses of the term in operator-based taxonomies, with several scholars emphasizing the initial, selection step in their definition of the *brushing* primitive and others emphasizing the secondary, transformation step, or one of Becker and Cleveland's (1987) four 'brushing operations'. Shepherd (1995) and Dykes (1997) focus on the former step, defining *brushing* as a data selection technique, a use that is synonymous with Ward and Yang's (2003) *selection* primitive. It is necessary to be critical of the *brushing*-as-*selection* interpretation, as it equates *brushing* with direction manipulation, making it an interface style rather than a unique operator. Conversely, MacEachren et al. (1999) and Masters and Edsall (2000) focus on the secondary stage of *brushing* in their definition of the primitive, particularly emphasizing a visual change that is applied once a subset of elements have been selected, or Becker and Cleveland's *highlight* and *shadow highlight*. Interestingly, three of the taxonomies explicitly conflate *brushing* with one of the other three commonly found operators, collapsing them into a single primitive. Keim (2002) and Edsall et al. (2008) conflate their use of *brushing* with *linking* (defined below), defining *brushing* as a selection operator that visually relates across multiple, coordinated visual isomorphs. Dix and Ellis (1998) conflate *brushing* (directly referred to as *highlight*) with *focusing* (defined below), which implies an emphasis on Becker and Cleveland's *delete* operation; however, their subsequent discussion of the primitive is much closer to the definition provided by Keim (2002) and Edsall et al. (2008). Finally, Becker and Cleveland's *label* primitive is related to Shneiderman's (1996) *details-on-demand*, Dix and Ellis's *accessing extra information*, and Edsall et al.'s *accessing exact information*; much of the subsequent work on Becker and Cleveland's *label* primitive falls within research on excentric labels (Fekete and Plaisant, 1999).

The second and third common primitives in **Figure 3.3**, *focusing* and *linking*, originate from the Buja et al. (1996) operator-based taxonomy presented in the context of ***coordinated, multi-view visualization***. Coordinated, multi-view visualization describes a class of interactive systems that allow the user to create multiple representations of the same dataset—cartographic representations being only a subset of potential views—with the operators performed upon one representation permutated to all others (Roberts, 2008). The exploratory visualization toolkits introduced in **Section 2.4** are examples of map-centric systems that provide coordinated interaction across multiple, user-generated representations (e.g., Takatsuka and Gahegan, 2002, Weaver, 2004, Chen, 2006, Hardisty and Robinson, 2011). Buja et al. (1996) discuss three types of 'interactive view manipulations' that support coordinated, multi-view visualization: (1) *focusing* individual views (any operation that changes the detail of a subset of objects),

(2) *linking* multiple views (posing a query graphically and then having all views update with the result), and (3) *arranging* multiple views (adjusting the order or position of a large number of views). These three manipulations then are paired by Buja et al. with three objectives (*finding Gestalt*, *posing queries*, and *making comparisons*, respectively). The primitives *focusing* and *linking* are defined inconsistently in subsequent taxonomies, while the primitive *arranging views* is similar to Persson et al.'s (2006) *arranging many views* (a taxonomy summarized in **Section 3.4** due to its overall focus on operands) and Yi et al.'s (2007) *reconfigure* (a taxonomy summarized in **Section 3.2** under objectives).

The primitive *focusing* is used in three different ways by subsequent scholars. Buja et al. (1996) emphasize the increase or decrease in detail in the displayed data elements. Edsall et al. (2008: 9) follow this definition, equating *focusing* to an action of "data zooming", which itself is synonymous with Shneiderman's (1996) and Keim's (2002) definition of *zoom*. In contrast, MacEachren et al. (1999) and Masters and Edsall (2000) define *focusing* as a technique for limiting the inclusion of data elements to those meeting user-defined conditions, a definition that is synonymous with Shneiderman's (1996) and Keim's (2002) definition of *filter* and Edsall et al.'s (2008) definition of *conditioning*. Finally, Dix & Ellis (1998) conflate *brushing* and *focusing*, which restricts application of *focusing* to the direct manipulation interface style; this use of *focusing* is similar to Edsall et al.'s (2008) *posing queries* primitive.

Several definitions of the *linking* primitive do not qualify it as an operator. Given the emphasis on coordinated, multi-view visualization, the Buja et al. (1996) definition of *linking* itself is conceptually similar to Cleveland and Becker's (1987) *brushing* when the interaction is permutated to other views; as noted above, Keim (2002) and Edsall et al. (2008) follow this conflation of *brushing* and *linking*. Such a perspective on *brushing* makes it a three-step action: (1) identification of items of interest through *selection*, (2) manipulation of the selected items through an interaction operator, and (3) coordination of this interaction operator to other views through *linking*. MacEachren et al. (1999: 323) are clear not to include this form of *linking* as an interaction operator, instead considering it a characteristic of the "representation forms" (i.e., a topic falling within the cartographic representation space indicated at the top of **Figure 1.4a**, and not the cartographic interaction space at the bottom of **Figure 1.4a**). Thus, perhaps only the second component of this three-step *brushing*+operator+*linking* action represents a true manipulation to the display, meaning *brushing* and *linking* in isolation do not qualify as interaction operators. Interestingly, Dix and Ellis offer an alternative definition of *linking* in which the user requests successful representations for sequential display. Such a definition is similar to Shepherd's (1995) *dynamic comparison* primitive and MacEachren et al.'s and Masters and Edsall's (2000) *sequencing* primitive, which both describe generation of a series of related representations for display atop one another, as small multiples, or as a cartographic animation. This kind of manipulation does qualify as an interaction operator and may be extended to the *linking* of individual data items (such as during the synthesis stage of science) or the coordinated linking of views indicated by the user through an enabling interaction (Hardisty, 2003).

The outer rim of **Figure 3.3** includes a large number of primitives included in only one or two of the extant operator-based taxonomies. Despite the range of terminology used, these less frequent primitives align with one of three general themes: (1) operators that manipulate the symbolization in the cartographic representation, (2) operators that manipulate the user's viewpoint of the cartographic representation, and (3) enabling interaction operators. Each category of operators is reviewed in the following.

The first theme includes operators that manipulate the symbolization included in the cartographic representation beyond what would be included in *highlight* (i.e., a temporary symbol change to indicate features of interest). The first set of primitives adjust the included map layers (in the context of reference mapping) or the mapped data variable(s) (in the context of thematic mapping); Edsall et al.'s (2008) *toggle visibility* primitive describes the former situation and MacEachren et al.'s (1999) and Masters and

Edsall's (2000) *assignment* primitive describes the latter. Keim's (2002) *dynamic projection* is similar to assignment, but also includes the number of axes to which variables can be assigned (e.g., in a self-organizing map representation); Edsall et al.'s *re-projection* extends *dynamic projection* to include changes to the cartographic projection as well. The second set of primitives adjust the kind of cartographic representation displayed without changing what is mapped (e.g., a change from a choropleth map to a proportional symbol map), producing a new visual isomorph; this operator primitive is described as *altering representation type* by Edsall et al., *dynamic re-expression*[29] by Shepherd (1995) and Dykes (1997), *encode data* by Chuah and Roth (1996), and *same data*, *changing representation* by Dix and Ellis (1998). A final set of primitives aligning with this theme adjust the symbolization parameters (e.g., classification scheme, color scheme) without changing the representation type or the underlying data; this operator primitive is described as *altering symbolization* by Edsall et al., *colormap manipulation* by MacEachren et al. and Master and Edsall, *same representation*, *changing parameters* by Dix and Ellis, and *set-graphical-value* by Chuah and Roth.

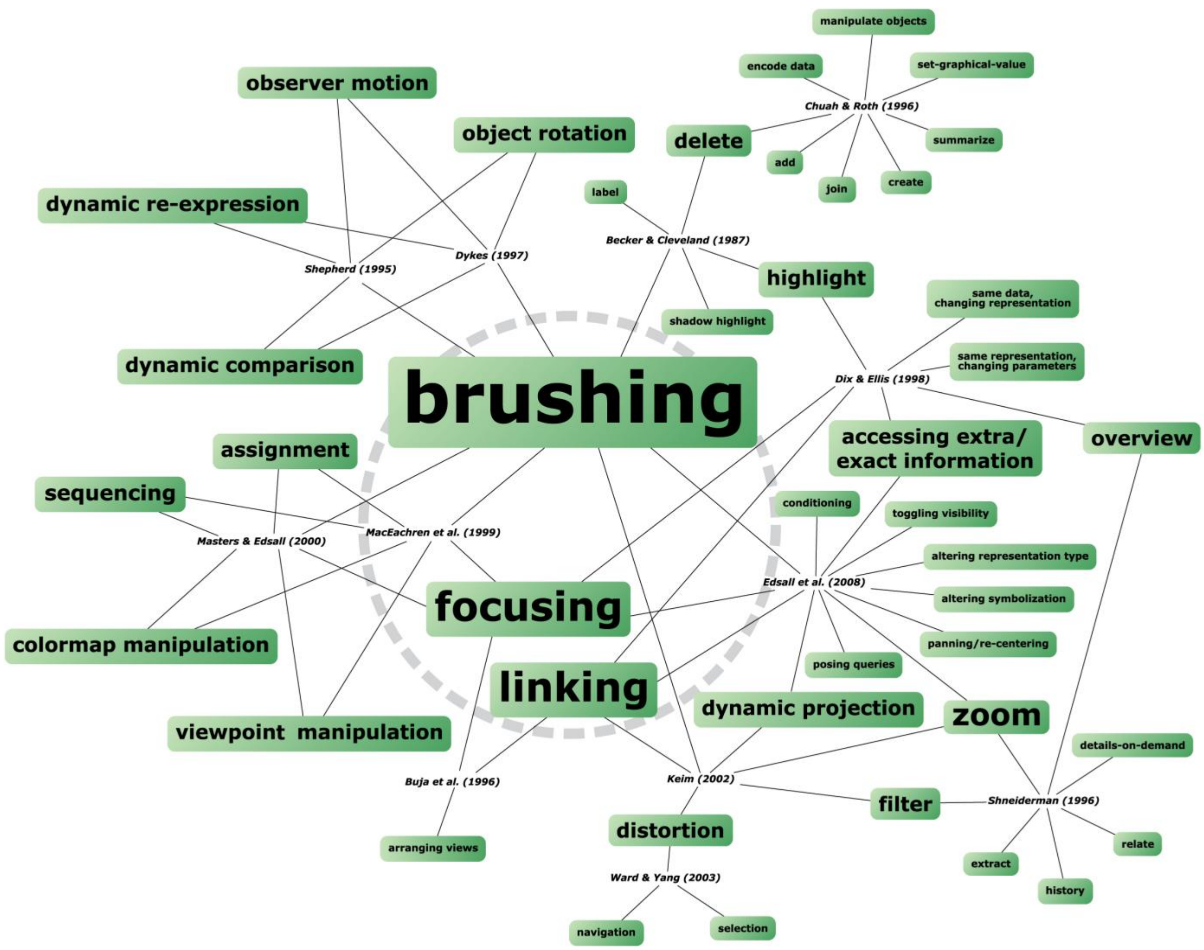


Figure 3.3: A Concept Map of Operator-based Primitives. The concept map shows the relationships among extant operator-based taxonomies and the relative frequency of the included interaction primitives. The operator-based concept map can be segmented into two subsections based on relations: **(center)** Commonly included primitives with contradicting or inappropriate definitions; **(outer rim)** Primitives included in only one or two taxonomies, but that altogether exhibit several common themes.

[29] The term *dynamic re-expression* originated from Tukey (1977) and was first used cartographically DiBiase et al. (1992)

The second theme crosscutting these peripheral primitives includes operators that manipulate the user's viewpoint. This theme covers primitives considered as part of ***map browsing*** (Harrower and Sheesley, 2005), which includes changes to the extent of the map (i.e., *pan*) and changes to the scale of the map (i.e., *zoom*). The combination of these manipulations are describe as *observer motion* by Shepherd (1995) and Dykes (1997), as *viewpoint manipulation* by MacEachren et al. (1999) and Masters and Edsall (2000), and *navigation* by Ward and Yang (2003). Edsall et al. (2008) maintain the two components of map browsing as individual primitives, using the term *panning/re-centering* and *zooming* respectively. *Zooming* is fundamental to Shneiderman's (1996)[30] ***visual information seeking mantra***, which combines *zoom* and the aforementioned *filter* to move from an overview of the information space to specific details. However, the use of *zoom* for map browsing, common within Interactive Cartography, is different from Shneiderman's use of *zoom* in that it indicates a change in map scale only, and not necessarily a change in detail of the displayed map features. The term ***semantic zoom*** sometimes is used within Cartography to describe a change in the abstraction of the cartographic representation when changing scales (Tanaka and Ichikawa, 1988). Further, Ward and Yang and Keim (2002) use the primitive *distortion* to describe a change in the detail while maintaining an overview or the surrounding context (i.e., without changing the scale of the entire map). Finally, MacEachren et al. and Masters and Edsall include the notion of rotation in their definition of *viewpoint manipulation* when applied in the context of 2.5D or 3D representations, such as virtual globes; Shepherd and Dykes reserve this as the separate primitive *object rotation* while Edsall et al. include it as part of their *re-projecting* primitive.

The final theme includes enabling interactions, or operators required to prepare for, or clean up from, operators that perform work (**Section 2.4**). The Chuah and Roth (1996) operator-based taxonomy emphasizes enabling operators, including the primitives *add*, *create*, *delete*, *join*, and *manipulate objects*. The selection step of *brushing* may be best conceptualized as an enabling operator, if included as a primitive by itself. The entire set of primitives related to map browsing also may be considered as enabling operators (Haklay and Zafiri, 2008), as described in **Section 2.4**. Although primarily an objective-based taxonomy, Yi et al. (2007) reserve a special primitive that includes *system interactions* such as undo and redo. Other ostensibly enabling operators include Shneiderman's (1996) primitives *extract* (save a sub-collection of items plus the querying parameters for future use outside of the application) and *history* (undo or redo an operation using the interaction history), which are both examples of an enabling interaction performed to clean up from past work.

In summary, extant operator-based taxonomies of interaction primitives exhibit the following characteristics:

- *Brushing* is the only primitive found in a majority of the reviewed objective-based taxonomies (Becker and Cleveland, 1987, Shepherd, 1995, Dykes, 1997, MacEachren et al., 1999, Masters and Edsall, 2000, Keim, 2002, Edsall et al., 2008), with *focusing* (Buja et al., 1996, Dix and Ellis, 1998, MacEachren et al., 1999, Masters and Edsall, 2000, Edsall et al., 2008) and *linking* (Buja et al., 1996, Dix and Ellis, 1998, Keim, 2002, Edsall et al., 2008) also found in many objective-based taxonomies (although not in a majority);

- The *brushing* primitive is at least a two-step action composed of a *selection* step and a subsequent manipulation step (e.g., *highlight*, *shadow highlight*, *delete*, *label*); scholars following Becker and Cleveland (1987) incorrectly emphasize only one or the other in their definition;

- The *focusing* primitive has been defined in three ways: (1) *focusing* as providing more detail (Buja et al., 1996, Edsall et al., 2008), (2) *focusing* as synonymous with *filtering* (MacEachren et

[30] Shneiderman's (1996) taxonomy is offered as a 'task taxonomy' (i.e., an objective-based taxonomy), but definitions for most of the primitives align more closely with other operator-based taxonomies

al., 1999, Masters and Edsall, 2000), and (3) *focusing* as the secondary action combined with *brushing* (Dix and Ellis, 1998);

- Most definitions of the *linking* primitive do not qualify it as an operator (e.g., Buja et al., 1996, Keim, 2002, Edsall et al., 2008), instead making it the third step constituting *brushing*;

- There is a large group of primitives that manipulate the symbolization included in a cartographic representation, including those for altering the map information that is symbolized (*assignment*, *dynamic projection*, *re-projecting*, *toggle visibility*), those for altering the type of cartographic representation that is displayed (*altering representation type*, *dynamic re-expression*, *encode data*, *same data-changing representation*), and those for altering the graphic parameters of the cartographic representation (*altering symbolization*, *colormap manipulation*, *same representation-changing parameters*, and *set-graphical-value*);

- There is a large group of primitives that manipulate the user's viewpoint to the cartographic representation, including *distortion*, *navigation*, *observer motion*, *object rotation*, *panning/re-center*, *re-projecting*, *viewpoint manipulation*, and *zooming*;

- Many of the primitives included in operator-based taxonomies represent enabling interactions.

As with objective-based taxonomies, there is a subset of purpose-driven operator-based taxonomies that are specific to Cartography. These taxonomies were developed for qualitative data analysis of ***interaction logs***, or a document listing every user interaction operator employed during an experiment or real-world interaction session, along with a timestamp. Cartographic interaction studies that construct a purpose-driven operator-based taxonomy for qualitative data analysis include MacEachren et al. (1998), Andrienko et al. (2002), Edsall (2003), and Robinson (2008a, 2008b); these studies are reviewed in **Section 6.3.1**, as they directly informed design of the reported interaction study.

3.5 Operand-Based Taxonomies

Finally, ***operand-based approaches*** compartmentalize interaction at the nexus of Norman's (1988) execution and evaluation, between the stages of Executing an Action (**Figure 3.1, #4**) and Perceiving the State of the System (**Figure 3.1, #5**). Here, the focus is on the operand, or the digital object with which the user is interacting. The user interface designer must ensure that proper feedback is provided to the user about how the operand has change as a result of the executed operator; as introduced in **Section 3.2**, the mismatch between the change to the operand affected by the interface operator and the change to the operand that the user sees in the display is referred to as the gulf of evaluation. **Table 3.3** summarizes extant operand-based taxonomies, which include: Haber and McNabb (1990), Wehrend (1993), Peuquet (1994), Chuah and Roth (1996), Shneiderman (1996), Chi and colleagues (1998, 2000), Crampton (2002), Keim (2002), Andrienko et al. (2003), Ward and Yang (2003), and Persson et al. (2006). The **Figure 3.4** concept map indicates the similarities and differences across operand-based taxonomies and the relative frequencies of each interaction primitive.

It is possible to segment the **Figure 3.4** concept map into two subsections that represent two very different avenues to identifying and articulating operand primitives: type-centric and state-centric. These sections are delineated by a horizontal dashed line through the middle of **Figure 3.4**. ***Type-centric*** operator-based taxonomies (**Figure 3.4: top**) discriminate primitives according to characteristics of the represented information. In contrast, ***state-centric*** operand-based taxonomies (**Figure 3.4: bottom**) emphasize the linear workflow from raw data through onscreen rendering, a sequence of computational transformations referred to as the ***information visualization pipeline*** (Card et al., 1999); operand primitives are discriminated according to the state in this pipeline at which the user is interacting. Both avenues are reviewed in the following.

Beginning with type-centric operand-based taxonomies located in the top half of **Figure 3.4**, Wehrend (1993) offers an early set of seven 'types of data' with which a user can interact. Data type primitives include: (1) *scalar* (a quantity specified by one number), (2) *nominal* (a property specified qualitatively), (3) *direction* (a position to which motion or another position is relative), (4) *shape* (the outline or surface of a feature), (5) *position* (the location of a point in space), (6), *spatially extended region or object* (the location of an area in space), and (7) *structure* (an arrangement of multiple objects into a single hierarchy or network). Although there is little overlap with this taxonomy and subsequent type-centric operand-based taxonomies, Wehrend did set a precedent in combining a type-centric operand-based taxonomy with an objective-based taxonomy (**Section 3.3**), producing a two-dimensional ***task-by-type taxonomy*** (i.e., objective-by-operand taxonomy) to prescribe the appropriate type of visual representation based upon the objective and operand context.

Author(s)	***Title***	***Operands***
Haber and McNabb (1990)	Data States	(1) data, (2) derived data, (3) visualization abstraction, (4) view
Wehrend (1993)	Types of Data	(1) scalar, (2) nominal, (3) direction, (4) shape, (5) position, (6) spatially extended region or object, (7) structure
Peuquet (1994)	TRIAD framework	(1) location, (2) time, (3) object
Chuah & Roth (1996)	Output State	(1) graphical, (2) data, (3) control
Shneiderman (1996)	Data Types	(1) one-dimensional, (2) two-dimensional, (3) three-dimensional, (4) temporal, (5) multi-dimensional, (6) tree, (7) network
Chi & Riedl (1998)	Data States	(1) data, (2) analytical abstraction, (3) visualization abstraction, (4) view
Chi (2000)	Data States	(1) data, (2) analytical abstraction, (3) visualization abstraction, (4) view
Crampton (2002)	Interactivity Types	(1) data, (2) representation, (3) temporal dimension, (4) contextualizing interaction
Keim (2002)	Data Types	(1) one-dimensional, (2) two-dimensional, (3) multi-dimensional, (4) text and hypertext, (5) hierarchies and graphs, (6) algorithms and software
Andrienko et al. (2003)	Components of Spatiotemporal Data	(1) space, (2) time, (3) objects
Ward & Yang (2003)	Interaction Operands and Spaces	(1) screen, (2) data, (3) data structure, (4) attribute, (5) object, (6) visualization structure
Persson et al. (2006)	Interaction Types	(1) representation, (2) algorithms for the creation of a representation, (3) database, (4) arranging simultaneous views, (5) dynamic linking, (6) temporal dimension, (7) three-dimensional, (8) system interaction

Table 3.3: Extant Operand-based Taxonomies of Interaction Primitives

Shneiderman (1996) and Keim (2002) each present a type-centric set of operand primitives as part of their own task-by-type taxonomies, with the pair of type-centric taxonomies exhibiting much overlap; there are no common data type primitives between the above Wehrend (1993) taxonomy and the Shneiderman and Keim taxonomies. Shneiderman lists seven 'data types': (1) *one-dimensional* (linear data, defined primarily as textual information rather than Wehrend's numerical *scalar*), (2) *two-dimensional* (geospatial information), (3) *three-dimensional* (defined as 'real world' objects, with the third dimension representing spatial position, not an attribute), (4) *temporal* (data collected over time, which differ from one-dimensional in that they have a start and end date and individual elements may overlap), (5) *multi-dimensional* (numerous attributes for each data element), (6) *tree* (a hierarchical variant of Wehrend's *structure*), and (7) *network* (an unordered variant of Wehrend's *structure*). Keim offers a similar listing of six 'data types', although there are several notable differences from Shneiderman: (1) *one-dimensional* (defined as data with a temporal dimension, matching Shneiderman's *temporal* rather than Shneiderman's

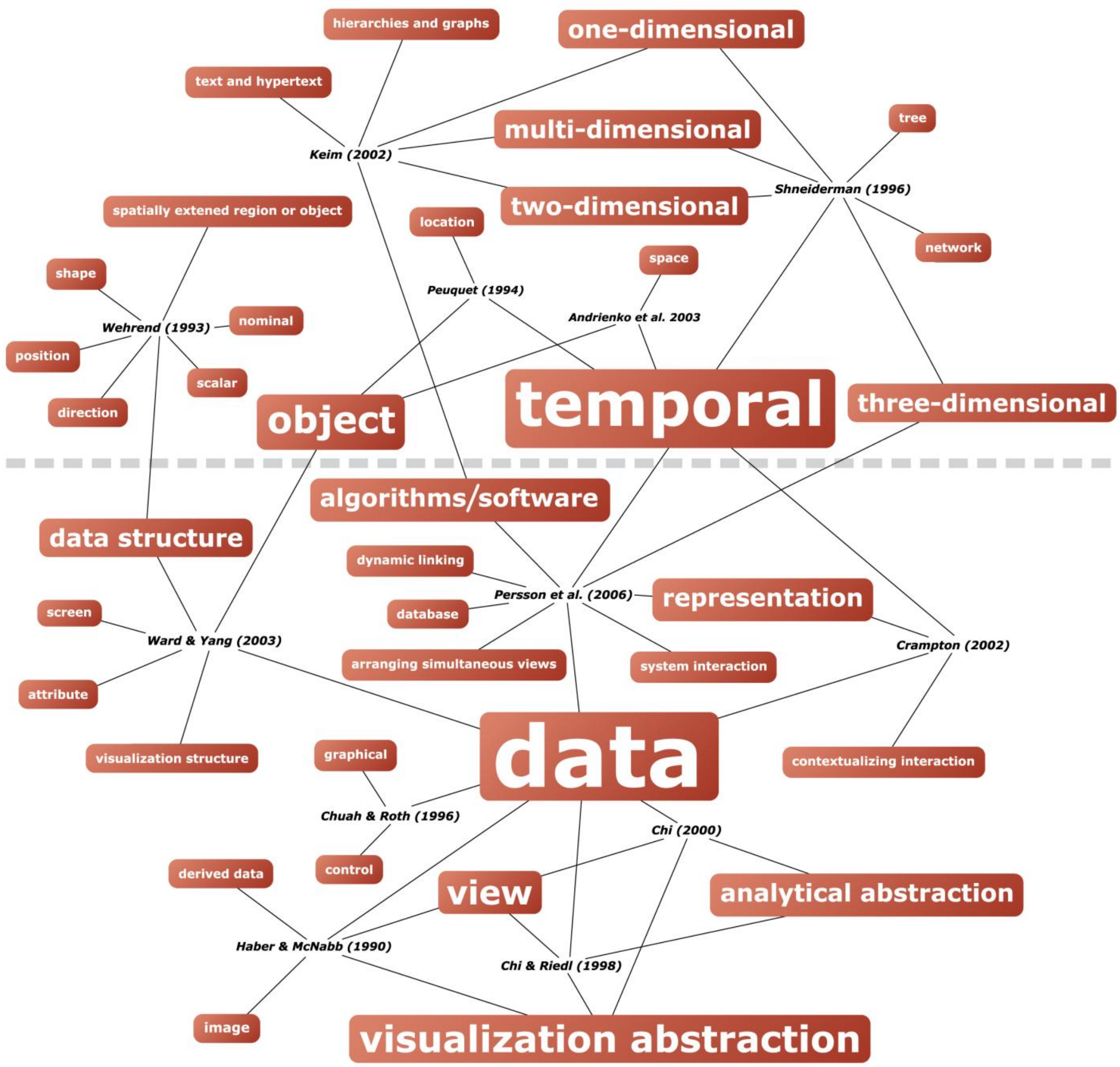


Figure 3.4: A Concept Map of Operand-based Primitives. The concept map shows the relationships among extant operand-based taxonomies and the relative frequency of the included interaction primitives. The operand -based concept map can be segmented into two subsections based on relations: **(top)** type-centric and (**bottom**) state-centric.

one-dimensional), (2) *two-dimensional* (as defined by Shneiderman), (3) *multi-dimensional* (as defined by Shneiderman), (4) *text and hypertext* (as defined as Sheiderman's *one-dimensional* primitive), (5) *hierarchies and graphs* (treating Shneiderman's *tree* and *network* types as a single primitive, equating to Wehrend's *structure*), and (6) *algorithms and software* (considered as Shneiderman's *one-dimensional* along with regular textual information). A key similarity in the Shneiderman (1996) and Keim (2002) type-centric operand-based taxonomies is that they both describe geographic information, and associated cartographic representations, using the primitive *two-dimensional*; Shneiderman reserves the primitive *three-dimensional* for geographic depictions such as virtual globes as well as non-geographic 3D representations. Thus, the data type primitive largely is fixed in the context of cartographic interaction, reducing the utility of a task-by-type, or objective-by-operand, taxonomy for Cartography.[31]

One type-centric operand distinction that remains influential in the context of Interactive Cartography and Geovisualization is provided by Andrienko et al. (2003: 510), who offer an ***operational task taxonomy*** to characterize the full suite of tasks that a user may need to complete with a spatiotemporal visualization tool (**Figure 3.5**). The Andrienko et al. operational task taxonomy includes three dimensions across which map use tasks vary: (1) ***cognitive operation*** (the visual analytic process applied to the representation), (2) ***search target*** (the component of the spatiotemporal information under investigation), and (3) ***search level*** (the percentage of all map features under consideration). The cognitive operation dimension is synonymous with the concept of an interaction objective; as summarized in **Section 3.3**, Andrienko et al. only include *identify* and *compare* as objective primitives. The search target dimension effectively is a simplification of the Shneiderman (1996) and Keim (2002) type-centric operand-based taxonomies that emphasizes the spatial and temporal components of information. Drawing on Peuquet's (1994) ***TRIAD*** framework for conceptualizing spatiotemporal information, Andrienko et al., identify three search targets: (1) *space* (the 'where', which is synonymous with the *two-dimensional* primitive described by Sheiderman and Keim), (2) *time* (the 'when', which is synonymous with the *temporal* primitive described by Shneiderman and the *one-dimensional* primitive described Keim), and (3) *objects* (the 'what' or 'who', which describes the attributes of the spatiotemporal phenomenon). The Andrienko et al. type-centric operand-based taxonomy is important for interactions that are explicitly cartographic, as the *space* primitive is kept under consideration at all times; the *space* primitive is either known *a priori*, acting as a constraint during interaction with the *time* and *object* operand primitives, or is the unknown operand primitive under investigation, with the *temporal* and/or *object* primitives acting as the constraints during interaction. The third dimension, the search level, simplifies Bertin's (1967|1983) concept of levels of map reading to include two primarily search levels: ***elementary*** (reading and interaction with only one map feature) versus ***general*** (reading and interaction with several to all map features) tasks; Bertin's intermediate level is removed from the Andrienko et al. framework to make the problem tractable, as they viewed its difference from the general level as conceptually minor. The Andrienko et al. operational task taxonomy is readdressed in **Section 5.3.2**, as it proved integral for interpreting the results of the objective card sorting study.

The bottom half of **Figure 3.4** spans state-centric operand-based taxonomies, which discriminate operand primitives according to the information visualization pipeline, or the transformations and rendering techniques applied to the data, rather than characteristics of this data itself. Haber and McNabb (1990) present an early visualization pipeline, described as the 'visualization process', that includes four state-centric primitives: (1) *data* (the raw data, particular to the output of simulations in the Haber and McNabb taxonomy), (2) *derived data* (usable abstractions of the raw data, or information), (3) *abstract visualization* (information that has been translated for representation), and (4) the displayable *image* (the representation itself). The user is able to interact with any of these four state primitives, as well as interactively request a transition between states through three operators: (1) *data enrichment/enhancement*

[31] Such task-by-type taxonomies remain important for map-centered coordinated, multi-view visualization, and of course Information Visualization generally.

(transition from data to derived data), (2) *visualization mapping* (transition from derived data to the abstract visualization), and (3) *rendering* (transformation from the abstract visualization to the view). The Haber and McNabb operand-based taxonomy illustrates the difference between type-centric and state-centric operand-based taxonomies: in the aforementioned type-centric taxonomies, primitives are defined as characteristics in the initial data, which then prescribe the proper representation form, whereas in the state-centric taxonomies, both the data and representation (and any abstraction in between) are primitives themselves, or points in the computational transformation from data to representation at which the user may interact.

Several subsequent scholars offer conceptual variants to the Haber and McNabb (1990) state-centric operand-based taxonomy. Chi and colleagues (1998, 2000) present a similar operand-based taxonomy, using slightly different terminology for the same four state-centric primitives: (1) *data*, (2) *analytical abstraction*, (3) *visualization abstraction*, and (4) *view*. Chuah and Roth (1996) simplify the Haber and McNabb pipeline into two state-centric primitives (*data state* and *graphical state*), but add a third *control state* primitive to include enabling interactions with the system, such as accessing permissions and undoing past interactions.

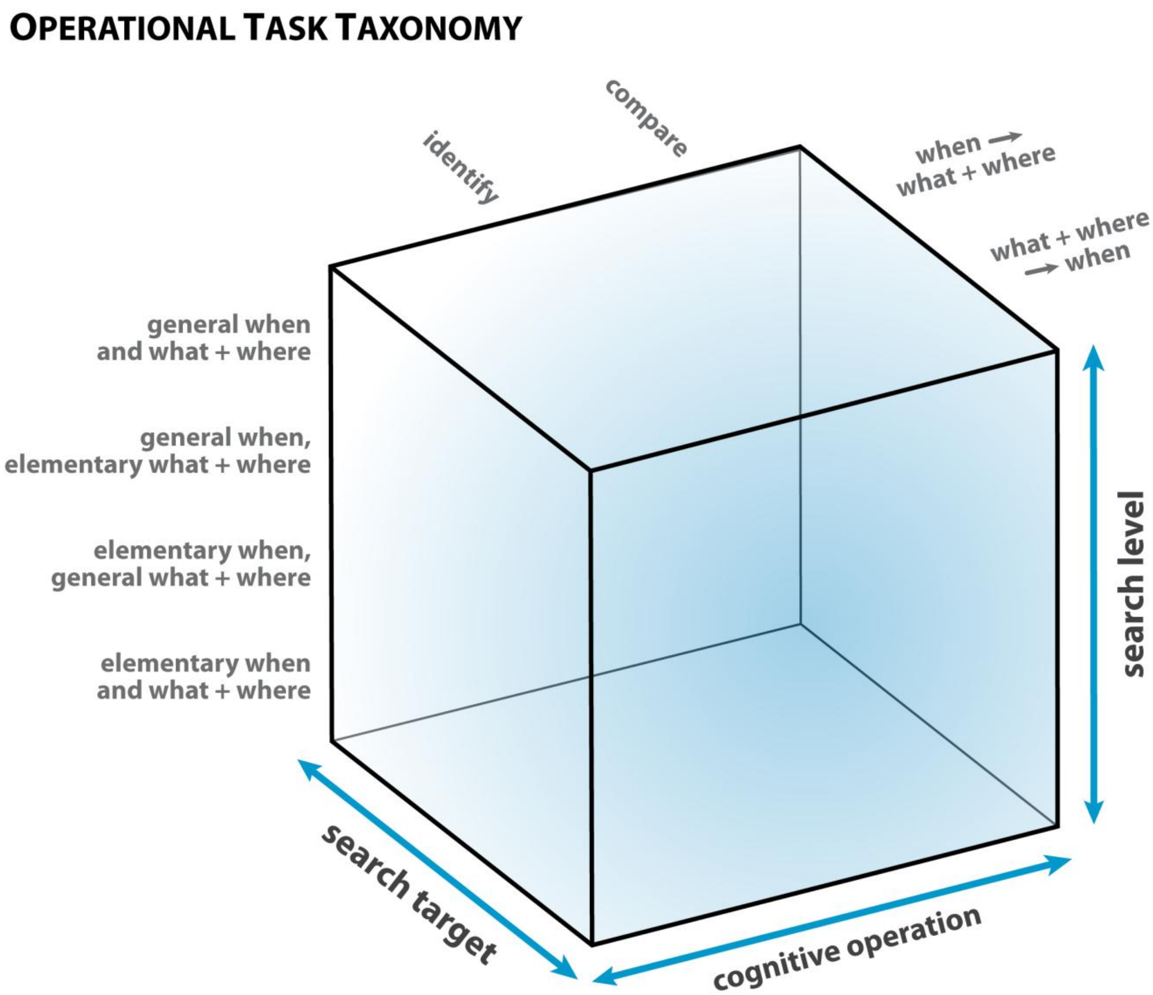


Figure 3.5: An Operational Task Typology for Spatiotemporal Visualization. Spatiotemporal visualization tasks vary according to three dimensions: (1) search target, (2) search level, and (3) cognitive operation (i.e., user objective). Image redrawn from Andrienko et al. (2003: 510).

Ward and Yang (2003) present a state-centric operand-based taxonomy of 'interaction spaces', defined as the conceptual object on which the interaction operator is applied. As with the state-based taxonomies described by Haber and McNabb (1990), Chuah and Roth (1996), and Chi and colleagues (1998, 2000), this taxonomy focuses primarily on the difference between data interaction and graphic interaction, although it includes several additional divisions within both. Interaction spaces include: (1) *screen-space* (interaction with screen pixels and not the data itself), (2) *data value-space* (interaction with multivariate data values), (3) *data structure-space* (interaction with components of data organization), (4) *attribute-space* (interaction with graphical widgets to adjust the visualization by attribute), (5) *object-space* (interaction on a 3D object onto which the visualization is projected), and (6) *visualization structure-space* (interaction on the labels and axes of the visualization). Ward and Yang pair these interaction spaces with three interaction operators (navigation, selection, or distortion), producing a state-based operator-by-operand taxonomy.

One interpretation of the state-centric perspective is an overall emphasis on the technological challenges in moving from the stage of Executing an Action (**Figure 3.1, #4**) to the stage of Perceiving the State of the System (**Figure 3.1, #5**), in contrast to the type-centric perspective that instead emphasizes characteristics of the operand itself; this difference is analogous to the difference between the technology-centered (**Figure 2.1: middle**) and interface-centered perspectives (**Figure 2.1: right**) on cartographic interaction. As discussed in **Section 2.5**, the technology-centered view—while essential for implementing a useful and usable interactive map[32]—is less appropriate as a subject of scientific inquiry for the scientific discipline of Cartography. It is for this reason that state-centric operands are not investigated in the **Chapter 5** card sorting studies.

In summary, extant operator-based taxonomies of interaction primitives exhibit the following characteristics:

- There are two avenues for identifying and articulating operand primitives: type-centric (Wehrend, 1993, Peuquet, 1994, Shneiderman, 1996, Keim, 2002, Andrienko et al., 2003) and state-centric (Haber and McNabb, 1990, Chuah and Roth, 1996, Chi and Riedl, 1998, Chi, 2000, Ward and Yang, 2003).

- Type-centric operand-based taxonomies often are paired with objective-based taxonomies to construct a task-by-type (objective-by-operand) taxonomy (Wehrend, 1993, Shneiderman, 1996, Keim, 2002); Ward and Yang (2003) provide the only example of a state-centric task-by-type taxonomy.

- The type-centric taxonomies offered by Shneiderman (1996) and Keim (2002) place geographic information under the *two-dimensional* primitive, which in turn limits the utility of these taxonomies for understanding interactions that are explicitly cartographic (although they remain useful in the context of coordinated, multi-view visualization).

- Andrienko et al. (2003) present a useful operational task typology that includes three dimensions: (1) cognitive operation (the visual analytic process applied to the representation, or the operator), (2) search target (the component of the spatiotemporal information under investigation), and (3) search level (the percentage of all map features under consideration).

- State-centric operand-based taxonomies are based on the visualization pipeline (Card et al., 1999) and separate interactions with the raw data from interactions with the representation or view.

[32]To achieve optimal map performance, designers and developers commonly grapple with the proper balance between user interaction with the raw data on the server-side and user interaction with a captured abstraction of the data on the client-side. This is particularly important in the context of Visual Analytics, as user interactions need to be scaled to underlying datasets that are voluminous and multivariate as well as graphical representations that are complex and multiscale..

Aside from the Andrienko et al. (2003) type-centric operand-based taxonomy, the previously reviewed set of operand-based taxonomies are derived from sources outside of the Cartography. Interestingly, two additional operand-based taxonomies within the cartographic literature blend type-based and state-based approaches; each is marked in the following. Crampton (2002) describes four broad-level 'interactivity types': (1) *interaction with the data* (state primitive), (2) *interaction with the data representation* (state primitive), (3) *interaction with the temporal dimension* (type primitive), and (4) *contextualizing interaction* (similar to the control state included in Chuah and Roth, 1996). In contrast, Persson et al. (2006) describe eight broad-level 'interaction types': (1) *interaction with the representation model* (state primitive), (2) *interaction with the algorithms for the creation of a representation* (state primitive), (3) *interaction with the primary model/database query* (state primitive), (4) *arranging many simultaneous views* (included under the control state in Chuah and Roth, 1996), (5) *dynamic linking with further display types* (this appears to be more of an operator distinction than an operand distinction), (6) *interaction with the temporal dimension* (type primitive), (7) *interaction with the 3D visualization* (type primitive), and (8) *system interaction* (similar to the control state in Chuah and Roth, 1996).

3.6 Conclusion: Cartographic Interaction Primitives

This chapter summarized existing work on the *how?* question of cartographic interaction, identifying the basic cartographic interaction primitives that then can be combined into interaction strategies. Establishing a taxonomy of interaction primitives is essential for unitizing and evaluating competing interaction strategies, which in turn may lead to identification and promotion of prototypically successful strategies for performing cartographic interaction. Most extant taxonomies of interaction primitives are offered at one of three stages of interaction (**Figure 3.1**), with the majority of **Chapter 3** reserved to review these three approaches (objective-based, operator-based, and operand-based). The reviews completed in **Chapter 2** and **Chapter 3** are used as the input for the coding scheme applied for the qualitative data analysis of the semi-structured interviews reported in **Chapter 4**; using a coding scheme based on secondary sources allows for the explicit comparison of cartographic interaction theory to cartographic interaction practice, an important component of the first research goal of the dissertation (**Section 1.5.1**). Further, interaction primitives identified in the **Section 3.3** (objective-based taxonomies) and **Section 3.4** (operator-based taxonomies) reviews are combined with comments elicited in the **Chapter 4** interviews to generate the universe of interaction primitives included in the **Chapter 5** card sorting exercises, ensuring that the interaction primitive taxonomy established to achieve the second research goal of the dissertation (**Section 1.5.2**) is influenced by both theory and practice.

Chapter Four: Cartographic Interaction Interviews
Bridging the Current States of Science and Practice

Overview:

This chapter reports on a set of semi-structured interviews investigating the current use of interactive maps and map-based systems, together described as cartographic interfaces, that supply cartographic interaction. The chapter begins by identifying the dual goals of the cartographic interaction interviews (**Section 4.1**). First, the interviews reveal the current state of practice regarding cartographic interaction, which then can be compared to the current state of science summarized in **Chapter 2** and **Chapter 3**. Second, the combined reviews of science and practice generate the complete universe of objective and operator primitives used in the **Chapter 5** card sorting studies, allowing for construction of an empirically derived interaction primitive taxonomy. Following this introduction, the parameters of the interview study are reviewed (**Section 4.2**). Twenty-one participants were recruited to participate in a set of semi-structured interviews, with each participant exhibiting expertise in one of seven application domains selected to represent the gamut of cartographic interaction contexts: Emergency Response & Crisis Management, Environmental Science & Human-Environment Geography, Epidemiology & Public Health, Intelligence Analysis, History & Historical Geography, News & New Media, and Resource Management. The interviews were transcribed and codified according to a 14-part coding scheme based on the six fundamental questions of a science of cartographic interaction (**Table 2.1**). The results then are summarized according to these six categories using a synoptic style of reporting (**Section 4.3**). The chapter closes with a concluding summary on the gap between the science and practice of cartographic interaction (**Section 4.4**)

4.1 An Empirical Approach to Examining Cartographic Interaction Practice

Chapter 2 and **Chapter 3** synthesize extant scholarship on digital interaction, focusing on interactions that are explicitly cartographic in nature when possible. This summary of secondary sources is organized around six fundamental questions that define the context of cartographic interaction: (1) *what?*, (2) *why?*, (3) *when?*, (4) *who?*, (5) *where?*, and (6) *how?* (**Table 2.1**). Care is taken in this review not only to summarize what we currently know about cartographic interaction, but also to identify important issues and themes about which we do not yet know. This chapter complements the **Chapter 2** and **Chapter 3** reviews of secondary sources with an empirical investigation of the contemporary use of interactive maps and map-based systems, together described as ***cartographic interfaces***, that afford cartographic interaction.

Such an empirical investigation of the current application of cartographic interaction is integral to the development of a science of cartographic interaction in at least two ways. First, it allows for a direct comparison of cartographic interaction *science* to cartographic interaction *practice*. As introduced in **Section 1.5.1**, it is conventional wisdom that science outpaces practice, with important discoveries from science taking time to transition to general practice. This no longer may be the case in Cartography given the extremely dynamic nature of computing technology—and Twenty-First Century Cartography's reliance upon it—as many-to-most substantive advances in cartographic interaction today occur outside of science, with science often struggling to keep pace. Once a gap is identified, it may be bridged to improve positively both the science and practice of cartographic interaction. Investigation of the current state of cartographic interaction practice, and a direct comparison to the current state of cartographic interaction science, is the focus of this chapter and achieves the first research goal of the dissertation (**Section 1.5.1**). Second, the combined review of cartographic interaction science and practice presents the complete universe of cartographic interaction primitives, which is needed to construct an interaction primitive taxonomy of basic cartographic interactions. **Chapter 5** reports on a set of card sorting studies that combine instances of objective and operator primitives from both secondary sources (the state of science) and empirical investigation (the state of practice) in order to construct an initial version of the interaction primitive taxonomy, achieving the second research goal of the dissertation (**Section 1.5.2**).

A set of semi-structured interviews was conducted to investigate the current application and use of interactive maps and map-based systems affording cartographic interaction. A total of 21 professionals and scholars across seven application domains were recruited to discuss how their daily work is supported by cartographic interaction. Interview questioning and reporting is organized according to the six fundamental questions introduced in **Chapter 2** and **Chapter 3**. Descriptions of the interview method, the applied qualitative data analysis, and the interview results are presented in the remainder of the chapter.

4.2 Method: Cartographic Interaction Interviews

4.2.1 Review of Ethnographic Methods

Ethnographic research describes the empirical investigation of the qualities, practices, and beliefs of a community of interest (Schienke, 2003). The product of such research is an ***ethnography***, or a narrative of the community under investigation; ethnographies typically are written descriptions, but can be primarily graphic, or even cartographic (e.g., Pearce and Hermann, 2010, Hermann and Pearce, 2011). For the ethnographic study reported here, the target community is any user of cartographic interaction, or those individuals that employ cartographic interfaces to complete their daily work. The focus on map users rather than mapmakers is consistent with a user-centered approach introduced in **Figure 2.1** and affords the opportunity to capture instances of interaction primitives from a variety of application domains, which in turn provides a more complete picture of the current state of cartographic interaction practice and ultimately a more generalizable interaction primitive taxonomy.

One of the primary methods in ethnographic research is ***participant observation*** method (Suchan and Brewer, 2000). In participant or field observation, the researchers watch the participants in their natural environment as they complete their daily work tasks. The aforementioned requirement of recruiting participants from a large number of domains makes administration of participant observation prohibitively time-consuming for this research, as this method requires a significant time investment in the field (Shneiderman and Plaisant, 2006). Further, use of cartographic interfaces commonly constitute only a small portion of an individual's daily responsibilities, leading to observation of a large amount of unrelated work activity.

Alternative knowledge elicitation techniques that may be employed to generate insights on community practice include surveys, interviews, and focus groups. ***Surveys***, sometimes referred to as questionnaires, require participants to fill out a document containing predetermined, typically structured questions (Adams and Cox, 2008). The survey methodology is conducive to web-based circulation, an advantage when recruiting participants from a variety of domains that may be geographically dispersed (see **Section 5.2.3**). However, the structured nature of the questions requires significant *a priori* knowledge about the studied community, which limits the utility of such an approach for formative ethnographic research (Valentine, 1997).

A final pair of methods used in ethnographic research are interviews and focus groups. Interviews and focus groups both rely upon an interviewer or moderator to ask discussion questions and follow-up probes. The primary distinction between these two methods is that ***interviews*** are conducted in a 1-on-1 format (one interviewer, one participant) while ***focus groups*** are conducted in a 1-to-many format (one moderator, 5-8 participants) (Morgan, 1998, Twohig and Putnam, 2002). Sampling from a large number of domains makes the arrangement of focus groups impractical, as experts across domains are unlikely to be geographically proximate (although distributed methods may achieve similar results) and to have enough knowledge of each others' area of expertise to support active and even discussion (Cameron, 2005). The interview method, on the other hand, allows for in-depth and uninterrupted discussion within each identified application domain and can be administered consistently across geographic locations, both advantages for understanding of current cartographic interaction practice. The interview method therefore is the most appropriate approach for reviewing the current state of cartographic interaction practice and for generating instances of cartographic interaction primitives; parameters of the interviews are outlined in the following subsections.

4.2.2 Participants

Twenty-one participants were sampled purposively to ensure that they were representative of the target community: cartographic interaction users. ***Purposive sampling*** describes the selection of participants based on their fitness to a small set of predefined criteria associated with the research topic (Patton, 1990). Criteria for participation included regular use of cartographic interfaces as part of their work responsibilities, expertise in one of the identified application domains, and 18 years of age or older; additional experience designing and developing interactive mapping applications was considered a plus given the expected added depth of knowledge regarding cartographic interaction, but was not required for participation given the focus on cartographic interaction users. Participants were recruited from one of seven identified application domains: (1) Emergency Response & Crisis Management, (2) Environmental Science & Human-Environment Geography, (3) Epidemiology & Public Health, (4) History & Historical Geography, (5) Intelligence Analysis, (6) News & New Media, and (7) Resource Management. Between two and four participants were interviewed from each of the seven domains (**Table 4.1**). These domains were chosen to capture map use across a breadth of cartographic interaction qualities, including the use of discrete versus continuous data, the use of homogenous versus heterogeneous data sources, the mapping of individual incidents versus spatial aggregates, reliance upon primarily 2D versus 3D interactive mapping environments, and the use of reference versus thematic interactive maps; **Table 4.2** summarizes the participant balance across these five cartographic interaction qualities. Potential participants were identified through previously developed Penn State GeoVISTA Center contacts in each of the seven application domains, with these contacts then acting as ***gatekeepers***, or individuals external to the research team that aid in recruitment (Valentine, 1997).

A background survey was administered at the start of each interview session to establish several characteristics of the interview participants. All participants (21 of 21) had earned at least one Bachelor's degree and the majority (17 of 21) of participants had earned a graduate degree; five participants had earned an MD or PhD. Given recruitment across domains, the degree programs themselves varied greatly. The majority (16 of 21) of participants reported using geographic information every day, with no participant directly using geographic information less regularly than monthly (**Table 4.3**). The regularity in use of static maps and interactive maps was more varied across participants, an indication that cartographic products typically constitute only a subset of work activities. The majority (18 of 21) of participants reported using both static maps and interactive maps at least monthly, with 16 participants using interactive maps at least weekly. The three participants that rarely use interactive maps indicated that they did use interactive maps more regularly in past positions, but now manage individuals that use interactive maps rather than use such tools themselves; these individuals therefore were qualified to participate in the interview study.

Application Domain	*#*
Emergency Response & Crisis Management	4
Environmental Science & Human-Environment Geography	2
Epidemiology & Public Health	4
History & Historical Geography	2
Intelligence Analysis	3
News & New Media	3
Resource Management	3
Total	**21**

Table 4.1: Cartographic Interaction Interview Participants by Application Domain

Interactive Mapping Quality	*former only*	*latter only*	*both*
Discrete versus ***Continuous*** Data	10	3	8
Homogenous versus ***Heterogeneous*** Data Sources	9	7	5
Individual Incidents versus ***Spatial Aggregates***	10	3	8
2D versus ***3D*** Interactive Mapping Environments	12	3	6
Reference versus ***Thematic*** Interactive Maps	10	5	6

Table 4.2: Participant Balance across Cartographic Interaction Qualities. The 'formerly only' column describes the number of participants indicating only the first condition in the 'versus' binary while the 'latter only' column indicates the number of participants indicating only the second condition in the 'versus' binary; the 'both' column describes participants that stated their work falls along both conditions in the binary.

Regularity of Use	*Geog. Info.*	*Static Maps*	*Interactive Maps*
Daily	16	9	7
Weekly	3	3	9
Monthly	2	6	2
Yearly	0	0	0
Rarely	0	3	3
Total	**21**	**21**	**21**

Table 4.3: Regularity of Using Geographic Information, Static Maps, and Interactive Maps.

4.2.3 Materials and Procedure

Interviews vary on the degree of structure in their questions (Robinson, 2009). ***Structured interviews*** include a series of focused questions that prompt short and equally focused responses; all participants are asked the exact same set of questions in the same order, making a structured interview much like an in-person survey. On the other end of the continuum, ***unstructured interviews*** include a set of broad discussion topics or general themes, with no preset order; these types of questions are exploratory in nature and prompt longer, open-ended responses that vary greatly from person to person. ***Semi-structured interviews*** fall in the middle of these extremes, starting with a set of focused questions while allowing the interviewer to ask follow-up or ***probe*** questions and to change the order of questioning if appropriate. The semi-structured variant was selected for consistency across the six fundamental questions of a science of cartographic interaction (**Table 2.1**), while providing the flexibility to probe participants about topics on which they are particularly knowledgeable. Interview questions were informed directly by the background reviews reported in **Chapter 2** and **Chapter 3** for comparison of the states of cartographic interaction science and practice, although an emphasis was placed on the *how?* question given the secondary goal of establishing an interaction primitive taxonomy. The set of interview questions and probes is available in **Appendix A**.

Following completion of the structured background survey (results reported in **Section 4.2.2**), questioning proceeded in three sections, with each section aimed at digging deeper into the participant's use of cartographic interfaces. In the first section of the interview, participants were asked to describe their daily work tasks and characteristics of the geographic information they collect and analyze to support these tasks. No explicit reference was made at this point to interactive mapping and cartographic interaction in order to allow users to discuss work that currently may not be supported by cartographic interaction, but possibly could be; once participants were prompted to think about cartographic interfaces, their ideas generally were constrained by their current or past mapping capabilities. This section also allowed participants to offer examples of objective and operator primitives without direct prompting, indicating prototypical instances of these primitives.

Questioning narrowed in the second section of the interview to address interactive maps and map-based systems (i.e., cartographic interfaces) directly. Prior to each interview session, a request was sent to the participants to forward a list of interactive mapping tools that met one of three conditions: (1) interactive maps or map-based systems currently integrated into their workflows, (2) interactive maps or map-based systems they would like to use, but currently do not, and (3) interactive maps or map-based systems that they have used in the past, but abandoned. Such collection of participant map examples prior to the interviews had proved useful for advancing and supplementing discussion in a past ethnographic study examining primarily static mapping practices (Robinson et al., 2010, Robinson et al., 2011). **Table 4.4** lists all tools identified by multiple participants; tools listed only once are not included in the table to avoid potential identification of the participant. The Esri ArcGIS system (primarily ArcMap) and the two Google mapping products were the only tools providing cartographic interaction that were identified by a majority or large minority of participants, making them the central digital map prototypes if broad adoption is used as one of the motivating characteristics (**Figure 1.2b**). Many of the other tools identified were one-off interactive maps generated for a single project or custom map-based systems that support a single work task. During the second section of the interviews, participants were asked to demonstrate each of the tools, to describe how each tool supports, could support, or did support their work, and to recall any ***critical incidents*** with tools that influenced their task performance and overall user satisfaction (Gabbard et al., 1999).

Interactive Map or Map-based System	***#***
Esri ArcGIS	15
Google Maps	13
Google Earth	9
GeoCommons	2
Remote Access (Group 1 Solutions)	2
SAS (Statistical Analysis System)	2
The National Map (USGS)	2
***45 other tools listed once**	

Table 4.4: Interactive Maps or Map-based Systems Demonstrated during the Interviews

In the final interview section, participants were asked directly about the six fundamental questions of a science of cartographic interaction. Importantly, participants explicitly were asked to identify the general objectives, and the operators supporting these objectives, that span their daily work responsibilities. This debriefing period also afforded participants the opportunity to provide any additional thoughts or final remarks regarding cartographic interaction that had yet to be discussed. The interview was designed to last approximately 60 minutes; most interviews took approximately 75 minutes and no interview lasted longer than 90 minutes.

4.2.4 Qualitative Data Analysis

All interviews were completed at the participant's work location in a private room and audio recorded for subsequent qualitative data analysis. ***Qualitative data analysis*** (QDA) describes the systematic interpretation of qualitative information, such as text reports, websites, photos, maps, and field observations (Dey, 1993, Miles and Huberman, 1994). In the most robust form of QDA, the documents in the set are decomposed to their smallest unit of analysis and a series of codes are applied to the units by several independent coders, with the coding then compared across coders to ensure reliability in interpretation of the document set and applied coding scheme (Haug et al., 2001).

Transcription of the interview recordings was completed using the Transana QDA software and then unitized at the statement level in Microsoft Excel for completion of ***margin coding***, or the marking of any units that are representative of one or several established codes (Bertrand et al., 1992). The background reviews in **Chapter 2** and **Chapter 3** were used to develop a 14-part coding scheme with six higher level categories relating to each of the six fundamental questions of a science of cartographic interaction; **Table 4.5** provides definitions of each of the 14 codes and the six higher level categories. Margin coding was completed by the principal investigator on all 21 transcripts using the 14-part coding scheme; **Table 4.6** lists the frequency of codes across the 21 transcripts. A total of 2,968 codes were applied to the 21 transcripts, an average of 141.3 codes per transcript.

Two coders with training in Interactive Cartography and Geovisualization were hired to apply independently the same 14-part coding scheme used in the initial coding, with code reliability assessed using the inter-rater reliability score described by Robinson (2008a). A condensed version of the **Chapter 2** and **Chapter 3** background summaries were given to the independent coders as training notes on each of the codes; review of these notes was followed by a 60-minute training session prior to coding. The two coders achieved inter-coder reliability scores of 90.7% and 90.2%, indicating a high degree of reliability in the interpretation and application of the coding scheme, particularly considering the large total number of codes applied across the 21 transcripts. Upon completion of coding, statements were sorted into a set of spreadsheets by code and summarized using the synoptic style reporting described by Monmonier and Gluck (1994) and Roth (2009b). The following section provides a summary of the interview results, organizing discussion by higher level code category, or the fundamental question of a science of cartographic interaction. Only those responses regarding the first five questions are summarized in this chapter (i.e., the five *W's*); the descriptions of statements concerning interaction objectives (how1) and interaction operators (how2) are reported when describing the interaction primitive taxonomy constructed in **Chapter 5**, while statements regarding interaction operands (how3) were used to construct **Table 4.2**.

4.3 Results and Discussion

4.3.1 What?

Codes included in the *what?* category identify statements about the meaning of cartographic interaction and the scope that it covers. As introduced in **Section 2.2**, the *what?* question is concerned with delineating what constitutes cartographic interaction and what does not. Two codes are included under the *what?* category, the first indicating a characteristic or example of cartographic interaction (what1) and the second indicating a characteristic or example that is not cartographic interaction (what2). Overall, participants described what cartographic interaction is (average of 10.3 statements per participant) more often than what it is not (average=4.6).

When asked to provide a general definition of cartographic interaction, many participants emphasized its ability to "manipulate" a cartographic representation, a definition of interaction common to the disciplines of Exploratory Data Analysis (Buja et al., 1996) and Information Visualization (Yi et al., 2007). One participant stated that "cartographic interaction is the ability to change [the map]" while a second participant defined cartographic interaction as the ability "to manipulate the map...not permanently, but temporarily to meet your needs." No participant explicitly described cartographic interaction as a conversation or a dialogue between a user and an interface, as presented in Norman's (1988) stages of action model. Instead, the more specific definitions of cartographic interaction were offered at the interaction operator level, or the Specifying the Action stage (**Figure 3.1, #3**), perhaps indicating a conflation of cartographic interactions with cartographic interfaces. Such definitions included "turn on and off layers," "filter down to specify information you want," "zoom in and zoom out," "view data in different ways," and "calculate something from the map." Several participants did acknowledge the importance of the interaction objective (i.e., the task or question) in the cartographic interaction, with one participant stating that cartographic interaction allows users "to ask a relevant question for themselves" and a second participant defining cartographic interaction "as a tool that answers questions before you ask them." Interestingly, all participants defined cartographic interaction within the context of a digital environment and computing technology, even when prompted to consider if interactions with paper maps should be included in the discussion on cartographic interaction. This finding provides justification for including in the definition of cartographic interaction the computing device (i.e., the technology) as a necessary mediator between the human and map (**Figure 2.1**).

ID	*Name*	*Definition*
What: ***Statements indicating the meaning of cartographic interaction and the scope it covers***		
what1	Cartographic Interaction	a characteristic(s) or example of cartographic interaction and interactive maps
what2	Not Cartographic Interaction	a characteristic(s) or example of a non-interactive map, defining cartographic interaction by what it is not
Why: ***Statements indicating the purpose of cartographic interaction and the value it provides***		
why1	Exploration	the use of cartographic interaction to support exploration
why2	Analysis	the use of cartographic interaction to support analysis
why3	Synthesis	the use of cartographic interaction to support synthesis
why4	Presentation	the use of cartographic interaction to support presentation
When: ***Statements indicating the appropriate level of cartographic interaction***		
when1	Interaction Freedom	the need to increase the amount and freedom of the cartographic interaction provided
when2	Interaction Constraint	the need to constrain the amount and freedom of the cartographic interaction provided
Who: ***Statements indicating the impact of the user on cartographic interaction***		
who1	Ability	the impact of user ability (i.e., perception, cognition, and motor skills) on cartographic interaction
who2	Expertise	the impact of user expertise (i.e., education, experience, and familiarity) on cartographic interaction
who3	Motivation	the impact of user motivation (i.e., interest and need) on cartographic interaction
Where: ***Statements indicating the impact of technology on the cartographic interaction***		
where1	Input Devices	the impact of the available input devices on cartographic interaction
where2	Bandwidth & Processing	the impact of bandwidth size and processing power on cartographic interaction
where3	Display Devices	the impact of the display capabilities on cartographic interaction
How: ***Statements indicating the fundamental types of cartographic interaction***		
how1	Objectives	the task that a user needs to complete using the cartographic interaction
how2	Operators	the forms of cartographic interaction provided through the interactive map
how3	Operands	the recipient of the cartographic interaction

Table 4.5: Coding Scheme Applied for QDA of the Cartographic Interaction Interviews

ID	EMG (4)		ENV (2)		EPI (4)		HIS (2)		INT (3)		NEW (3)		RES (3)		ALL	
	sum	avg	sum	avg	sum	avg	sum	avg	sum	avg	sum	avg	sum	avg	sum	avg
What1	20	5	21	10.5	54	13.5	19	9.5	47	15.7	40	13.3	15	5	216	10.3
What2	12	3	4	2	23	5.8	6	3	17	5.7	29	9.7	6	2	97	4.6
What	**32**	**8**	**25**	**12.5**	**77**	**19.3**	**25**	**12.5**	**64**	**21.3**	**69**	**23**	**21**	**7**	**313**	**14.9**
Why1	5	1.3	5	2.5	17	4.3	12	6	7	2.3	28	9.3	13	4.3	87	4.1
Why2	26	6.5	13	6.5	60	15	15	7.5	30	10	12	4	33	11	189	9
Why3	6	1.5	1	0.5	6	1.5	4	2	9	3	5	1.7	8	2.7	39	1.9
Why4	35	8.8	20	10	23	5.8	5	2.5	23	7.7	54	18	48	16	208	9.9
Why	**72**	**18**	**39**	**19.5**	**106**	**26.5**	**36**	**18**	**69**	**23**	**99**	**33**	**102**	**34**	**523**	**24.9**
When1	19	4.8	19	9.5	29	7.3	13	6.5	25	8.3	33	11	33	11	171	8.1
When2	10	2.5	12	6	12	3	1	0.5	12	4	26	8.7	18	6.0	91	4.3
When	**29**	**7.3**	**31**	**15.5**	**41**	**10.3**	**14**	**7**	**37**	**12.3**	**59**	**19.7**	**51**	**17**	**262**	**12.5**
Who1	1	0.3	0	0	0	0	1	0.5	1	0.3	9	3	0	0	12	0.6
Who2	15	3.8	11	5.5	20	5	8	4	27	9	40	13.3	34	11.3	155	7.4
Who3	1	0.3	1	0.5	1	0.3	0	0	0	0	30	10	7	2.3	40	1.9
Who	**17**	**4.3**	**12**	**6**	**21**	**5.3**	**9**	**4.5**	**28**	**9.3**	**79**	**26.3**	**41**	**13.7**	**207**	**9.9**
Where1	7	1.8	1	0.5	0	0	1	0.5	1	0.3	6	2	0	0	16	0.8
Where2	13	3.3	0	0	7	1.8	3	1.5	14	4.7	6	2	11	3.7	54	2.6
Where3	9	2.3	0	0	0	0	1	0.5	4	1.3	2	0.7	2	0.7	18	0.9
Where	**29**	**7.3**	**1**	**0.5**	**7**	**1.8**	**5**	**2.5**	**19**	**6.3**	**14**	**4.7**	**13**	**4.3**	**88**	**4.2**
How1	86	21.5	37	18.5	144	36	43	21.5	55	18.3	68	22.7	112	37.3	545	26
How2	98	24.5	96	48	91	22.8	42	21	125	41.7	166	55.3	205	68.3	823	39.2
How3	25	6.3	15	7.5	43	10.8	20	10	39	13	34	11.3	31	10.3	207	9.9
How	**209**	**52.3**	**148**	**74**	**278**	**69.5**	**105**	**52.5**	**219**	**73**	**268**	**89.3**	**348**	**116**	**1575**	**75**
Total	**388**	**97**	**256**	**128**	**530**	**132.5**	**194**	**97**	**436**	**145.3**	**588**	**196**	**576**	**192**	**2968**	**141.3**

Table 4.6: Frequency of Codes Applied for QDA of the Cartographic Interaction Interviews

One topic regarding the *what?* identified in **Section 2.2** for follow-up investigation is the immediacy of the cartographic interaction, or the timeframe available for a map to respond to the user input for it to be considered 'interactive.' Recommendations from HCI indicate that the system should respond within one or two seconds of the user input (Wardlaw, 2010), although GIScientists note that such immediacy is uncommon to cartographic interaction given the volume of the underlying geographic information (Haklay and Li, 2010). A subset of participants did indicate that immediacy of system response matters, stating that an interactive map requires "instant modification" or that interactions should result in "immediate changes on the fly." One participant bounded the time for completing the cartographic interaction, stating that "a good interactive map would only take seconds" to update the display. Although there was general agreement that "the more time it takes between map updates, the less interactive it becomes," most participants did not believe that there is a hard constraint on system response time in order to consider the map as 'interactive'. One participant identified the USGS National Map as an example of an interactive web map that rarely responds within the two second timeframe due to the large data volume included in the system, stating that "sometimes you ask it to do something and it takes a minute or two, but that's still an interactive map to me." A second participant stated that it is still a cartographic interaction even if the system takes a month or year to respond, but that it is just "a less satisfying interaction," potentially indicating that response time is a key component of subjective user satisfaction. It is important to note that interaction time was discussed not just in terms of the immediacy of the system response, but also in the speed it takes for users to achieve their objectives. As one participant stated, the benefit of cartographic interaction "is coming to a decision point faster" and went on to say that "you can do [a task] faster if you aren't doing it with your eyes, visually inspecting the map." Thus, the utility of cartographic interaction may be a reduced reliance on the cartographic representation itself, a somewhat unexpected conclusion given that maps work because they leverage the eye's broad bandwidth to the mind, but one that matches arguments for overcoming the one-map solution (Monmonier, 1991).

A second open question posed in **Section 2.2** addresses the difference between an interactive map-based system and the unique map views these systems allow users to create (described together as the more general 'cartographic interfaces'). Specifically, do users view these map-based systems as interactive maps? Participants were split with regard to the inclusion of map-based systems as interactive maps. This was most evident in discussion concerning the three commonly identified map-based systems listed in **Table 4.4**: Esri ArcGIS, Google Maps, and Google Earth. The desktop GIS suite provided by Esri, particularly the ArcMap application, supported the work of 15 of the 21 participants interviewed. While all participants agreed that ArcMap provides cartographic interaction, many participants also categorized ArcMap (i.e., one example of a map-based system) as an interactive map when explicitly questioned. However, several participants were clear to make a distinction between ArcMap itself and the cartographic products created using the system. One participant stated "it is certainly interactive...but not in the spirit of interactive maps" while a second participant stated "the product you produce [with ArcMap] is an interactive map," but indicated that ArcMap is not an interactive map itself. This lack of consensus supports inclusion of ArcMap as a peripheral example in the **Figure 1.2b** radial categorization of a digital map.

There was similar disagreement over the two products from Google, despite these products having a consistent multiscale basemap design and therefore more closely resembling a prototypical digital map (**Figure 1.2b**). Google Maps supported the work of 13 of 21 participants, while Google Earth supported the work of 9 of 21 participants. Proponents of Google Maps and Google Earth as interactive maps noted that "you can always enter something [into Google Maps and Google Earth] and it will modify the map immediately" and that "you are able to view the data in different ways." However, several participants also enforced the aforementioned distinction between the overall system and products of the system with regard to Google products. One participant stated "Google Maps by itself is not an interactive map" and a second participant stating that "if you had a .kml...and you load it into Google Earth, that's an interactive map; Google Earth is not an interactive map." Such an interpretation possibly suggests that a 'slippy' web map service on its own is not necessarily an interactive map and further, as suggested by one participant, that panning and zooming are not interaction operator primitives; the latter opinion is related to Davies's (1998) treatment of panning and zooming as enabling interactions and not work interactions (**Section 2.4**). This interpretation also contrasts with several of the participants that identified a map in the .pdf file format as an interactive map because of the ability to pan and zoom (or additional operators, as with GeoPDFs). It remained unclear if the distinction between interactive maps and map-based systems impacted map use practice in any way, despite probing.

An important component of the debate between interactive maps and map-based systems is the direct manipulation interface style. As introduced in **Section 2.2**, the interface style is a characteristic of the cartographic interface—which should not be confused with the cartographic interactions afforded by those interfaces—and includes direct manipulation, menu selection, form fill-in, command language, and natural language (Shneiderman and Plaisant, 2010). Interestingly, several participants only considered cartographic interaction to include maps that can be manipulated directly. For instance, one participant divided ArcMap into components that provide cartographic interaction and those that do not, stating that "only the map view is interactive." A second participant stated that it matters if "you are going through the map interface or the controls outside it," arguing that it is interaction with the map itself that makes the interaction "cartographic." The majority of participants disagreed with the requirement of the direct manipulation interface style for cartographic interaction. One participant stated that "the map itself does not have to be interactive as long as there is a system around it that allows you to manipulate it." A second participant stated "you also can use dialog boxes and buttons and menus to [interact] with the map," identifying both direct manipulation of non-map widgets as well as the menu selection and form fill-in interface styles as potential examples of cartographic interaction. The most poignant example of cartographic interaction provided through an interface style other than direct manipulation came from the pair of participants in the domain of Epidemiology & Public Health that rely primarily upon the Statistical Analysis System (SAS) to complete their work (**Table 4.4**). SAS uses a powerful command line interface style to provide sophisticated spatial analysis and modeling. Although the output maps generated by SAS are static images, the act of generating the maps was considered "an interactive process." One SAS-user stated that it is an interactive map "because I tell SAS what I need and it gives me the maps I need" while the second stated that "I am writing the code on the fly...the code is an interface." Such a perspective appropriately includes the command language interface style as one solution for implementing cartographic interaction.

An additional question posed in **Section 2.2** relates to the association of cartographic interaction, particularly web-based interactive mapping, and Web 2.0 technologies (O'Reilly, 2007). One aspect of Web 2.0 technologies important to cartographic interaction is the ability to map real-time data provided through live feeds, such as GeoRSS. The importance of live data on the quality of cartographic interaction was emphasized by a large subset of participants. One participant stated that "having live data is a key characteristic of interactive maps" while another stated that having live data behind the map is the "main property I think of when I think of an interactive map"; this second participant went on to qualify that the data does not have to be live for the map to be interactive, but "it makes it more interactive." The strongest stance was taken by a third participant, who emphasized that "the data has to be live...the link between the web map and the database cannot be broken." Such a position confuses dynamism related to system changes (such as geographic information updates) versus dynamism related to user-input (i.e., cartographic interaction). Thus, it is more appropriate to say that system- and user-based changes fall into the same broader category of ***dynamic cartography***—and further that live data is one reason why increased levels of cartographic interaction may be appropriate due to the inherent dynamism—but live data is not a quality of the cartography interaction itself. Web 2.0 technologies also include services for manipulating live data feeds, which then can be combined into web map mashups (Roth and Ross, 2009). Participant discussion on web map services focused on tile-based web map services such as Google Maps and OpenStreetMap. As reviewed above, such slippy web map services were not unanimously considered as interactive maps. Interestingly, the strongest arguments against considering web map services as interactive maps came from the three participants in the domain of News & New Media, the subset of participants that most commonly worked with web maps and therefore were most familiar with the ways in which these products can be mashed-up and enhanced with custom datasets and interactions. It is important to note that several web-based, software-as-a-service applications were identified as interactive maps, including CloudMade, GeoCommons, and Indiemapper.

One issue related to the *what?* question of cartographic interaction on which participants generally agreed is that cartographic interaction should not be conceptualized as a binary between 'interactive' and 'non-interactive', but rather as a continuum from low interactivity to high interactivity. Conceptualizing cartographic interaction as a continuum matches MacEachren's (1994) inclusion of human-map interaction as an axis in the Cartography^3 schematic (**Figure 2.3**) and Crampton's (2002) notion of differing levels of sophistication across cartographic interaction. Participants described such a continuum as "a range of interactivity," "different levels of interaction," or "shades of gray." Primary considerations for this continuum are the number of interactions implemented in a cartographic interface and the freedom in performing each provided interaction, together referred to as the ***interface complexity*** (see **Section 2.4**); as one participant stated, "the higher level of interaction goes along with the ability to choose and select more things." As described above, additional qualities that influence the perceived level of cartographic interaction include the immediacy of the map response to the cartographic interaction, the direct manipulation interface style, and live underlying geographic information. The cartographic interaction continuum is explored further in **Section 4.3.3** when summarizing statements regarding the *when?* category.

4.3.2 Why?

Codes included in the *why?* category identify statements about the purpose of cartographic interaction and the value it provides. As introduced in **Section 2.3**, the *why?* question is concerned with the broader goals that motivate use of cartographic interfaces. Four codes are included under the *why?* category to identify statements related to each of DiBiase's (1990) four stages of science constituting the swoopy diagram (**Figure 2.1**): (1) exploration (why1), (2) analysis (why2), (3) synthesis (why3), and (4) presentation (why4). The DiBiase framework was chosen here for simplicity due to its formative role in the field of Geovisualization, although cartographic interaction potentially supports a broader set of goals (see **Section 2.3**). Participants engaged with the *why?* question more frequently than the other four *W's* of cartographic interaction (but not the *how?* question, given the secondary purpose of the interview study to generate examples of interaction primitives), producing a total of 523 unique statements (average of 24.9 statements per participant). Participants most commonly discussed the stages of presentation (average=9.9) and analysis (average=9). The goal of exploration (average=4) was discussed less than half as often as analysis and presentation, a somewhat surprising finding given the emphasis on supplying high levels of cartographic interaction in Exploratory Geovisualization (**Figure 2.3**). The synthesis stage (average=1.9) was the least frequently discussed of DiBiase's four stages of science.

The ***exploration*** stage of science describes the examination of data from multiple perspectives to generate new research hypotheses and to reveal unknown insights about the phenomenon under investigation (DiBiase, 1990, MacEachren, 1994). High levels of cartographic interaction are considered essential for seamless map-based exploration to occur, as these interactions allow the user to generate a new cartographic representation once the need for it is identified (MacEachren and Monmonier, 1992). Several participants did acknowledge the value of cartographic interaction for exploration. One participant stated that cartographic interaction helps to "see patterns [that] lead us to new questions," a second offered that "for me, maps aren't the final answer, [they are] a starting point," and a third suggested that interactive maps are useful because "you can use them as a sand table to play out scenarios." Aside from several isolated statements, questioning on exploration did not yield the expected depth of discussion, with most participants stating that exploration was not a primary goal of their daily work motivating application of cartographic interaction. Many participant responses included the general terms "get a feel for" or "familiarize yourself", indicating that exploration may be an informal preparation stage of their work that is completed quickly before continuing onto other core tasks. Only participants from the domain of Epidemiology & Public Health evoked the term "hypothesis."

One possible explanation for this gap between the expected application of cartographic interaction for exploration, as drawn from scholarly arguments on Geovisualization, and the actual real-world practice is that all interview participants were experts in their domain, meaning they were very familiar with the phenomenon under investigation and very efficient at their work tasks. In support of this explanation, one participant asserted that cartographic interfaces mostly are used "for things I already have a clear idea about" while a second suggested that the use of cartographic interaction for exploration "is better when whoever is using it doesn't know what they want right away." Such an interpretation brings into question the contemporary appropriateness of the 'user' as an axis in the Cartography[3] schematic (**Figure 2.3**)—at least when using the MacEachren et al. (2004) distinction between 'public' and 'specialist' users—as successful applications of cartographic interaction for the exploration stage may require less user expertise than applications for the analysis stage (as well as synthesis and presentation). A second explanation of the relatively infrequent application of cartographic interaction for exploration may relate to the difference between expertise in cartographic interaction use and expertise in the application domain; Roth (2008, 2009a) found this distinction to be important when using static maps for decision making. Expertise in cartographic interaction use may be more important for the exploration stage due to the expected increased flexibility in manipulating the cartographic representation, while expertise in the application domain may be more important for the analysis stage due to the improved understanding of the mapped phenomenon needed for interactive application and interpretation of sophisticated spatial models and statistics. A third equally plausible explanation for this discrepancy between science and practice may be that the exploration stage is harder to formalize than others due to its open-ended, highly iterative nature, and therefore simply is more difficult to articulate in an interview format. It should be noted that a difference between scientists and non-scientists in depth of discussion concerning exploration was not observed, an important consideration given that DiBiase's (1990) swoopy framework is specific to the mission of science; the average number of statements regarding cartographic exploration actually was slightly less for the five participants that had earned an MD or PhD (average=3.4)—and thus those participants who have worked within the mission of science in the past, if not still doing so currently—than the remaining 16 participants that had not earned an MD or PhD (average=4.4).

Participants engaged more heavily with questions regarding the analysis stage. This stage originally was described by DiBiase (1990) as ***confirmation*** to follow Tukey's (1980) distinction in statistics between exploratory and confirmatory data analysis, which emphasizes the difference between generating hypotheses and testing hypotheses. Using the label ***analysis***, MacEachren and Kraak (1997: 339) expanded this stage beyond statistics, redefining it as the "manipulation of known data in search for unknown relationships and answers to questions." Many participants indicated that it was more important in their work to answer questions rather than generate them. One participant stated that "I think the question is why you are using the interactive map; I think we definitely have some research questions that we want to answer, where we have something that we want to find from the map." Similarly, a second participant stated that submitting spatial queries through cartographic interaction "gets most questions answered immediately" and went on to say that "live interactive mapping quickens the analytical process." Much of the discussion on the analysis stage was generated when geoprocessing or spatial analysis algorithms were applied using ArcMap or similar GIS tools during the demonstration portion of the interview; here, the cartographic interactions provided by ArcMap and other map GUIs were used both to inform the parameters of the applied computational procedures as well as to interpret the output of these procedures. Participants from the domains of Emergency Response & Crisis Management and Epidemiology & Public Health also discussed examples of using cartographic interaction to configure, monitor, and interpret spatial models, an interesting finding given the focus on interactive steering of models and simulations in the McCormick et al. (1987) report on Visualization in Scientific Computing (ViSC). Yet, multiple participants revealed that the links between interactive cartographic representations and geoprocessing, spatial modeling, and spatial statistics did not yet sufficiently meet their needs. One participant suggested, "in my opinion, I think if we can combine or incorporate additional statistical analysis methods into our interactive maps, that would be very helpful" while a second stated that "it would be nice to have an interface between a map and our model." Tight integration between visual and computation methods is a primary goal of the emerging research thrust of Visual Analytics (Thomas et al., 2005); the general emphasis on analysis over exploration across the interviews provides support for the transition from isolated research on Geovisualization (**Figure 1.4e**) to integrated research on Geovisual Analysis (**Figure 1.4f**).

Discussion concerning the synthesis stage was minimal. ***Synthesis*** describes the integration of insights generated from multiple iterations of the exploration and analysis stages to develop a final solution for presentation (DiBiase, 1990). The discussion on synthesis that did occur primarily was related to Web 2.0 technologies, particularly the gathering and integration of multiple data feeds and services. Several participants indicated the potential of using mashups to combine disparate information, with one participant stating that it was useful to "take two disparate web services and combine them in a new way" and a second stating "we'll get all these data feeds together...to load disparate information." Among the interactive maps and map-based systems demonstrated, one was a web geoportal that primarily supported synthesis. The user of this geoportal described it as being extremely well-received, stating that "people come to this tool to get the big picture because it incorporated all of these data feeds; it was a Web 2.0 capability and no one had anything like that." There was no discussion of cartographic interaction to support the collection of unique pieces of evidence and the evaluation of these pieces of evidence against competing hypotheses, a primary function of synthesis in the context of sensemaking (Robinson, 2008b).

Participants most frequently discussed the value of cartographic interaction in support of ***presentation***, which describes the map-based dissemination of findings or results to a wider audience (DiBiase, 1990). While the focus on designing the optimal map within the communication model of Cartography would predict that cartographic interaction would be least appropriate for purposes of presentation (**Figure 2.3**), the depth of discussion concerning the presentation stage is perhaps not surprising given the ubiquity of online, interactive mapping services primarily leveraged to disseminate geographic information. A key theme discussed across all domains was the potential of using the online, interactive mapping services to "share mission critical information" with decision makers, a finding that supports the MacEachren et al. (2004) revision to the labels of the 'task' axis of Cartography^3 (**Figure 2.3**) as 'knowledge construction' (exploration and analysis) versus 'information sharing' (presentation). As one participant explained, "with mashup technology, the bar is being lowered so that more people can develop their own mapping application...to promote data-driven decision making." Participants identified cartographic interaction as particularly valuable for presentation of geographic information that are highly dynamic; one participant stated that "you can use [cartographic interaction] for decision making...particularly for dynamic incidents." The presentation of real-time information for situational awareness and decision making perhaps explains why many participants emphasized live data as an important attribute of cartographic interaction when discussing the *what?* question (**Section 4.3.1**). Interestingly, in several cases, cartographic interaction was applied for geocollaborative decision making; as one participant stated "folks call in [to a net meeting] from different parts of the country and use the interactive tool to view the incident...and collaboratively make decisions." Aside from decision making, participants identified several other advantages of cartographic interaction for the presentation stage, including "sharing important information," "report generation and documentation," "visual storytelling," and "quality control." The latter relates to the discussion on the ***cartographic problematic*** and the uncertainty inherent to all cartographic representations introduced in **Section 2.3** (Pickles, 2004, Roth, 2009b). As one participant explained, "The number one advantage [of cartographic interaction] is getting good data...we are having a paradigm shift where people are saying put [the map-based system] out there because that will shame people essentially to correct their data, because the whole organization has visibility to it."

4.3.3 When?

Codes included in the *when?* category identify statements about the appropriate level of cartographic interaction in terms of both the number of provided interactions and the freedom in performing each interaction. As introduced in **Section 2.4**, the *when?* question takes an interface-centered view on cartographic interaction (**Figure 2.1**), delineating the appropriate use contexts of interactive versus static maps in order to optimize productivity. However, cartographic interaction is best conceptualized as a continuum from low to high levels of interaction, as illustrated by **Figure 2.3** and confirmed in **Section 4.3.1**; such a conceptualization effectively conflates the question *when?* with *how much?* The *when?* category therefore also is concerned with the balance between interaction freedom and interaction constraint. A code is included under the *when?* category to identify statements that indicate each side of this balance, the first indicating characteristics or examples when the amount and freedom of cartographic interaction should be increased (when1) and the second indicating characteristics or examples when the amount and freedom of cartographic interaction should be constrained (when2), including when a static map should be used in place of an interactive one. Participants were approximately twice as likely to describe situations requiring additional freedom in the supplied cartographic interaction (average of 8.1 statements per participant) than situations requiring additional constraint in the supplied cartographic interaction (average=4.3).

Overall, participants advocated for an increased level of cartographic interaction, both in the number of unique interactions and the freedom in performing each interaction. One participant asserted "generally, the more functionality, the better" while a second stated "from what I've seen of the R&D world, we are going to keep pushing that high interactivity...it is a goal to keep trying to do more and better." Further, most participants agreed that increased levels of cartographic interaction act to increase their individual productivity and decrease their perceived workload. One participant stated that "I'm starting to view interaction as production...because it saves time and money" while a second stated "an interactive map saves a lot of space and time, it can reduce my workload and people can learn some information quickly." This finding is interesting given the **Section 2.4** review of the productivity paradox (Landauer, 1995, Haklay and Nivala, 2010) and the initial set of studies indicating that a less-is-more approach to the design of cartographic interfaces may be one potential remedy to the paradox (e.g., Davies, 1998, Keehner et al., 2008, Keim, 2002, Dou et al., 2010). This general agreement on the positive impact on productivity made by increased levels of cartographic interaction in part is explained by the participants' expertise with interactive mapping and familiarity with their work tasks. However, this agreement provides initial evidence that the productivity paradox may no longer be observed regarding the use of cartographic interaction, perhaps due to the pervasiveness of computing technology in contemporary society. Minimally, participant agreement suggests that a less-is-more approach cannot be applied broadly in all interactive mapping contexts and that other factors need to be taken into account when determining the appropriate level of cartographic interaction. It is important to note that a large number of the interaction operators elicited from the interviews are best considered as enabling actions, as discussed in **Section 5.4**, indicating that productivity remains an important research topic for a science of cartographic interaction.

When asked to explain why provision of increased cartographic interaction is seen as a wholesale benefit, several interesting responses were elicited from participants in the domain of News & New Media. To do their work well, this subset of participants expressed that it was essential to understand the degree to which emerging technologies, such as interactive mapping, can be transitioned from specialist application to popular consumption. Thus, these participants were deeply interesting in the *when?* question, particularly in identifying the level of cartographic interaction that promotes the most interest in the mapped topic. Arguing for increased levels of cartographic interaction, one participant stated "I see people's reactions when they use interactive maps; they immediately engage with it, there's something that we love about the feedback, about clicking on a map, about getting that sense of ownership over the map itself or the process." This participant went on to say that "they get this sense of being involved with the process of the map itself." This sense of ownership over the map, and the empowerment and engagement it engenders, falls in line with discussions on the Democratization of Cartography (Rød et al., 2001, Wood, 2003b) and NeoGeography (Turner, 2006) and provides further evidence that productivity should not be the only consideration when designing a cartographic interface. A second participant stated that it is not enough just to provide high levels of cartographic interaction to users, but that interactive maps and map-based systems need to go beyond the "out-of-the-box" or "cookie cutter" design common to web map mashups. This participant asserted "There's a certain look and feel in interaction that's being established by non-cartographers; there's something being lost with the emotional impact, the affective nature, of maps when every map out there starts to look and feel the same." This participant went on to say that "we're losing the nuance of the artistic side of Cartography" and encouraged exploration with alternative cartographic interactions and cartographic interface styles. This discussion relates to the importance of avoiding the ***lorem ipsum map***, or the inappropriate use of a generic interface shell that improperly relates to the mapped phenomenon (Roth and Harrower, 2008).

Participants did provide several reasons for constraining cartographic interaction despite broadly arguing for increased freedom. Institutional limitations were identified as the primary reason why higher levels of cartographic interaction are not encouraged. A first institutional concern is the lack of available resources for modernizing interactive mapping practices by either acquiring licenses to commercial map-based systems or developing custom, in-house products. One participant stated that "it's just a time investment we often don't have" while a second stated that use of "the more sophisticated [interactive maps] tend to be at places that have money." Several participants identified institutional perception as a secondary concern to the institutional limits on time and money. One participant stated that "I think there's probably a kind of stigma with [cartographic interaction], it's perceived as complicated to do, maybe difficult to use products like that" and went on to suggest that "it's just kind of a resistance to change; we've been using static maps for a long time, they're used to looking at maps in that format, and it's hard to change perception." This particularly is a concern given the highly dynamic nature of computing technology; as one participant stated, "we have fixed price projects and if something wasn't included in the original scope, we can't include it." Therefore, a new cartographic interaction development project may be dated before it is completed, a truism that acts to decrease institutional-level interest in chasing emerging mapping technologies. Effective solutions for overcoming institutional limitations were not offered when probed. Aside from institutional limitations, several participants discussed the practical tradeoff between usability and utility that occurs when designing and developing interfaces that provide cartographic interaction (Grinstein et al., 2003, Fuhrmann et al., 2005). Several participants were able to offer examples when cartographic interaction was limited to make the interface transparently usable for a target user group, although this discussion of these examples was unexpectedly abbreviated; the lack of depth to the discussion on the usability-utility tradeoff likely is a result of recruiting cartographic interaction users rather than cartographic interaction designers and developers.

4.3.4 Who?

Codes included in the *who?* category identify statements about the impact of the user on cartographic interaction, rather than the cartographic interface and its level of complexity; as indicated in **Figure 2.1**, this difference is described as a user-centered versus interface-centered approach to identifying the appropriate level of cartographic interaction for a particular interactive map or map-based system. Three codes are included under the *who?* category relating to each of the three user characteristics summarized in **Section 2.5**; the first code indicates the impact of user ability on cartographic interaction, such as perception, cognition, and motor skills (who1), the second code indicates the impact of user expertise, such as education, experience, and familiarity (who2), and the final code indicates the impact of user motivation, such as interest and need (who3). The majority of participant discussion related to user expertise (average of 7.4 statements per participant). There was minimal discussion across participants on the impact of user motivation (average=1.9) and user ability (average=0.6).

The who1 code was the least frequently applied code of the 14-part scheme. Overall, only 12 statements regarding user ability were offered, the majority (9 of 12) coming from participants in the domain of News & New Media. One participant indicated that the user's "spatial awareness" is important for successful use of cartographic interaction, a user characteristic related to Golledge's (1992) spatial ability. There is conflicting scientific evidence concerning the impact of spatial ability on cartographic interaction use, with some studies observing a difference across spatial ability (e.g., Montello et al., 1999) while others showing no difference (e.g., Keehner et al., 2008); the one participant that did discuss spatial awareness did not clarify how the amount or freedom of cartographic interaction should be adjusted according to variation in spatial ability. Several participants indicated that age plays an important role in application of cartographic interaction, but did not clarify which user abilities are most impacted across age and did not suggest how the level of cartographic interaction should be revised given variation in age. The poor depth of discussion on user ability perhaps should have been expected given the recruitment of cartographic interaction users, as the issues of perception, cognition, and motor skills primarily fall within the scope of basic cartographic science.

With regard to the *who?* category, participants focused their attention on the topic of user expertise. Expectedly, participants agreed that increased user expertise affords provision of higher levels of cartographic interaction. However, there was disagreement on which of the possible measures of expertise mattered more when determining the appropriate level of cartographic interaction: user education or user experience. To some participants, appropriate and continued user education was essential to successful cartographic interaction use. As one participant stated, "it is a struggle we have now, maintaining the skills of our user base" lamenting that often "there's a resistance to learn new things, because it's not what people are used to." Therefore, there may be an individual level resistance to increased levels of cartographic interaction that parallels the broader institutional resistance revealed in **Section 4.3.3**. Advocates of the importance of education were comprehensive in their listing of educational materials and activities; examples included educational artifacts like "code documentation," "guidebooks," "map brewers and wizards," "training exercises," "user examples," and "web resources," as well as educational communications like "conferences," "discussion forums," "expert GIS users on staff," "formal coursework," and "training workshop." All of these learning methods can be leveraged to improve the utility of the interactive map or map-based system (Roth et al., 2009). Other participants noted that it was experience, and not education, through which they gained their expertise, stating that they were "self-taught" or that they received "on-the-job training." This subset of participants suggested that the education that they did receive did not prepare them to use cartographic interaction appropriately. One participant stated that "the person who goes through [the training] has the leg up on everyone else, probably, but for me the more important training is that of being out there and doing it" while a second participant stated "I think most of the things I've learned have been as a result of working alongside people...formal coursework, all it does is build a vocabulary around things that you probably already understand fairly well." The lack of agreement across participants and domains reveals that both education and experience should be collected when administering scientific experiments on cartographic interaction. Finally, participants across domains generally noted that user familiarity with cartographic interaction has increased to a point where extensive education or experience is not needed in some cartographic interaction use contexts, again perhaps due to the pervasiveness of computing technology in contemporary society. As one participant noted, "we're at the point where [our group] can use geospatial tools without much help; it's not a specialty field anymore." This finding relates to the **Section 4.3.2** discussion that expertise is not necessarily related to the broader map use goal, as predicted by the Cartography^3 schematic (**Figure 2.3**).

Despite the overall small amount of discussion, several important insights were revealed about the impact of user motivation on cartographic interaction. Three-quarters (30 of 40) of the statements regarding user motivation came from the domain of News & New Media, the only domain exhibiting wide variation in user motivation due to the application of cartographic interaction for entertainment-related tasks as well as work-related tasks. One participant from this domain reported that "there are two types of people [that use interactive news graphics], there's someone that wants their hand held, and someone that wants to dive right in" and went on to describe these two types of users as "Bart Simpson people" (unmotivated) and "Lisa Simpson people" (motivated), informal terminology used in newspaper design. Bart Simpson people are "more organic" and desire interactive maps "that have a clear entry point into the graphic" and that let them "quickly come away with some [message]." In contrast, Lisa Simpson people are "more quantitative" and will want to "dive right into the map" and "get into the weeds." The challenge, at least in News & New Media, is to design an interactive map that supports both motivation levels, a goal that relates to scholarly arguments for multi-layer cartographic interfaces (Kang et al., 2003) that exhibit a cascading information-to-interface ratio (Roth and Harrower, 2008). It is important to note that several participants outside of News & New Media described the use of incentives to improve user motivation and promote buy-in; one participant recommended the release of "little teasers" to generate interest before the complete release of a cartographic interface, while a second participant commended the administration of "contests" that "offer a cash prize" for the best application of the cartographic interface.

Finally, interview questioning related to the *who?* elicited several responses about the general utility and pervasiveness of a user-centered approach to design and development of the interfaces that provide cartographic interaction. Across domains, participants indicated that what may be described as a user-centered approach was not common; as one participant bluntly stated, "it is not super popular." A second participant stated that "there's a big gap, in that the people who are designing this stuff are not talking or getting a feeling for the people who use it," later stating that "you have to design products to meet [our] needs, but no one has done a good needs assessment." A third participant went as far as saying that the lack of continual user input throughout design and develop is "the biggest problem" in the use of cartographic interaction; this participant went on to say that "it's hard to design something if you don't know your audience." When probed, all participants stated that they wanted greater input into the design and development of the cartographic interfaces that they use to support their work.

4.3.5 Where?

Codes included in the *where?* category identify statements about the impact of the technology on cartographic interaction (i.e., a technology-centered view), rather than the user or the interface. Three codes are included under the *where?* category relating to each of the three groups of technology summarized in **Section 2.6**; the first code indicates the impact of the available input devices on cartographic interaction (where1), the second code indicates the impact of bandwidth size and processing power (where2), and the third code indicates the impact of the display capabilities (where3). As argued in **Chapter 2**, a technology-centered view (**Figure 2.1**) is less appropriate for a science of cartographic interaction given the constant evolution of mapping technologies; the theories, frameworks, and guidelines generated by a science of cartographic interaction should persist even as the individual technological solutions vary over time (Olson, 2004). Technological advancements and limitations therefore were not emphasized in the interview protocol in order to focus on topics more pressing to a science of cartographic interaction. Expectedly, this resulted in very little discussion regarding the *where?* question of a science of cartographic interaction (average of only 4.2 statements per participant); participants engaged with issues related to bandwidth size and processing power most frequently (average=2.6), followed by issues related to the display capabilities (average=0.9) and input devices (average=0.8).

The small amount of discussion on user input focused on pointing devices. All cartographic interface demonstrations were completed primarily with a mouse or touchpad excepting the demonstration of the

Statistical Analysis System, which relied heavily on keyboard input. There was punctuated discussion of technologies beyond the standard pointing and keying devices, particularly the potential of touch screens. A pair of participants from the domain of Emergency Response & Crisis Management reported that their agency was switching to tablet laptops for in-vehicle use by first responders. In both cases, the participant's in-house map-based systems were modified for the touch screen input device to account for the reduced precision in pointing, particularly moving towards "bigger buttons" so that users can "hit them easily." The pair of participants indicated that the touch screen was well received by users; one participant stated that "it is convincing a lot of these guys that GIS is a good thing." Several participants discussed the potential of speech input, or a "voice control map," but no participant was currently using such an input device. Researchers have identified both touch screen (White, 2009) and multimodal (MacEachren et al., 2005a) input devices as fruitful for cartographic interaction. There also were several references to the use of large size scanners, an indication that many firms still are in the process of digitizing their collections of geographic information.

In **Section 2.6**, bandwidth and processing were considered as a single issue because together they determine the speed of the cartographic interaction. Participants identified speed as the most important issue technologically. One participant stated that "speed is the utmost importance," mirroring Gahegan's (1999: 290) "need for speed." Interestingly, participants were more concerned with bandwidth than processing power. While participants offered isolated examples of poor processing performance—particularly when cartographic interaction is employed to support analysis (**Figure 2.2**)—most participants perceived modern processing capabilities to be sufficient. One participant stated "you can run [the interactive map] in real time or faster," while a second said that "it was computationally intensive in the earlier days...but now it moves forty times faster." This finding may be an indication that the supposed 'catch-22' of offsetting increases in processing and data volume is not occurring, and that processing power has improved to handle the largest spatial datasets. Alternatively, it could be that users simply are not employing cartographic interaction for the largest of spatial datasets because they have learned that their computing devices cannot handle them; thus, users are getting better at working around known limitations in processing.

Participants instead expressed concern with Internet bandwidth, an indication of the growing influence of web-based mapping applications. One participant stated that "a network may not support geospatial work yet [because] it's a load on the bandwidth" while a second stated that the bandwidth is "often so poor...that the utility of using a [web-based] application in the field isn't really there yet." Further, many participants were hesitant to move their work online because of general problems with network connectivity, despite the promise of combining cartographic interaction and cloud computing. One participant stated "I wouldn't want to take the computing I do locally and move it entirely to the web because then I'm dependent on an Internet connection," while a second participant asserted "we don't work off the server...because normally we lose connectivity during emergencies." Multiple participants also were concerned about network security, providing additional reasoning for not moving cartographic interaction online.

Of the nine characteristics identified in **Section 2.6** across which displays vary, participants focused discussion on screen size. Participants from the domains of Emergency Response & Crisis Management and Intelligence Analysis described wall size digital displays available to support group discussion and decision making. Cartographic interaction with these displays was performed by a single user at a central terminal (i.e., not touch screen or speech/gesture recognition). These participants indicated that these wall size displays were useful for geocollaborative purposes, but that most emergency operations centers "don't really have the luxury of a huge video wall." No statements were offered about the other eight characteristics of displays.

4.4 Conclusion: Cartographic Interaction Science versus Practice

The semi-structured interviews reported in this chapter provide a snapshot of the current state of practice of cartographic interaction. Responses regarding each of the five *W's* of a science of cartographic are interpreted in the **Section 4.3** subsections, allowing for direct comparison to the background reviews on the state of science completed in **Chapter 2**. There are clear gaps between the science and practice of cartographic interaction. In many ways, advancements generated through practical application of cartographic interaction currently are outpacing those developed through science. Further, the small set of insights about cartographic interaction developed through robust scientific inquiry has had only a minimal uptake in practice. It is essential that scientists and practitioners work together—rather than in parallel—on pressing critical issues and key unanswered questions regarding cartographic interaction; both groups have a great deal to contribute to Interactive Cartography and Geovisualization. As stated in **Section 4.1**, the secondary purpose of the cartographic interaction interviews is the empirical generation of examples of primitives for construction of an interaction primitive taxonomy. Statements coded under the sixth *how?* question of a science of cartographic interaction were combined with definitions from the **Chapter 3** background review to generate the complete universe of objective and operator primitives. A pair of card sorting studies then were administered to categorize each set of primitives into a meaningful structure, producing an initial interaction primitive taxonomy. A summary of the discussion regarding the *how?* question is provided in **Chapter 5** following description of the card sorting results.

Chapter Five: Interaction Primitive Card Sorting
A Taxonomy of Cartographic Interaction Primitives

Overview:

This chapter reports on a pair of card sorting studies administered to generate logical categories of interaction primitives for inclusion in the taxonomy of cartographic interaction primitives. The chapter begins by emphasizing the importance of theory to a science of cartographic interaction and providing an overview of the empirical approach taken to construct a theoretical framework for investigating the *how?* question of cartographic interaction (**Section 5.1**). Following this introduction, parameters of the pair of card sorting studies are reviewed (**Section 5.2**). Fifteen participants with expertise in Interactive Cartography and Geovisualization completed a pair of card sorting studies, the first guided by the concept of cartographic interaction objectives and the second guided by the concept of cartographic interaction operators. The textual contents of the cards primarily were drawn from the **Chapter 4** cartographic interaction interview study, but were supplemented by definitions of interaction primitives identified in the **Chapter 3** review of extant taxonomies. Variations in sorting across participants were reconciled using average linkage hierarchical clustering on pairwise card agreement and visual interpretation of associated statistical graphics, producing the initial four-dimensional taxonomy of goal, objective, operand, (all three treated in **Section 5.3**) and operator (**Section 5.4**) primitives. The chapter closes with an outlook on the extension and evolution of the initial interaction primitive taxonomy (**Section 5.5**).

5.1 A Theoretical Framework for a Science of Cartographic Interaction

Theory is essential for science. Abstract models and conceptual structures reveal inconsistencies and gaps in existing knowledge and frame investigation and experimentation for generating new knowledge. As stated in **Section 1.5.2**, one of the largest breakthroughs for Twentieth Century Cartography (and Information Visualization generally) was the identification and articulation of the ***visual variables*** (Bertin, 1967|1983, Morrison, 1974, Caivano, 1990, MacEachren, 1992). The visual variables, and the associated syntactics that inform their application, provide a theoretical framework that enables both the science and practice of cartographic representation. The science of cartographic interaction is not without several influential theoretical frameworks, including Norman's (1988) stages of action model (**Figure 3.1**) regarding the *what?*, DiBiase's (1990) swoopy schematic (**Figure 2.2**) and MacEachren's (1994) Cartography^3 (**Figure 2.3**) regarding the *why?*, and MacEachren and Ganter's (1990) pattern-matching model for visual thinking (**Figure 2.5**) regarding the *who?*; the six fundamental questions of a science of cartographic interaction (**Table 2.1**) are themselves a broad contribution to this effort. Yet, the science of cartographic interaction is still in need of comprehensive and practically useful theoretical frameworks, particularly regarding the basic cartographic interaction primitives and the associated *how?* question.

The remainder of the dissertation builds upon the reviews of science (**Chapter 2** and **Chapter 3**) and practice (**Chapter 4**) to contribute new theory to the science of cartographic interaction. This chapter reports on an empirically derived taxonomy of cartographic interaction primitives, contributing to extant theory on cartographic interaction. The interaction primitive taxonomy identifies and articulates the basic units of cartographic interaction, or ***interaction primitives***, that can be combined into individual ***interaction exchanges*** and overall ***interaction strategies*** (see **Section 3.2**). Once constructed, the taxonomy affords evaluation of competing interaction strategies (**Chapter 6**), potentially leading to a set of practical guidelines informing the design and use of cartographic interfaces.

As illustrated in **Chapter 3**, there are multiple, conflicting theoretical frameworks that enumerate cartographic interaction primitives, many of which fall outside of Cartography. One limitation of extant taxonomies, perhaps contributing to their lack of general adoption, is that the vast majority of these taxonomies are not empirically derived. Of the subset of extant interaction taxonomies reviewed in **Chapter 3** that are based upon a systematically collected set of interaction primitives, these primitives are drawn solely from secondary sources or available software tools and techniques. While leveraging such resources is useful for design and development of a single cartographic interface, there are several concerns with relying solely upon a literature or technology survey. First, the taxonomy only can be as contemporary as the literature or software in existence at the point of the review, possibly making it more of a historical synthesis than a useful categorization with which to move forward. Secondly, it is extremely difficult to identify gaps in current theory or tools, as the universe of instances is based not on what is needed, but what has already been accomplished. Finally, such an approach says nothing on how theory has influenced practice or how the software is actually being used in the field, making the ecological validity of the taxonomy unknown. However, it is important to remain cognizant of extant theory—and to continue to apply logic when constructing an empirically derived taxonomy—as humans have their own misconceptions that may manifest themselves in the collected empirical data.

Following an integrated empirical approach to complementing and extending existing scientific research on cartographic interaction, two guided card sorting studies were administered to categorize two sets of interaction primitives delineated according to objectives versus operators. The universe of example primitives was collected through the reviews on the states of science (**Chapter 3**) and practice (**Chapter 4**) of cartographic interaction. A total of 15 professionals and scholars with experience and training in cartographic interface design and development completed the card sorting studies using the online WebSort tool (http://www.websort.net); the same set of 15 professionals completed both studies. Descriptions of the card sorting method, the applied statistical analysis, and resulting interaction primitive taxonomy are presented in the remainder of the chapter. The pair of card sorting studies accomplishes the second research goal of the dissertation (see **Section 1.5.2**) and contributes directly to the "grand challenge of interaction" identified by Thomas et al. (2005).

5.2 Method: Card Sorting of Interaction Primitives

5.2.1 Review of Methods for Eliciting Cognitive Structures

Many scholars have indicated the impact that cognitive structures, such as categories and relationships, have on the generation and organization of knowledge (e.g., Abler et al., 1971, Lakoff, 1987, MacEachren, 1995, Margolis and Laurence, 1999). An initial step of constructing an interaction primitive taxonomy from an established universe of primitive examples is an exercise in categorization; the interaction primitive examples need to be placed into logical categories that describe the general case of each specific example. Subsequent experimentation to identify prototypically successful interaction strategies then adds the relationships between the categorizations, with the synthesis of numerous experiments potentially generating a robust syntactics of cartographic interaction primitives.

There are several empirical approaches for eliciting a participant's cognitive structures concerning a universe of instances. Potential options include paired comparison, triad comparison, concept mapping, affinity diagramming, and card sorting. ***Paired comparison*** and ***triad comparison*** require participants to rate the similarity between two instances or to choose the two most similar instances out of three, respectively (Cooke, 1994), with the categorization then determined by analyzing ***agreement*** across instances, or the percentage of participants that rated a given pair of instances as members of the same group (Rugg and McGeorge, 2005). While these two methods are appropriate for categorizing simplistic instances that require little interpretation (i.e., instances that differ along only one, perceptually-salient characteristic), they are less useful for categorizing complex instances whose similarities and differences may not be initially clear at the start of the study. In these situations, participants should be allowed to refine the developing structure iteratively in order to avoid order bias, which can become prohibitively tedious with a large set of instances; paired comparison and triad comparison were not feasible for this research given the large number of interaction primitives included in each sort (see **Section 5.2.3**).

Concept mapping, affinity diagramming, and card sorting are methods for eliciting cognitive structures that allow participants to view the entire universe of instances throughout the session, which in turn support initial exploration and iterative refinement. ***Concept mapping*** is a technique for arranging a set of concepts (i.e., instances) into a comprehensive relational structure, often grouping concepts according to more abstract ideas or themes (Novak and Cañas, 2008). However, concept mapping is not appropriate for achieving the second research goal of the dissertation because it is used to generate the set of instances (which already was completed by the reviews of science and practice as part of accomplishing the first research goal) and it focuses more on determining relations among instances than developing homogenous groupings of instances. ***Affinity diagramming*** does not suffer from these two limitations, as it uses an input set of instances and focuses upon grouping instances according to similarity, rather than simply identifying relationships (Amar et al., 2005). However, affinity diagramming generally is implemented as a consensus building technique, requiring all participants to be present during a single session. Scheduling multiple participants into a single session was not feasible because participation was restricted to experts in cartographic interface design and development and because none of the participating experts were co-located.

The card sorting method therefore is the most appropriate approach for eliciting and reconciling cognitive structures concerning the collected sets of cartographic interaction primitives. ***Card sorting*** requires participants to organize a set of instances (i.e., ***cards***) into internally-homogenous groupings (i.e., ***categories***) based on similarity along an identified sorting principle (i.e., the ***sorting criterion***) (Spencer, 2009). Card sorting has its origins in Psychology as a method for testing traumatic brain injuries (Berg, 1946, Berg, 1948), but regularly is applied in the discipline of Usability Engineering (e.g., McDonald et al., 1986, Nielsen and Sano, 1995) to generate coherent interface designs as well as the discipline of Cognitive GIScience to develop qualitative spatial formalisms and geographic ontologies (Klippel, 2009, Klippel and Li, 2009). Roth et al. (2010a, 2011) provide an example of the card sorting method for map symbol design while Lloyd et al. (2008) describe the potential of card sorting for the user-centered design of cartographic interfaces.

A pair of card sorting studies was administered to sort interaction objectives and interaction operators respectively, two important dimensions for establishing a syntactics of cartographic interaction primitives. As defined in **Section 3.2**, an ***objective*** describes the user's intention in using the interface, while an ***operator*** describes the functions provided by the cartographic interface to support the user's objective. The objective card sorting study unexpectedly generated insight into a potential taxonomy of interaction ***goals***, or the reasons motivating use of the cartographic interface in the first place, as well as interaction ***operands***, or the recipient of the cartographic interaction. Thus, a four-dimensional taxonomy of cartographic interaction primitives was generated from the pair of card sorting studies. Parameters of the two card sorting studies are outlined in the following subsections.

5.2.2 Participants

Fifteen participants were sampled purposively from the domains of Interactive Cartography and Geovisualization to complete the pair of card sorting studies. As introduced in **Section 4.2.2**, ***purposive sampling*** describes the recruitment of participants according to their fitness to a small set of predefined criteria regarding the research (Patton, 1990). The primary criterion for inclusion in the pair of card sorting studies was experience and training in the design and development of digital cartographic interfaces. Such expertise is required to elicit ecologically valid cognitive structures from the participants regarding the presented universes of objective and operator primitives. Criteria for participation also included availability to complete both card sorting studies in the set and being 18 years of age or older. Potential participants were identified through previously developed Penn State GeoVISTA Center contacts in the fields of Interactive Cartography and Geovisualization. All potential participants were deemed to have sufficient experience and training in the design and development of cartographic interfaces before being sent the call for participation; a background survey therefore was not administered as part of the pair of card sorting studies.

The appropriate sample size of a single card sorting study is a topic of discussion in the field of Usability Engineering. A power study conducted by Tullis and Wood (2004) indicated that inclusion of five participants—the typical number of participants included for discount usability studies (see **Section 6.4**)—produced a final structure with only 0.75 correlation to the 'correct' structure, generated from an exhaustive sample size of 168 participants. A sample size of 15 produced a correlation of 0.90, with increases to the sample size from n=15 producing only diminishing returns in explanatory power; a sample size of 20 produced a correlation of 0.93, a sample size of 30 produced a correlation of 0.95, and a sample size of 60 produced a correlation of 0.98. Based on these findings, Nielsen (2004) recommends inclusion of 15 participants to balance between explanatory power of the study results and project resources, which includes access to participants, their available time, and compensation for their time. It therefore was justifiable to set the participant total to the minimum n=15 given the tradeoff between project resources and explanatory power described by Nielsen. This further was justified by the requirement to have each participant complete both studies, which increased fatigue and decreased the available sample pool of experts. Participants were compensated $50 for successful completion of both card sorting studies.

5.2.3 Materials and Procedure

The results obtained from card sorting studies vary according to the combination of two important experimental parameters: the contents of the cards being sorted and the guidelines given to participants for sorting the cards into categories. Depending on the combination of these parameters, the card sorting study may be primarily ***generative*** in nature (revealing the most appropriate sorting criterion, a logical set of categories, and additional cards to add to the universe), primarily ***evaluative*** (providing feedback about an *a priori* sorting criterion, set of categories, or universe of cards), or a combination of both generative and evaluative (Nielsen, 2004). Roth et al. (2010a, 2011) provide a framework for predicting the kind of results obtained from a card sorting study depending upon the selected pairing of card contents and sorting instructions; although the initial framework was offered in the context of cartographic design of a unique map symbol set, it can be generalized to all research contexts with only minor modifications (**Figure 5.1**).

The contents of the cards included in the sort (the first parameter listed in **Figure 5.1**) generally fall into one of three categories: text, graphics, and physical objects (Rugg and McGeorge, 2005). The reviews on the current states of cartographic interaction science (**Chapter 3**) and practice (**Chapter 4**) yielded primarily textual instances of objective and operator primitives. Graphics, such a screen captures or short videos of interactions, were not considered for the cards due to the increased complexity of interpreting the specific interaction exchange outside of the broader use context and the possible confusion during sorting of cartographic interactions with interface styles or interface designs (see **Section 2.2** for details regarding the difference). Physical objects typically only are included in analog, in-person sorts not facilitated by digital sorting software; as noted in Roth et al. (2010a, 2011), virtual geo-environments offer the potential of sorting virtual objects at the geographic scale, although no known examples are listed.

The textual content for the pair of interaction primitive card sorting studies was drawn from two sources: (1) definitions of interaction primitives included in the objective-based or operator-based taxonomies reviewed in **Chapter 3** (**Table 3.1** and **Table 3.2** respectively) and (2) statements indicating characteristics or examples of objective or operator primitives elicited during the **Chapter 4** cartographic interaction interviews (coded as how1 and how2 respectively). A total of 600 statements regarding objectives and 895 statements regarding operators were generated from the two sources; however, the complete set of statements derived from both sources were filtered before inclusion in the pair of studies. Two conditions were used to filter statements resulting from the **Chapter 3** literature review on extant interaction primitive taxonomies: (1) a complete definition must be provided for every primitive in the taxonomy; and (2) if the taxonomy is based on a prior taxonomy, the taxonomy must make a clear extension or revision to the included primitives or their definitions. Four criteria were used to filter statements resulting from the **Chapter 4** cartographic interaction interviews: (1) both independent coders must agree that the statement is an example of an objective or operator, (2) the statement indicating an objective or operator cannot be repeated exactly within a single interview session (only one of a set of duplicates was included), (3) statements describing examples of objectives or operators must have a clear referent, and (4) the statements must identify objectives that are geographic in nature or operators that are cartographic in nature. The filtering resulted in 178 objective cards and 206 operator cards; both totals are either below or very near the 200 card limit recommended for card sorting studies to avoid participant fatigue (Maurer and Warfel, 2004) and so were not reduced further. **Table 5.1** lists the raw and filtered card frequencies for both card sorting studies, showing that the cards were drawn primarily from the set of cartographic interaction interviews, but were supplemented by the background review of secondary sources; the complete card contents used for both card sorts are provided in **Appendix B**.

Guidelines given to participants for sorting the cards into categories (the second parameter listed in **Figure 5.1**) also fall into one of three categories, varying according to the amount of constraint placed on the participant during sorting: open sorting, guided sorting, and closed sorting (Spencer, 2009). ***Open sorting*** is the least constrained variant, allowing each participant to identify independently both the sorting criterion and set of categories during the sort, while ***closed sorting*** is the most constrained, forcing the participant to sort the cards into a pre-determined set of categories using a pre-determined sorting criterion; the requirement of having the sorting criterion and categories determined *a priori* makes the closed sort primarily evaluative in nature, compared to the primarily generative open sort (Wood and Wood, 2008). ***Guided sorting*** describes an intermediate set of sorting guidelines in which the investigators wish to enforce a pre-determined sorting criterion, but are not yet aware of the final categories that will be produced using the identified sorting criterion (Roth et al., 2010a, Roth et al., 2011). The sorting criterion was fixed for each of the two interaction primitive card sorting studies; the criterion for the first card sorting study was the concept of an interaction objective while the criterion for the second was the concept of an interaction operator. While the sorting criterion was fixed in each study, the categories themselves were not (i.e., the purpose of the studies was to generate the categories), making guided sorting most appropriate.

After agreeing to participate in the study, participants were sent a protocol document that included two sections: background information on the study and instructions for completing the pair of card sorting studies (see **Appendix C** for the complete card sorting protocol). The background section of the protocol provided essential information about the pair of sorting criteria for use in the guided card sorting studies. The introductions to the concepts of interaction objectives and interaction operators from **Section 3.2** were distilled into a paragraph each. Terms that are conceptually similar to the concepts of objectives and operators were listed and several primitive examples were given; no examples of categories were listed to avoid biasing the sort. At the end of the background section, participants explicitly were instructed to sort on the concepts of interaction objectives and interaction operators for the first and second card sorting study respectively, fulfilling the guided aspect of the card sorting studies. Participants were asked to avoid sorting the cards according to the seven application domains included in the **Chapter 4** cartographic interaction interviews from which the statements were elicited (i.e., participants were asked to make connection across domains, rather than sort according to domain).

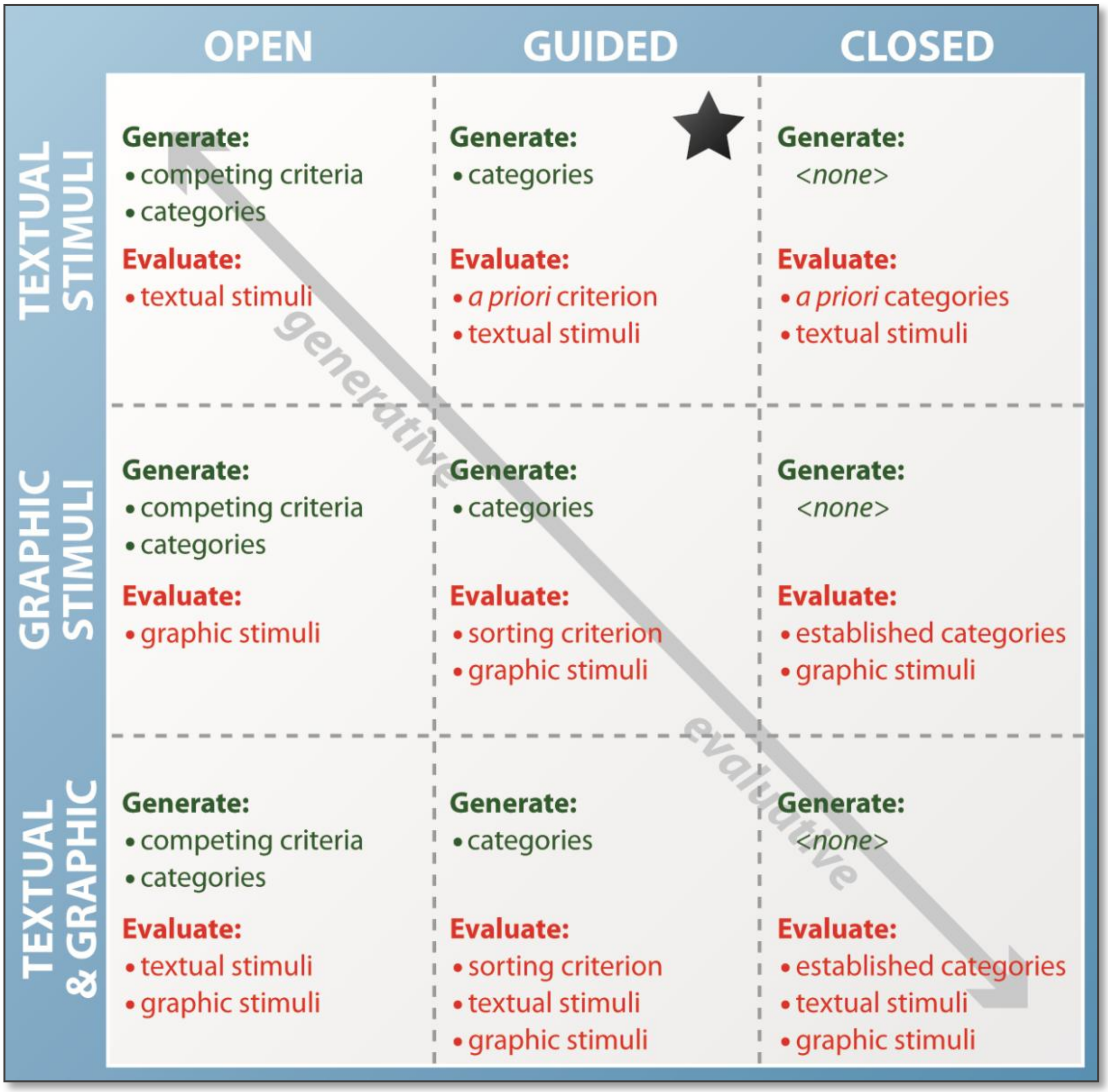


Figure 5.1: A Framework for Administering the Card Sorting Method. There are two important experimental parameters of the card sorting method that determine if the results will be generative, evaluative, or a combination of both: (1) the contents of the cards being sorted (text, graphic, or both) and (2) the guidelines given to participants for sorting the cards into categories (open, guided, or closed). The star marks the appropriate combination for the pair of cartographic interaction primitive card sorting studies reported in this chapter. Image redrawn from Roth et al. (2010a, 2011b).

Study #	*Science (Literature)*		*Practice (Interviews)*		*Total*	
	raw	*filtered*	*raw*	*filtered*	*raw*	*filtered*
#1: Objectives	55	40	545	138	600	**178**
#2: Operators	72	51	823	155	895	**206**

Table 5.1: Raw versus Filtered Card Frequency for the Pair of Card Sorting Studies

Instructions for completing the pair of card sorting studies were provided following the background section of the protocol document. Both card sorting studies were administered online using the WebSort card sorting application (http://www.websort.net). A ***competitive analysis***, or comparison of software products providing similar functionality, found WebSort to be the best online application for creating and analyzing card sorting studies (Chaparro et al., 2008); WebSort also supports all parameter combinations in the **Figure 5.1** framework. The card sorting studies were administered online because of the participation restriction to expert cartographic interface designers and developers. Online administration affords efficient participation with a geographically distributed population and allows participants to complete the sorts at their convenience, an important consideration the participants are professionals (Robinson, 2011). The negative of online administration is the lack of a controlled experimental setting, making it impossible to ensure that participants apply their undivided attention to the study (i.e., to avoid splitting attention on other work or entertainment tasks) and do not employ the assistance of supplementary materials; measures of completion time are particularly susceptible to issues of split attention and therefore cannot be reliably collected and reported from studies administered online (Roth, 2008, Roth, 2009a).

Hyperlinks to the pair of WebSort studies were provided at the end of the protocol document. The WebSort card sorting interface includes two primary panels: the card stack (**Figure 5.2: left**) and the sorting workspace (**Figure 5.2: right**). The filtered subset of objective and operator statements compiled from **Chapter 3** and **Chapter 4** were entered into the left card stack; the order of cards in the left card stack was randomized and therefore different for each participant. WebSort uses a tabletop metaphor for completing the sorting, providing a direct manipulation 'drag-and-drop' interface solution for moving the cards from the card stack to the workspace. Dragging a statement on the empty portion of the workspace creates a new category while dragging a statement into an existing category adds it to that category. Participants were instructed to create a 'Discard' category for cards that were not examples of an objective or operator as well as an 'Other' category for cards that were clearly objectives or operators, but did not fit cleanly into the generated classification. During the study, participants had access to an 'Instructions' tab that included the same background and instructional content included in the protocol document. Once all cards were sorted, participants were instructed to refine their categorization by reviewing the category contents and making modifications, if appropriate. Before submitting their sorting structure, participants were required to provide a name for each created category and an explanation about their categorization using the 'Leave a comment' tab. All participants completed the objective card sorting study first and the operator card sorting study second. Combined, the two sorts were designed to take approximately 120-150 minutes to complete; most participants completed the pair of card sorting studies within 150 minutes, with several participants requiring more than 180 minutes.

5.2.4 Statistical and Visual Analysis

Results of the pair of card sorting studies were interpreted using descriptive statistics and exploratory statistical information graphics (Hannah, 2005). The primary metric used to interpret open and guided card sorting studies is pairwise or card-versus-card agreement, described in **Section 5.2.1** as the percentage of participants that rated a given pair of cards as members of the same category (Rugg and McGeorge, 2005). Other measures common to closed card sorting studies (e.g., accuracy, category-versus-category agreement, or card-versus-category agreement) cannot be applied to open or guided sorts given the lack of an *a priori* set of categories (Roth et al., 2010a, Roth et al., 2011). Using the pairwise agreement scores, the cards can be analyzed using ***hierarchical clustering***, a technique that builds a nested hierarchy of clusters in which smaller, more homogenous clusters are combined incrementally to form larger, less heterogeneous clusters based on similarity (Everitt, 2001). The WebSort tool supports average linkage hierarchical clustering, a hierarchical clustering algorithm that uses the average statistical distances between all pairs of observations to determine the point at which a pair of individual cards, or smaller clusters of cards, should be combined into a new cluster.

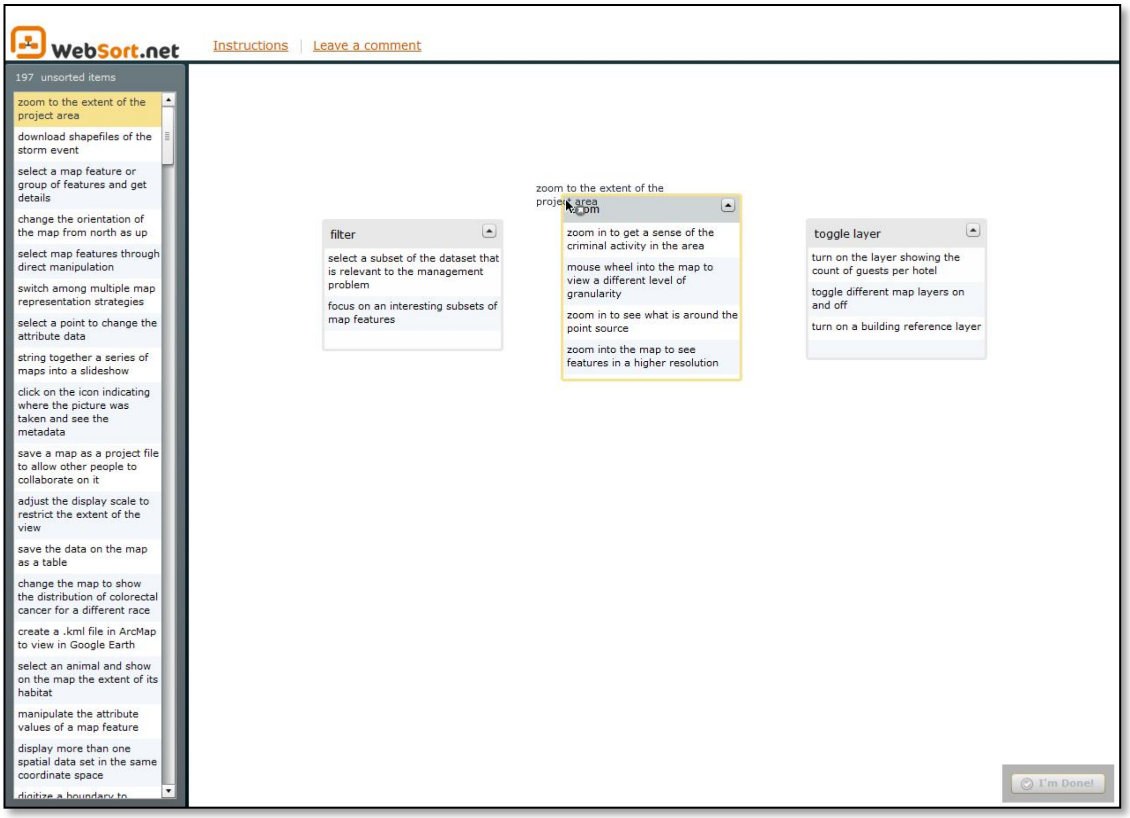


Figure 5.2: The WebSort Card Sorting Interface.

While hierarchical clustering explicates consolidated groupings of similar cards and key areas of confusion across the elicited cognitive structures, it does not prescribe the optimal number of categories for inclusion in the final taxonomy (i.e., the location at which the hierarchy should be 'cut' or 'sliced'). A pair of statistical information graphics was generated for each card sorting study to identify the proper category divisions in the universes of cards: (1) an interactive dendogram and (2) a card-by-card agreement matrix; both graphics are generated automatically by WebSort.

The first information graphic, a ***dendogram*** view, or tree graph, uses the results of hierarchical cluster analysis to sort the cards one-dimensionally according to agreement (O'Sullivan and Unwin, 2003). The degree of similarity between individual cards or card clusters then is represented by the length of a line extending from the card or cluster to the broader, unifying cluster (Chen et al., 2008). The dendogram view provided by WebSort is interactive, allowing users to change the location at which the hierarchy is split into individual clusters and then to view the resulting changes to the categorization.

The second leveraged information graphic, a ***card-by-card agreement matrix***, uses the card order produced for the dendogram for both axes in a two-dimensional table and indicates the pairwise agreement score for each cell in the matrix (Guo, 2007). WebSort applies a sequential color scheme to the agreement scores to aid with interpretation of the card-by-card agreement matrix. Because agreement is non-directional, the produced card-by-card agreement matrices are symmetrical in that both halves of the matrix show the same information, with null values along the diagonal; one half of the each card-by-card agreement matrix therefore is masked to simplify interpretation. The matrices generated for interpreting the interaction primitive card sorting studies differ from the bivariate matrix found in Roth et al. (2010a, 2011) because of the inability to generate an accuracy score along with an agreement score for open and guided card sorts.

Both Kos and Psenicka (2000) and Clatworthy et al. (2005) recommend evaluating the stability of categories across subsets of participant responses as one way to characterize the reliability of hierarchical clustering results. The reliability of the dendogram and card-by-card matrix views derived from the average linkage hierarchical clustering of the objective and operator card sorts was assessed by comparing the categories produced by a set of three samples from the 15 total sorts to the categories produced by all 15 sorts together. For each card sorting study, the set of 15 sorts was divided into three groups of n=5 (sample A, B, and C), with these samples then combined to produce three composite samples of n=10 (A+B, A+C, B+C) such that each individual participant sorting strategy was included in two of the three composite samples; such a sampling strategy represents a modification to the reliability assessment performed by Klippel et al. (2009)—who used two samples with no overlap—in order to account for a smaller number of total participants performing the sorts (n=15) and to produce directly comparable samples of equal sizes (n=10). The resulting card-by-card agreement matrix for each sample then was compared against the overall card-by-card agreement matrix (i.e., the baseline) to identify the pairs of cards that were categorized differently in the given sample compared to overall categorization; card-by-card pairings were compared rather than card-in-category pairings due to the use of guided sorting, rather than closed sorting with an *a priori* set of categories (**Figure 5.1**). The number of card pairs categorized similarly in the sample and baseline were tallied and divided by the total number of card-by-card pairs in the baseline, resulting in a similarity percentage. The three objective samples shared on average 63.0% similarity with the overall objective structure while the three operator samples shared on average 83.3% similarity with the overall operator structure. The distinction between reliability measures indicates that participant sorting strategies varied much more for the objective card sorting study compared to the operator card sorting study, meaning that resulting objective categories need to be treated cautiously when considering their broad applicability and therefore are a candidate for follow-up research. **Section 5.3** includes several explanations for this variability in the objective sort, drawn from both participant closing responses and background theory.

The same pair of statistical and visual analysis was used for reconciliation of both the objective and operator sorting studies. Multidimensional scaling and an associated spatialization plot were not generated due to the large number of cards and complexity of the card contents (i.e., the long textual statements, rather than pictorial icons or map symbols). Finally, it is important again to note that interpretation of the agreement scores and the hierarchical clustering for both studies also was informed by existing scholarly arguments reviewed in **Chapter 3**, allowing for the integration of both empirical evidence and logical arguments into the final interaction primitive taxonomy. **Figure 5.3** provides a summary of the interaction primitive taxonomy, which includes four dimensions: (1) goals, (2) objectives, (3) operators, and (4) operands.

5.3 Results and Discussion: Objectives

5.3.1 Participant Agreement on Objectives

The **Figure 5.4** card-by-card agreement matrix illustrates the pairwise agreement across participants for the objective card sorting study. As stated in **Section 5.2.4**, the cards are listed in the same order on both axes according to average linkage hierarchical clustering on agreement. Key divisions identified in the hierarchical clustering structure using the WebSort interactive dendogram are marked in the **Figure 5.4** matrix, with the resulting 16 objective categories labeled A-P for discussion. **Appendix D** provides the detailed objective dendogram resulting from the hierarchical clustering, which includes the position and contents (i.e., the statement placed on the card) of each objective card in the overall structure.

Structures elicited from participants in the objective card sorting study exhibited a large amount of variation, as indicated by the similarity score of only 63.0% calculated for the objective card sorts. A card-by-card agreement matrix revealing consistent, homogenous categories contains contiguous, triangular-shaped subsets of card pairs along the diagonal of the matrix that have a high degree of agreement, with very little agreement found in card pairs outside of these contiguous, triangular subsets (see the **Figure 5.5** operator card-by-card agreement matrix for a much more conclusive card-by-card agreement matrix). Participant comments provided through the 'Leave a comment' tab explicated much of the observed variation across participant sorting strategies. While the order of cards resulting from the hierarchical clustering primarily reflects the provided objective criterion, participants applied at least three competing criteria while sorting. In other words, many participants used additional salient qualities of the card universe to subdivide the initial objective categories further. Two of these criteria are related to the interaction operand while the third reveals a set of user goals; the former two criteria are discussed in **Section 5.3.2** while the latter is described in detail in **Section 5.3.3**. **Section 5.3.4** details the objective-based taxonomy identified once controlling for interaction operands and user goals, which includes five objective primitives: (1) *identify*, (2) *compare*, (3) *rank*, (4) *associate*, and (5) *delineate*.

5.3.2 Cartographic Interaction Operand Primitives

The first two confounding criteria on which participants sorted the objective cards describe components of the interaction operand. Following discussion in **Section 3.5**, an individual card sorting exercise was not included for interaction operands, as the operand was assumed to be fixed in the context of cartographic interaction (e.g., the *two-dimensional* data type from the Shneiderman, 1996, and Keim, 2002, type-centric operand-based taxonomies). However, many of the objective examples elicited during the **Chapter 4** cartographic interaction interviews included the operand as part of the example statement. It therefore is not surprising that many participants integrated characteristics of the operand into their sorting structures, with the revealed operand-based taxonomy described below representing an unplanned benefit of the objective card sorting study.

Both of the confounding operand-based sorting criteria closely match one of the dimensions in the Andrienko et al. (2003) operational task taxonomy (**Figure 3.5**) introduced in **Section 3.5**. The most influential Andrienko et al. dimension on the objective card sorting was the ***search target***, which draws from Peuquet's (1994) ***TRIAD*** framework and includes combinations of *space* (i.e., 'what'), *time* (i.e., 'when'), and *objects* (i.e., 'what' or 'who', or the attributes of the spatiotemporal phenomenon) as operand primitives. For any cartographic interaction, one or two of the three operand primitives are the target of investigation, with the other one or two operand primitives acting as constraints on the interactive, visual investigation. The Andrienko et al. search target dimension therefore is a type-centric operand-based taxonomy.

Interestingly, participants sorted according to search target combinations that privileged the spatial component of the information without prompting. Such an emphasis is explained in part by the nature of the card contents (i.e., the cards were generated from a review of the science and practice of cartographic interaction, which emphasized the geographic component of the represented information) as well as the participants' emphasis on and expertise in cartographic interface design and development; together, these characteristics resulted in a taxonomy of operand primitives that are explicitly cartographic. While all Andrienko et al. (2003) search target combinations remain important for spatiotemporal visualization broadly, the operand-based taxonomy identified from the objective card sorting study represents an ecologically valid simplification for Interactive Cartography and Geovisualization. The objective card sorting therefore revealed three type-centric cartographic interaction operand primitives:

(1) ***Space-Alone*:** The *space-alone* operand primitive describes cartographic interactions in which the user interacts only with the geographic component of the cartographic representation. Translating this operand into the Andrienko et al. (2003) operational task taxonomy, such interactions include examples of user objectives in which the 'what' and 'when' are known *a priori* or are not meaningful for the user's goals and objectives.

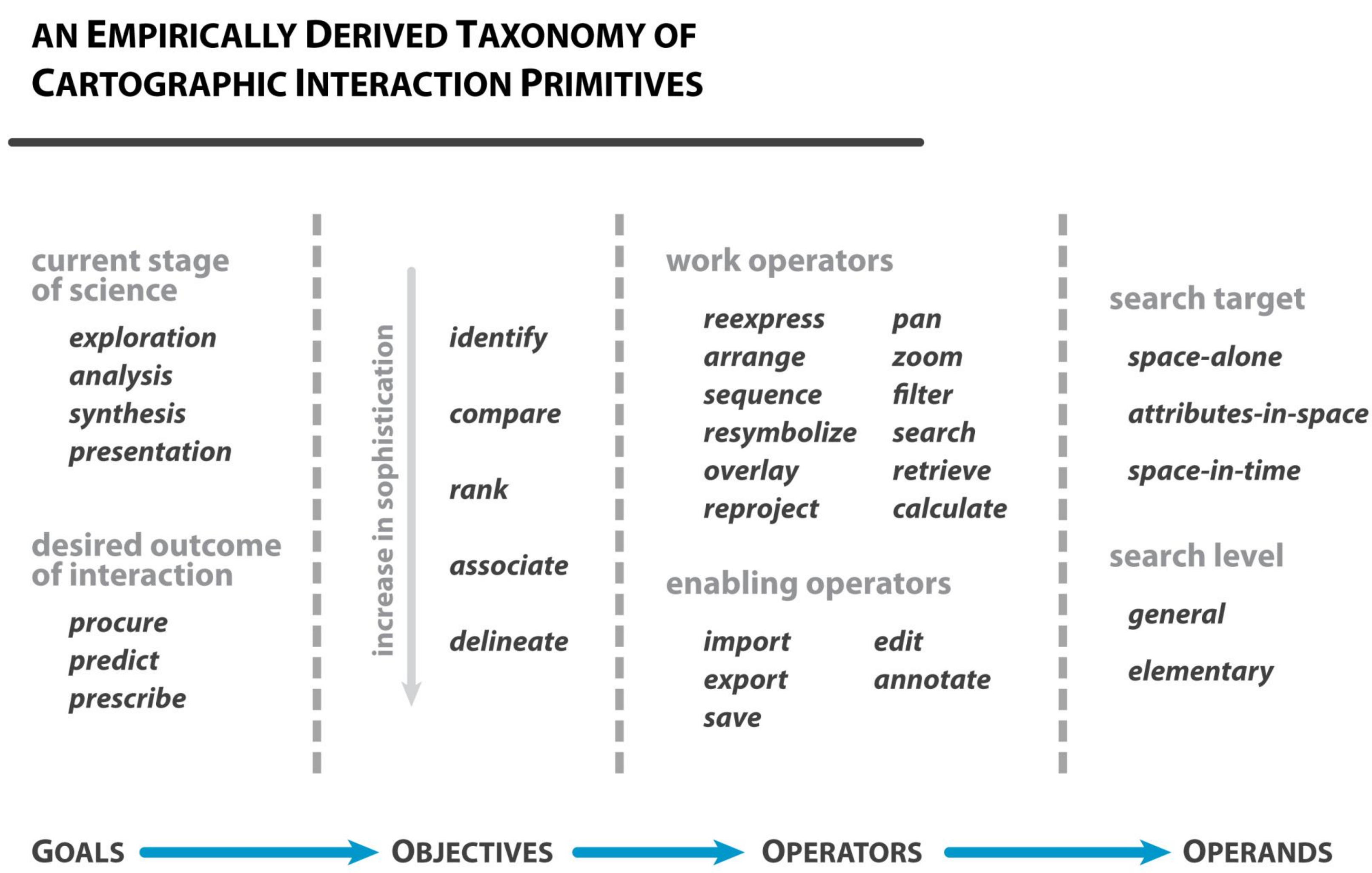


Figure 5.3: An Empirically Derived Taxonomy of Cartographic Interaction Primitives.

(2) ***Attributes-in-Space*****:** The *attributes-in-space* operand primitive describes cartographic interactions in which the user interacts with the attribute component of the cartographic representation to understand how one or several characteristics of a geographic phenomenon vary in space. Based on participant sorting, this cartographic interaction operand includes examples of user objectives in which the 'what' is known, with the user interactively seeking information about the 'where', as well as those in which the 'where' is known, with the user interactively seeking information about the 'what'.

(3) ***Space-in-Time*****:** The *space-in-time* operand primitive describes cartographic interactions in which the user interacts with the temporal component of the cartographic representation to understand how a dynamic geographic phenomenon acts over time. Based on the participant sorting, this cartographic interaction operand includes examples of user objectives in which the 'when' is known, with the user interactively seeking information about the 'where', as well as those in which the 'where' is known, with the user interactively seeking information about the 'when'.

Many participants applied this three-part operand distinction to further subdivide the objective categories (see **Section 5.3.4** for definitions), as a single objective primitive typically was composed of two or more smaller categories discriminated by the handling of *space-alone*, *attributes-in-space*, and, at a lesser frequency, *space-in-time*. The card-by-card agreement matrix reflects this overall approach to sorting. The *compare* objective was divided into two categories (**Figure 5.4a**: *attributes-in-space* and **Figure 5.4k**: *space-alone*), the *rank* objective was divided into two categories (**Figure 5.4l**: *space-alone* and **Figure 5.4m**: *attributes-in-space*), the *associate* objective was divided into three categories (**Figure 5.4b**: *space-in-time*, **Figure 5.4c**: *attributes-in-space*, **Figure 5.4d**: *space-alone*), and the *delineate* objective was divided into two categories (**Figure 5.4g**: *attributes-in-space* and **Figure 5.4h**: *space-alone*). The *space-in-time* operand was sorted by participants more frequently into its own category; aside from instances of the *associate* objective (**Figure 5.4b**), which primarily include objectives regarding trends and cause/effect relationships, cards including the *space-in-time* operand were placed into a single category (**Figure 5.4i**). **Table 5.2** provides example cards from the objective card sorting study representing each cartographic interaction operand and objective combination.

Most of the variation shown in the **Figure 5.4** card-by-card agreement matrix is explained by variation in participant reliance on this three-part operand-based taxonomy during their sorting. The variation is manifested in the matrix as linear subsets of card pairs with high agreement that are not along the diagonal; these linear subsets of high agreement indicate groups of cards that were sorted frequently by interaction operand instead of, or in addition to, interaction objective. However, many participants further divided the *identify* objective according to a second operand-based sorting criteria: the Andrienko et al. (2003) search level dimension. As described in **Section 3.5**, the ***search level*** describes the percentage of all map features under consideration. Andrienko et al. simply Bertin's (1967|1983) levels of map reading to include only two search levels: ***elementary*** (reading of and interacting with only one map feature) and ***general*** (reading of and interacting with several to all map features). The card-by-card agreement matrix reflects participant sorting on both search target and search level within the *identify* objective only, resulting in four sub-categories from the hierarchical clustering: (1) *attributes-in-space* at the general level (**Figure 5.4j**), (2) *space-alone* at the general level (**Figure 5.4n**), (3) *attributes-in-space* at the elementary level (**Figure 5.4o**), and (4) *space-alone* at the general level (**Figure 5.4p**). Interestingly, participants were less inclined to sort according to search level within the other objective primitives, perhaps because there were less total instances of the other objectives in the card universe. Finally, other characteristics of the interaction operand reviewed in **Section 3.5**, such as the dimensionality or the view state of the representation, did not appear to influence the sorting.

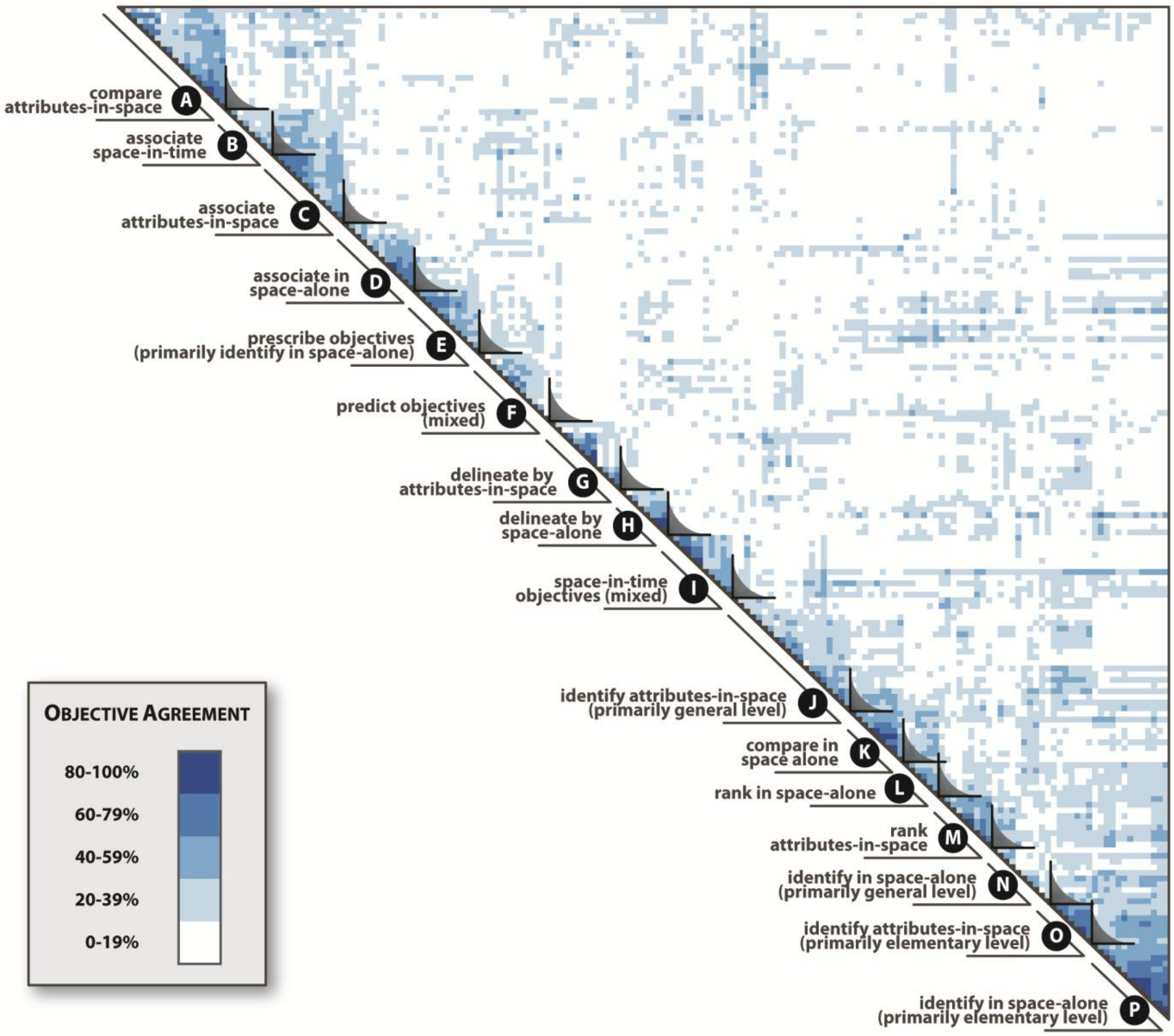


Figure 5.4: The Card-by-Card Agreement Matrix for the Objective Card Sorting Study. The matrix shows the category agreement between each possible pair of objective cards across the 15 participants, with higher agreement in darker blue and the order of cards on each axis in the matrix determined by hierarchical clustering. 16 clusters, identified using the interactive dendogram feature of WebSort, are marked and labeled with letters for discussion.

5.3.3 Cartographic Interaction Goals

Many participants identified a small subset of the objective cards as different from the rest of the card universe according to the "cognitive involvement" of the objective, a distinction that is related to the concept of user goals introduced in **Section 3.2**. Discussion thus far emphasizes very broad user goals based on DiBiase's (1990) ***swoopy diagram*** (**Figure 2.2**), which relates the appropriate number of unique map solutions to the current stage of science (exploration, confirmation/analysis, synthesis, presentation). The objective card sorting study revealed a secondary, less general taxonomy of interaction goals based on the kind of outcome the user is attempting to attain by performing the cartographic interaction.

Most of the included objective cards provide examples of basic information retrieval from the map. In other words, they describes situations when the user can procure an answer to a question from the map directly, with the question varying according to the three operand primitives described in **Section 5.3.2** and the five objectives described in **Section 5.3.4**. However, roughly two dozen of the cards required what participants described as a "broader assessment" or "advanced decision making." The objective card-by-card agreement matrix indicates that participants generally separated these cards from the rest of the set as two individual categories; the first category includes situations requiring the user to predict what may occur based on current conditions and domain knowledge, while the second category includes situations requiring the user to prescribe what should occur next, again based on current conditions and domain knowledge. The objective card sorting therefore identified three broad user goals, or meta-objectives, motivating use of cartographic interfaces, described together as the ***three P's*** of cartographic interaction:

(1) ***Procure*****:** The *procure* user goal describes cartographic interactions that are performed in order to retrieve information about the represented geographic phenomena. The *procure* goal is the most straightforward of the three *P*'s of cartographic interaction identified from the objective card sorting study. Approximately 150 of the 176 cards included in the objective card sorting study exemplify this user goal, indicating that the *procure* goal perhaps is the most common user goal motivating employment of cartographic interfaces (or at least the easiest to articulate). Such an emphasis on the *procure* goal mirrors sentiment from the **Chapter 4** cartographic interaction interviews that the primary utility of cartographic interaction is to answer questions more quickly than visual interpretation alone. Unless otherwise noted, all card examples described in the **Section 5.3.4** are examples of the broader *procure* goal.

(2) ***Predict*****:** The *predict* user goal describes cartographic interactions that are performed in order to assist the user in forecasting what may occur in the future based on current conditions of the represented geographic phenomena. The *predict* goal describes uses of cartographic interfaces that are an order of magnitude more complex cognitively from the aforementioned *procure* goal, as the user must combine the insight procured interactively from the cartographic representation with their domain knowledge and past experience to estimate what may occur at a later date. Example cards from the objective card sorting study representing the *predict* goal include "predict the spatial outbreak pattern of a disease," "when will the bluff erosion reach my house?," and "what will happen at the same location in five years from now when there is another hurricane?" (**Figure 5.4f**).

(3) ***Prescribe*****:** The *prescribe* user goal describes cartographic interactions that are performed in support of deciding what should occur in the future based on current conditions of the represented geographic phenomena. The *prescribe* goal is the most complex cognitively of the three *P*'s of cartographic interaction, as it typically requires prediction of what is likely to happen in the future with an additional intervention step to alter the future course towards one deemed more appropriate or optimal. The *prescribe* goal is related directly to the emerging research thrust of ***GeoDesign***, or the use of geographic information and interactive cartographic representations to determine how best to modify the built environment (Goodchild, 2010). Example cards from the objective card sorting study representing the *prescribe* goal include "where is the best place to put a new sensor?," "prioritize potential sites to build a natural gas plant," and "who should I move first after a sustained chemical release?" (**Figure 5.4e**).

5.3.4 Cartographic Interaction Objective Primitives

The objective card sorting study revealed five objective primitives once controlling for the three competing sorting criteria described above. The sub-clusters within each objective primitive, produced from further subdivision by operand primitive (**Section 5.3.2**), are proximate in the **Figure 5.4** card-by-card agreement matrix, with the *compare* primitive the lone exception (i.e., the **Figure 5.4a** and **Figure 5.4k** sub-clusters are separated in the card order produced from the hierarchical clustering). Such overall proximity of these smaller clusters indicates that the provided objective sorting criterion remained the most influential criterion on participant sorts, with the operand criteria applied secondarily to refine the categories further. However, it is important to note that the objective dimension of the **Figure 5.3** interaction primitive taxonomy exhibited the greatest amount of variation across participant sorting (as indicated in the **Figure 5.4** matrix), with several sets of cards sorted illogically or inconsistently; several of the more common areas of confusion are discussed in the following explanation of objective primitives. Therefore, it is likely that the objective dimension, and to a lesser degree the other three dimensions, will require revision and extension as subsequent research is completed on cartographic interaction primitives and prototypically successful interaction strategies (see **Section 5.5**).

One open issue regarding objective-based taxonomies identified through the **Section 3.3** review is the appropriateness of including primitives in an objective-based taxonomy that are not at the same semantic level of meaning. Yi et al. (2007) explicitly argued against including primitives in an objective-based taxonomy that vary in their level of meaning. They did not include the *compare* primitive in their taxonomy—the most common objective primitive in **Figure 3.2** and one of the objective primitives consistently identified by participants during the objective card sorting study (see below)—because it was considered a composite objective that required application of two or more *identify* primitives. In contrast, Zhou and Feiner (1998) organized their 15 objective primitives into larger categories according to ***visual accomplishments*** (i.e., the change to the operand, provided to the user through feedback, as a result of the completion of the objective) and ***visual implications*** (i.e., the new objectives that can be achieved after first completing a given objective). Further, Crampton (2002) organized his five objective primitives along a continuum according to level of ***sophistication***, defined as the amount and complexity of the operators required to complete the objective, indicating a continuum from basic objective primitives (Crampton's *examine* and *compare*) to sophisticated ones (Crampton's *(re)order/(re)sort*, *extract/suppress*, and *cause/effect*). Most participants accepted this latter continuum of sophistication in their discrimination of objective categories; in the comments, one participant stated that the sort followed a "progression from simple objectives to complex decision making tasks" while a second stated that the resulting categories varied from "simple geographic non-computational questions/actions" to "complex geographic inquiries." The objective card sorting therefore revealed five cartographic interaction objective primitives that increase in sophistication in the following order; as noted in **Section 5.3.2**, **Table 5.2** provides an example card from the sort for each objective and operand combination:

(1) ***Identify*****:** The *identify* objective describes cartographic interactions that are performed to examine and understand a single map feature, either an individual object when at the elementary search level or a broader region when at the general search level. The *identify* objective is the simplest of the five objective primitives revealed by the first card sorting study, positioned at a similar level of sophistication as Crampton's (2002) *examine* (which overlaps conceptually with *identify*), and is the only objective primitive that was further subdivided by search level during the card sorting study. The *identify* primitive is included in a majority of the objective-based taxonomies reviewed in **Section 3.3** (e.g., Wehrend and Lewis, 1990, Wehrend, 1993, Zhou and Feiner, 1998, Blok et al., 1999, MacEachren et al., 1999, Andrienko et al., 2003). The *identify* objective describes a geographic search (i.e., 'find in space' or 'locate in space') with regard to the *space-alone* operand primitive and an attribute search (i.e. 'find attribute' or 'retrieve attribute') with regard to the *attributes-in-space* operand. This difference is synonymous to Albrecht's (1997) distinction between *spatial search* and *thematic search* in the context of GIS operators and is related to Wehrend's and Zhou and Feiner's inclusion of a *locate* primitive in their respective taxonomies to discriminate the application of *identify* in space (*locate*) versus attribute (*identify* generally). Example cards from the objective card sorting study representing the *identify* objective paired with the *space-alone* operand include "identify your house based on an aerial image in Google Earth" (elementary search level; **Figure 5.4p**) and "what is the range of the endangered species?" (general search level; **Figure 5.4n**), while example cards representing the *identify* objective paired with the *attributes-in-space* operand include "what explosives materials are known to be inside a building that is on fire?" (elementary search level; **Figure 5.4o**) and "quantify the amount of damage caused by a natural disaster" (general search level; **Figure 5.4j**). Finally, when applied to the *space-in-time* operand primitive, the *identify* objective describes a temporal search (i.e., 'find when' or 'locate when') or a spatial search with time used as a constraint. Several of the cards included in the **Figure 5.4i** *space-in-time* cluster illustrate the *identify* objective; example cards include "how many hotels were in the town in the late 1800s?" and "when will the bluff erosion reach my house?" (an example with a *predict* goal).

(2) ***Compare*****:** The *compare* objective describes cartographic interactions that are performed to determine the similarities and differences between two or more map features. The *compare* objective is a level of sophistication greater than the *identify* objective, as two or more individual *identify* objectives must be achieved in order to achieve the *compare* objective; *compare* also is the second least sophisticated objective in Crampton's (2002) taxonomy, following *examine*. The *compare* primitive is the most commonly listed primitive in the objective-based taxonomies reviewed in **Section 3.3** (e.g., Wehrend and Lewis, 1990, Wehrend, 1993, Zhou and Feiner, 1998, Blok et al., 1999, MacEachren et al., 1999, Crampton, 2002, Andrienko et al., 2003), despite Yi et al.'s (2007) argument against including it as a fundamental objective. Regarding the *space-alone* operand, the *compare* objective examines the difference in bearings or distances of two map features to a reference point as well as the difference in the distributions (e.g., the overall extent or general shape) of two kinds of geographic phenomena; example cards include "where is our location in relation to another response team?" and "compare the distribution of patients over 65 years old to the distribution of patients that were not treated with radiation." Participants illogically sorted the subset of cards denoting identification of the distance between a pair of locations—and not comparison between a pair of distances (e.g., compare the distance between Point A and Point B to the distance between Point A and Point C)—into the *compare* in *space-alone* category (**Figure 5.4k**). Such examples more logically belong under the *identify* in *space-alone* category and provide additional explanation of the low reliability (63.3%) reflected in the objective card sorting results. It is possible that this sorting strategy was adopted given the presence of two map features in the card statements, rather than a single map feature, as with most other *identify* card examples (i.e., the *operand* was more salient than the *objective*, for this subset of cards). This inconsistency in sorting perhaps explains the distance between the *compare* in *space-alone* and the *compare* in *attributes-in-space* clusters in the **Figure 5.4** matrix. When the *compare* objective is applied to the *attributes-in-space* operand, the *compare* objective either evaluates the difference between attribute values of two map features (when the attributes are quantitative/numerical) or determines if the map features are members of the same or different feature type (when the attributes are qualitative/categorical); example cards include "compare the estimated air pollution levels from two models that include a different set of predictive variables" (quantitative) and "discern between two types of policies on the map" (qualitative; **Figure 5.4a** includes both quantitative and qualitative examples). Finally, the *compare* objective applied to the *space-in-*

time operand examines the time between two geographic events or the difference between geographic patterns exhibited at different time periods, temporal composites, and temporal resolutions; several of the cards included in the **Figure 5.4i** *space-in-time* cluster illustrate the *compare* objective, including "compare the historic vegetation to the current vegetation" and "was there a change in the rate of prostate cancer here between the two years?"

(3) ***Rank*:** The *rank* objective describes cartographic interactions that are performed to determine the order or relative position of two or more map features. The *rank* objective exhibits yet another level of sophistication greater than *compare*, as the objective requires the user not only to determine the difference between the two or more map features either in space, time, and/or attribute, but also to determine an ordering based on this difference. This increase in sophistication again follows Crampton's (2002) objective-base taxonomy, who instead uses the term *(re)order/(re)sort*; the term *rank*, drawn from Wehrend (1993) and Zhou and Feiner, (1998) is used over *order* or *sort* (the latter also is used by Amar et al., 2005) to avoid confusion with cartographic interaction operators, specifically cartographic interfaces that allow users to sort the data according to an attribute, as well as use of the term for sorting into

Objective	***Space-Alone***	***Attributes-in-space***	***Space-in-time***
Identify	locate in space (where?)	find attribute (what?)	locate in time (when?)
	identify your house based on an aerial image in Google Earth	*what explosives materials are known to be inside a building that is on fire?*	*how many hotels were in the town in the late 1800s?*
Compare	difference between bearings, distances, extents, or shapes	difference between values (quantitative), same or different type (qualitative)	difference in time lengths, composites, or resolutions
	compare the distribution of patients over 65 years old to the distribution of patients that were not treated with radiation	*discern between two types of policies on the map*	*compare the historic vegetation to the current vegetation*
Rank	order by nearer/farther	order by more/less, better/worse	order by before/after
	where are the nearest schools to the toxic chemical release?	*which county has the highest mesothelioma mortality rate?*	*have any apprehensions occurred in the last seven days in this area?*
Associate	strength of connectedness, routing/topology	correlation between variables	trend across time, cause/effect
	this small town community is connected to which major urban systems?	*is socioeconomic status correlated spatially to gonorrhea rates?*	*see if the remediation procedure resulted in reducing the geographic extent of the chemical*
Delineate	division into distinct regions, clustered/disperse	division into distinct types according to attribute values	division into distinct periods, spikes/troughs
	where are the high risk clusters of disease morbidity?	*find clusters of similar attribute values within a set of map features*	*look into a spike of disorderly conduct cases in an area*

Table 5.2: Definitions and Examples of Each Objective and Operand Primitive Combination

categories (which falls under the *delineate* objective primitive). The prototypical example of the *rank* objective produces the complete order of all map features under investigation. However, participants also included the relative ranking of a set of map features to determine only the first or last map feature in the order (a use of the *rank* objective synonymous with Amar et al.'s *find extremum* objective) or for the purpose of isolating map features with attributes above or below a critical threshold (a use that more logically may fall under the *delineate* category, particularly if the threshold is determined by the user). When applied to the *space-alone* operand, the *rank* objective orders map features by spatial proximity (i.e., 'nearer' or 'farther'), with map features sorted according to their distance from a reference point; map features also can be ranked according to other geographic characteristics, such as bearing and size, although ranking by distance was the only example elicited from the **Chapter 4** cartographic interaction interviews. Example cards from the objective card sorting study representing the *rank* objective paired with the *space-alone* operand include "where are the nearest schools to the toxic chemical release" and "where are the nearest sewers to a hazardous chemical release?" (**Figure 5.4l**). Regarding the *attributes-in-space* operand, the *rank* objective orders map features according to a numerical attribute value (i.e., 'more' or 'less', or, in the context of the *prescribe* goal, 'better' or 'worse'); given the nature of nominal level data, the *rank* objective generally is not appropriate for application to attributes that are qualitative or categorical in nature. Example cards illustrating *rank* by *attributes-in-space* include "which county has the highest mesothelioma mortality rate?" and "which area has the highest frequency of available insurance adjustors?" (**Figure 5.4m**). Finally, the *rank* objective applied to the *space-in-time* operand orders map features according to temporal proximity (i.e., 'before' or 'after'), with map features ordered according to their linear position from a start date or relative position to one another; map features also can be ranked according to other temporal characteristics, such as their position in a cyclical, reoccurring set of temporal units or their temporal extent. Example cards indicating *rank* by *space-in-time* include "where was this salesman before and after his stay in the town?" and "have any apprehensions occurred in the last seven days in this area?"

(4) ***Associate*****:** The *associate* objective describes cartographic interactions that are performed to determine the relationship between two map features or among three or more map features. The *associate* objective represents a slight increase in sophistication from the previously reviewed objective primitives, as the user needs to characterize the often nuanced connection between map features, rather than determine the difference between the map features (*compare*) or determine the ordering of map features (*rank*). Such a use of *associate* follows Wehrend (1993) and Zhou and Feiner (1998). When applied to the *space-alone* operand, the *associate* objective describes the strength of spatial connectedness across multiple locations or map features. Example cards include "this small town community is connected to which major urban systems?" and "how does corn move across the landscape from farms to homes?" (**Figure 5.4d**). Interestingly, participants also included cards describing routes between locations and topology between regions under the *association* in *space-alone* category, instances that may not be the prototypical example of *associate* but do characterize the relationship between locations or map features nonetheless. Regarding the *attributes-in-space* operand, the *associate* objective is synonymous with the more specific *correlate* objective primitive included in several of the objective-based taxonomies (Wehrend, 1993, Zhou and Feiner, 1998, Amar et al., 2005), in which geographic distribution of two variables are characterized according to their dependency on one another (e.g., positive, negative, or no correlation); example cards include "is there a spatial association between age and rural status?" and "is socioeconomic status correlated spatially to gonorrhea rates?" (**Figure 5.4c**). As noted in **Section 5.3.2**, *associate* is the only objective that participants generally subdivided according to the *space-in-time* operand (**Figure 5.4b**), with all other objectives regarding the *space-in-time* operand falling into a single, mixed category according to the hierarchical clustering (**Figure 5.4i**). When applied to the *space-in-time* operand, the *associate* objective includes the notion of trends over time as well as cause and effect relationships (i.e., a before/after relation, as determined by the *rank* objective, that also implies the before condition caused the after condition); the latter is synonymous with Crampton's (2002) *cause/effect* primitive. Example cards illustrating the *associate* objective as applied to the *space-in-time* operand include "see if the remediation procedure resulted in reducing the geographic extent of the chemical" and "did the added policing resources cause the criminal activity to shift away from that area?"

(5) ***Delineate*****:** The *associate* objective describes cartographic interactions that are performed to organize map features into a logical structure. The *delineate* objective encapsulates both the *categorize* (place objects into a predetermined set of divisions for organization) and *cluster* (join objects into groups based on similar characteristics without an *a priori* set of intervals) objectives from the Wehrend (1993) and Zhou and Feiner, (1998) objective-based taxonomies; participants did not make a distinction between *categorize* and *cluster* during sorting, indicating either that the objectives are conceptually similar or that the participants did not understand this distinction. The *delineate* objective is the most sophisticated objective of the five identified from the objective card sorting study, as participants need to use the insights generated through application of *identify*, *compare*, *rank*, and *associate* to divide the set of map features under investigation into distinct groups. When applied to the *space-alone* operand, the *delineate* objective divides map features into internally homogenous and externally identifiable geographic neighborhoods or regions. Participants also included cards illustrating examples of spatial clustering of a geographic phenomenon in this category during their sorts, which characterizes regions as clustered, disperse, or randomly arranged. Example cards illustrating the *delineate* objective as applied to the *space-alone* operand include "look for clusters of robberies within a section of the city" and "where are the high risk clusters of disease morbidity?" (**Figure 5.4h**). Regarding the *attributes-in-space* operand, the *delineate* objective divides map features into internally homogenous and externally identifiable groups according to feature characteristics; example cards include "find clusters of similar attribute values within a set of map features" and "place map features into specifically defined divisions in a classification" (**Figure 5.4g**). Finally, the *delineate* objective applied to the *space-in-time* operand divides map features into internally homogenous and externally identifiable eras; *delineate* by *space-in-time* also can be extended to include determination of spikes and troughs of a dynamic geographic phenomenon. None of the cards included in the **Figure 5.4i** *space-in-time* cluster perfectly represent a *delineate* by *space-in-time* example; the few examples instead were sorted into the *associate* by *space-in-time* (**Figure 5.4i**), such as "look into a spike of disorderly conduct cases in an area."

5.4 Results and Discussion: Operators

5.4.1 Participant Agreement on Operators

The **Figure 5.5** card-by-card agreement matrix illustrates the pairwise agreement across participants for the operator card sorting study. Like the **Figure 5.4** matrix of objective primitives, operator cards in the **Figure 5.5** matrix are ordered according to average linkage hierarchical clustering on agreement and one half of the symmetrical matrix is masked to avoid errors in interpretation. Also like **Figure 5.4**, key divisions between clusters of cards, identified using the WebSort interactive dendogram, are marked in the **Figure 5.5** matrix, with the resulting 17 operator categories labeled A-Q for discussion. The detailed operator dendogram resulting from the hierarchical clustering is provided in **Appendix D**.

Unlike the objective card sorting study, the cognitive structures elicited during the operator card sorting study exhibited a high degree of similarity across participants, as indicated by the relatively high similarity score of 83.3%. The consistency across sorting solutions is illustrated by the **Figure 5.5** operator card-by-card matrix, as most of the identified categories of operator primitives are manifested in the matrix as contiguous, triangular-shaped subsets of card pairs along the diagonal. Interestingly, participants appeared to isolate operator primitives that support work interactions from those that support enabling interactions. **Section 5.4.2** details enabling operators identified through the operator card sorting study, which includes five operator primitives: (1) *import*, (2) *export*, (3) *save*, (4) *edit*, and (5) *annotate*. **Section 5.4.3** then details the operator-based taxonomy comprising work operators, which includes 12 operator primitives: (1) *reexpress*, (2) *arrange*, (3) *sequence*, (4) *resymbolize*, (5) *overlay*, (6) *reproject*, (7) *pan*, (8) *zoom*, (9) *filter*, (10) *search*, (11) *retrieve*, and (12) *calculate*.

5.4.2 Enabling Cartographic Interaction Operators

A subset of the operator primitives identified from the operator card sorting study primarily support enabling interactions. As introduced in **Section 2.4**, ***work interactions*** describe interactions that directly accomplish the desired objective, while ***enabling interactions*** describe interactions that are required to prepare for, or clean up from, these work interactions. Several of the operator-based taxonomies reviewed in **Section 3.4** also separate enabling interactions from work interactions (e.g., Chuah and Roth, 1996, Shneiderman, 1996, Yi et al., 2007). In the **Figure 5.5** matrix, enabling operators are isolated at both ends of the diagonal, while work operators are grouped in the center. Approximately 50 of the 206 operator cards (~25%) represent enabling interactions, illustrating the importance of considering such operator primitives during the conceptual design and development of a cartographic interface. In total, the operator card sorting study revealed five enabling cartographic operators:

(1) ***Import*****:** The *import* operator describes enabling cartographic interactions that load an existing dataset or previously generated cartographic representation into the cartographic interface. The *import* operator is applied primarily at the beginning of an interaction session to initialize the cartographic interface for work interactions, but can be performed throughout the session if additional datasets are needed. In the context of web-based cartographic interfaces, the *import* operator includes downloading of datasets from external web repositories (but not downloading one's own work for future use; such examples were sorted under the *export* operator) and dynamic loading of real-time data feeds from web services. Example cards from the operator card sorting study representing the *import* operator include "get started by loading a stock map design of the world," "import the model results from NOAA into a GIS system," and "import a real-time data feed on hospital patients to generate a map" (**Figure 5.5a**).

(2) ***Export*****:** The *export* operator describes enabling cartographic interactions that extract part or all of a generated cartographic representation, the geographic information underlying the representation, or the status of the system for future use outside of the cartographic interface. The *export* operator represents the conceptual opposite of the *import* operator and generally is performed when moving to a different map use setting in order to clean up from prior work interactions within the current setting. The new setting may support ***analog*** map use only (see **Section 1.3**), such as printing a hardcopy of the cartographic representation or generating a text-based report of the extracted geographic information. The *export* operator is similar to Shneiderman's (1996) *extract* operator, but can be applied to the entire set of map features (rather than a filtered subset) and to the cartographic representation or the represented geographic information. Example cards representing the *export* operator include "export the map as a .pdf," "get a screenshot of the map," and "make a hard copy of the map to give to a coordinating officer" (**Figure 5.5b**).

(3) *Save*: The *save* operator describes enabling cartographic interactions that store the generated cartographic representation, the geographic information underlying the representation, or the status of the system for future use within the cartographic interface. The *save* and *export* operators are conceptually similar, with the primary difference being the future setting of map use (internal versus external to the cartographic interface, respectively). The *save* operator is essential for support of undo and redo interactions, a pair of enabling interactions that falls under Shneiderman's (1996) *history* primitive; participants generally did not distinguish between saving and undo/redo in their sorting approaches given their reliance on each other. The *save* operator also is related to the concepts of ***data provenance***, or the tracking of how the original, input dataset is manipulated across interactions (Ludäscher et al., 2006), and

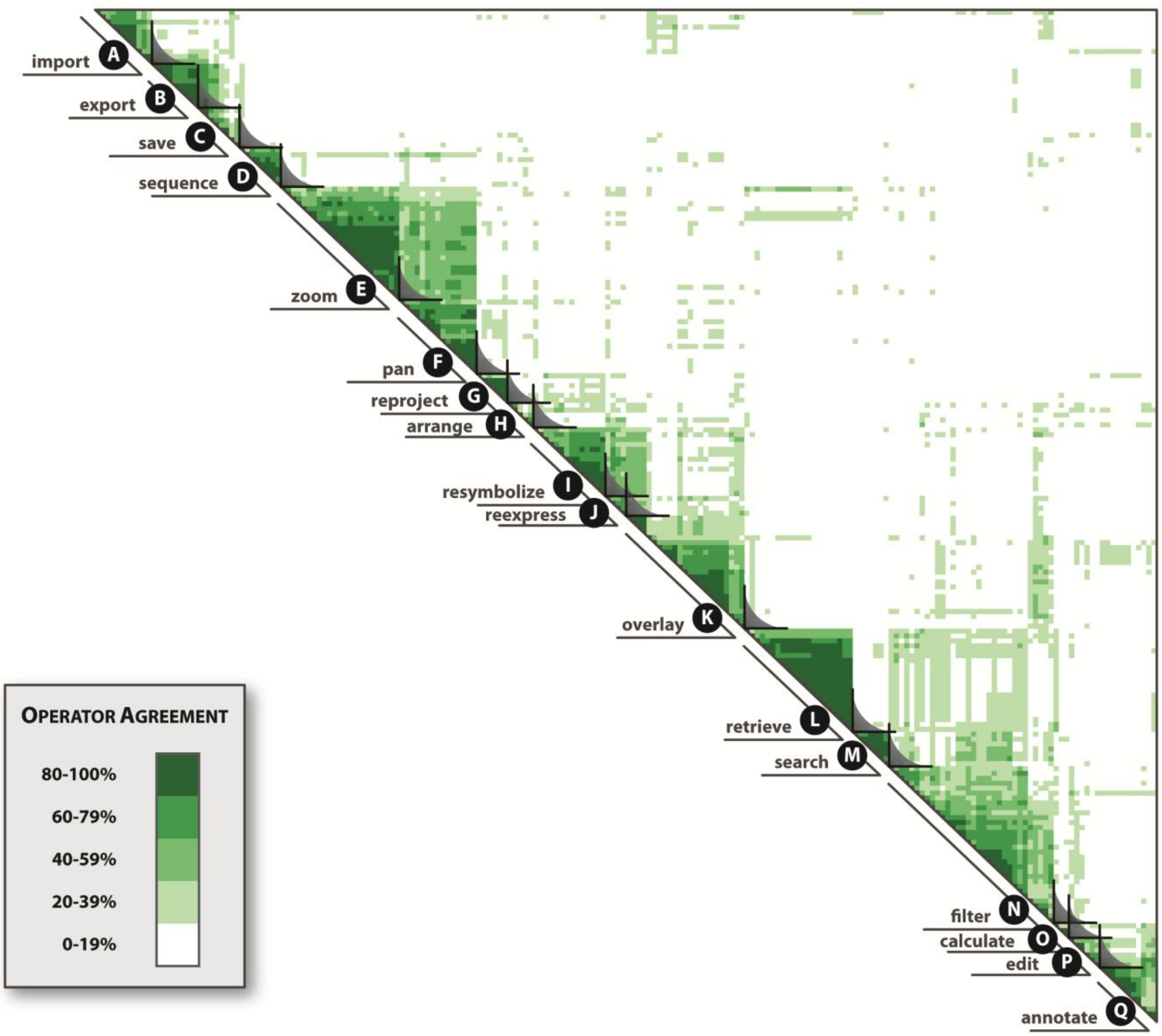


Figure 5.5: The Card-by-Card Agreement Matrix for the Operator Card Sorting Study. The matrix shows the category agreement between each possible pair of objective cards across the 15 participants, with higher agreement in darker blue and the order of cards on each axis in the matrix determined by hierarchical clustering. 17 clusters (5 representing enabling operators, 12 representing work operators), identified using the interactive dendogram feature of WebSort, are marked and labeled with letters for discussion.

revisualization, or the capture and visualization of an interaction session itself (i.e., the application of cartographic interaction to understand cartographic interaction; Robinson and Weaver, 2006). Example cards representing the *save* operator include "save the map so that you can come back later to make a modification," "save a map as a project file to allow other people to collaborate on it," and "roll back to an earlier version of the map" (**Figure 5.5c**).

(4) ***Edit*****:** The *edit* operator describes enabling cartographic interactions that manipulate the geographic information underlying the representation, which then alters all subsequent cartographic representations of that information. The *edit* operator is unique in that it is specific to a state-centric perspective of interaction operand primitives (**Section 3.5**), distinguishing between operators applied to the data-state (i.e., *edit*) and operators applied to the visualization-state (i.e., work interactions, or the cartographic interaction operators listed in **Section 5.4.3**). According to participant card sorting, all enabling interactions (e.g., *add*, *create*, *delete*, *join*, and *manipulate objects*) listed by Chuah and Roth (1996) fall within the scope of the *edit* operator. Example cards representing the *edit* operator include "select a point to change the attribute data," "delete the selected map features," and "redraw a line feature in ArcMap that needs to be edited" (**Figure 5.5p**).

(5) ***Annotate*****:** The *annotate* operator describes enabling cartographic interactions that add graphic markings and textual notes to the cartographic representation to externalize insight generated from work interactions. Annotation relates to the use of maps in support of ***distributed cognition*** (see **Section 2.3**), with the *annotate* operator explicitly facilitating visual thinking (i.e., map-mediated cognition) by allowing the user to externalize insights directly onto the cartographic representation as they interact with it. Therefore, the *annotate* operator is less an enabling interaction applied to prepare for or clean up from work interactions, but instead an enabling interaction that enhances the analytical value—and longevity of analytical insights—of work interactions. The *annotate* operator also is important in the context of ***Geocollaboration***, described in **Section 2.6** as a subfield of Cartography that focuses upon the design and use of cartographic interfaces that support cooperative and collaborative activities; this is particularly true when the cartographic interaction operators are performed collaboratively in support of *prescribe* goals (see **Section 5.3.3**). Example cards representing the *annotate* operator include "use the annotation editor to add notes about each hospital to the map," "use the annotation tools to draw arrows on the map indicating important locations," and "mark up the map to indicate where to send resources" (application of the *annotate* operator in support of the *prescribe* goal; **Figure 5.5q**).

5.4.3 Cartographic Interaction Operator Primitives

The operator card sorting study revealed a diverse set of 12 fundamental cartographic interaction operators that are distinct from the subset of enabling cartographic interaction operators reviewed in **Section 5.4.2**. Interestingly, neither *brushing* nor *linking*—two of the three most common operator primitives included in the **Figure 3.3** operator concept map—were identified as unique operator primitives across the participant sorts. As introduced in **Section 3.4**, ***brushing*** is a two-step process in which the direct manipulation interface style is used to select one or more map features of interest, with a cartographic interaction operator then applied to this selected map feature or set of map features (i.e., *brushing*+operator). The reviewed operator-based taxonomies were split in their emphasis on the first step (i.e., *brushing* as *selection*) or second step (i.e., *brushing* for applying some interaction operator, most commonly *highlight*). That the participants did not include *brushing* in its own category, despite numerous potential examples, indicates that participants generally acknowledged this two-step condition of brushing in their sorting; one participant explained this issue using the 'Leave a comment' tab, stating that "operators that happen when a user brushes the display could be in several different categories...all methods for extracting information are treated together, whether that is by brushing, clicking, or the identify tool." As noted in the following review of primitives generated from the operator card sorting study, participants sorted most cards denoting the concept of *brushing* under the *filter* and *retrieve* operators, with example cards illustrating brushing of multiple map features sorted into the *filter* category and example cards illustrating brushing of a single map feature generally sorted in the *retrieve* category.

The **Section 3.4** review also notes a potential conceptual problem with *linking* as an operator primitive. ***Linking*** often is implemented as a third step in the *brushing*+operator process, applying the same changes made interactively to the brushed map feature or features to the associated data item or items in linked isomorphic views (i.e., *brushing*+operator+*linking*). It is possible to conceptualize *linking* as an operator primitive when the user interactively specifies the coordination among information views (e.g., Hardisty, 2003) or when a cartographic interface is provided that allows the user to link explicitly a set of associated map features (as in the case of cartographic interfaces supporting the synthesis stage of science); however, no card examples of these two kinds of cartographic interaction were generated by the background review on operators (**Chapter 3**) or cartographic interaction interviews (**Chapter 4**). As noted in the following review of primitives generated from the operator card sorting study, participants sorted the few cards denoting *linking* under the *arrange* operator.

Most of the 12 operator primitives identified through the operator card sorting study also are identified in the **Figure 3.3** summary of extant operator-based taxonomies, although less frequently than *brushing* and *linking*. The 12 operator primitives span across four broad and overlapping categories: (1) operators that manipulate the type, layout, and order of cartographic representations and linked information graphics (*reexpress*, *arrange*, and *sequence* respectively); (2) operators that manipulate the design of the cartographic representation (*resymbolize*, *overlay*, and *reproject*; this higher level category also was identified in the **Section 3.4** review of extant operator-based taxonomies); (3) operators that manipulate the user's viewpoint of the cartographic representation, once designed (*pan* and *zoom*; a similar subset of primitives was identified in the **Section 3.4** review of extant operator-based taxonomies); and (4) operators that further examine an individual map feature or set of map features within the representation (*filter*, *search*, *retrieve*, *calculate*). The grouping of operator primitives in the **Figure 5.5** card-by-card agreement matrix resulting from the hierarchical clustering generally reflects these four categories, with several exceptions (e.g., the *sequence* operator is ordered next to the enabling operators *import*, *export*, and *save*, the *reproject* operator is ordered next to the *pan* and *zoom* map browsing operators). The 12 primitives constituting the cartographic interaction operator taxonomy include:

(1) ***Reexpress*****:** The *reexpress* operator describes cartographic interactions that set or change the visual isomorph used in the cartographic representation or information views linked to the cartographic representation. The concept of a ***visual isomorph*** is introduced in **Section 2.3** as a representation of equivalent information in a different visual structure. The term 'dynamic reexpression' originates from Tukey (1977), first was used cartographically by DiBiase et al. (1992), and later was included in the Shepherd (1995) and Dykes (1997) operator-based taxonomies. When applied to the cartographic representation alone, the *reexpress* operator describes a change to the kind of map displayed (choropleth, dot density, isoline, proportional symbol, etc.), a use of the term that is similar to Edsall et al.'s (2008) *altering representation type*, Chuah and Roth's (1996) *encode data*, and Dix and Ellis's (1998) *same data, changing representation*. Following Tukey, DiBiase et al. include within their definition of *reexpress* any transformation to the original geographic information that produces a new visual isomorph, which can be based on attributes in the dataset (e.g., providing a logarithmic or smoothed representation) or the temporal component of the dataset (e.g., switching between a linear versus composite representation of time). Example cards from the operator card sorting study representing the *reexpress* operator include "switch among multiple map displays of the same spatial data," "alternate between more than one graphic version of a spatial data set," and "switch among multiple map representation strategies" (**Figure 5.5j**).

(2) ***Arrange*****:** The *arrange* operator describes cartographic interactions that manipulate the layout of a visual isomorph when multiple, typically linked visually isomorphic views are provided. The *arrange* operator is synonymous with Buja et al.'s (1996) *arranging views* primitive and primarily is implemented in the context of ***coordinated, multi-view visualization***, introduced in **Section 3.4** as a class of interactive systems that allow the user to create a number of linked visual isomorphs of a dataset, maps being perhaps only one in a suite of representation forms. As stated above, the small subset of cards describing *linking* were sorted by participants into the broader *arrange* primitive. Example cards representing the *arrange* operator include "arrange a large number of maps for simultaneous comparison" and "link multiple representations of the same spatial data together" (**Figure 5.5h**).

(3) ***Sequence*****:** The *sequence* operator describes cartographic interactions that generate an ordered set of related cartographic representations. Such a definition follows MacEachren et al.'s (1999) and Masters and Edsall's (2000) *sequence* operator primitive. The generated set of representations often are not visual isomorphs—although they can be—but instead may be a related set of cartographic representations that each show only a subset of the complete geographic information set; the *sequence* operator therefore is associated with the *filter* operator, which extracts a subset of the map features that match user specified constraints (i.e., *filter* may be applied non-interactively to generate the sequence of representations). The *sequence* operator typically is performed on the temporal component of a dynamic geographic phenomenon in the context of ***cartographic animation***, using the dynamic visual variable *order* to represent the sequencing order. However, the *sequence* operator also can be used to generate a cartographic animation according to the geographic or attribute components of the dataset as well as to generate a series of ***small multiples***, displaying each cartographic representation in the sequence simultaneously as a separate view (the positions of which can be manipulated by applying the *arrange* operator). Example cards representing the *sequence* operator include "string together a series of maps into a slideshow," "display one time slice after another on the map," and "click play to begin the map animation" (**Figure 5.5d**).

(4) ***Resymbolize*****:** The *resymbolize* operator describes cartographic interactions that set or change the design parameters of a cartographic representation form without changing the represented map features or the cartographic representation form itself. The symbolization parameters that can be manipulated through the *resymbolize* operator are specific to the cartographic representation form selected (choropleth, dot density, isoline, proportional symbol, etc.) and may include interactions with the classification scheme (all graduated map types), the color scheme (for choropleth maps or hypsometric tinting of isoline maps), the dot value (for dot density maps), the contour interval (for isoline maps), the scaling ratio (for proportional symbol maps), the applied symbol styling (for reference maps), etc. The *resymbolize* operator therefore differs from the *reexpress* operator in that the user does not request a different visual isomorph, but instead a different graphic presentation of the same visual isomorph. Such a use of *resymbolize* is synonymous with Chuah and Roth's (1996) *set-graphical-value*, Dix and Ellis's (1998) *same representation, changing parameters*, and Edsall et al.'s (2008) *altering symbolization* and is related to MacEachren et al.'s (1999) and Masters and Edsall's (2000) *colormap manipulation* (which implies interaction with a choropleth map, although is stated to be general to all map types). Example cards representing the *resymbolize* operator include "alter map symbolization choices such as classification scheme, color scheme, interpolation type, or contour interval," "change the relative sizing of circular proportional symbols," and "apply a different style to the look of the basemap" (**Figure 5.5i**).

(5) ***Overlay*****:** The *overlay* operator describes cartographic interactions that adjust the features types (i.e., categories of map features) included in the cartographic representation. Based on participant sorting strategies, the *overlay* operator primarily includes card examples describing the on/off toggling of map layers in the context of reference mapping, but also includes several card examples describing manipulation of the mapped data variable in the context of thematic mapping. The former instance of *overlay* is described as *toggle visibility* by Edsall et al. (2008) while the latter is described as *assignment* by MacEachren et al. (1999) and Masters and Edsall (2000). The *overlay* operator differs from the *reexpress* operator in that geographic information is either added or removed from the overall cartographic representation (i.e., the new representation is not a visual isomorph). Example cards representing the *overlay* operator include "turn on the tactical infrastructure layer," "turn on the layer showing the count of guests per hotel," and "click on the layer panel to show layers of different types of crimes" (**Figure 5.5k**).

(6) ***Reproject*****:** The *reproject* operator describes cartographic interactions that set or change the cartographic projection used to transform the three-dimensional geographic information to a two-dimensional screen. The *reproject* operator is synonymous with Edsall et al.'s (2008) *re-projection* operator, but slightly different than Keim's (2002) *dynamic projection* operator, which primarily applies to the assignment of variables to the axes of a multivariate representation (particularly one in which the number of dimensions have been reduced, such as multidimensional scaling). Although an issue primarily associated with map design, the *reproject* operator also relates to ***map browsing*** (i.e., the combination of the *pan* and *zoom* operators, as defined below), as the map center (*pan*) and map scale (*zoom*) are important parameters of the projection algorithm; all participants distinguished *reproject* from *pan* and *zoom* (as indicated by the high agreement scores within the *reproject* category), perhaps because the *pan* and *zoom* operators do not affect a change to the projection in many cartographic interfaces. Finally, the *reproject* operator is related to Keim's and Ward and Yang's (2003) notion of *distortion*, which describes a dynamic projection that provides a detail view of a portion of the area under investigation while preserving an overview of the surrounding context. Example cards representing the *reproject* operator include "set an appropriate projection and coordinate system for the map," and "project the map using the Albers equal area conic projection" (**Figure 5.5g**). Although the *reproject* operator comprises only six cards from the operator card sorting study, the operator remains important in the context of Interactive Cartography and Geovisualization given the influence that the selected projection has on the interpretability of the resulting cartographic representation; the propensity of popular web mapping services to stream map tiles in a single projection (Web Mercator)—and the numerous distorted, non-equivalent choropleth mashups using these services—is a prime example of the misleading maps that users may be forced to generate when the *reproject* operator is not supported.

(7) ***Pan*****:** The *pan* operator describes cartographic interactions that change the geographic center of the cartographic representation. The *pan* operator is performed when the cartographic representation is too large at the current map scale to display onscreen in its entirety, forcing a portion of the map offscreen. The result of a *pan* operator is a change to the extent of the cartographic representation that currently is viewable, although a change to the map extent can occur without performing the *pan* operator (e.g., by applying the *zoom* operator or by changing the screen real-estate provided for the map, such as maximizing or minimizing the window containing the cartographic interface). *Pan* is included as an operator primitive by

Edsall et al. (2008), and is a component of Shepherd's (1995) and Dykes's (1997) *observer motion* as well as MacEachren et al.'s (1999) and Masters and Edsall's (2000) *viewpoint manipulation*. Interestingly, participants included cards describing manipulations to the viewing angle as part of the *pan* operator, rather than splitting this subset of cartographic interactions into a separate operator primitive, as with the Shepherd and Dykes *object rotation* primitive. Example cards representing the *pan* operator include "pan the map to a different location," "view map features hidden off-screen," and "orbit around the digital globe" (**Figure 5.5f**).

(8) ***Zoom*****:** The *zoom* operator describes cartographic interactions that change the scale and/or resolution of the cartographic representation. Within Interactive Cartography and Geovisualization, the *zoom* operator commonly is applied to magnify or reduce a portion of the cartographic representation in order to improve its legibility or return to an overview respectively (i.e., a change in map scale), but also can be applied to show more or less detail in the map features within the magnified portion of the cartographic representation (i.e., a change in map resolution). As stated in **Section 3.4**, this latter application of the *zoom* operator is referred to as a ***semantic zoom***, and is related to Buja et al.'s (1996) initial definition of *focusing* (i.e., data zooming). Like the *pan* operator, *zoom* is included as an operator primitive by Edsall et al. (2008), and is a component of Shepherd's (1995) and Dykes's (1997) *observer motion* as well as MacEachren et al.'s (1999) and Masters and Edsall's (2000) *viewpoint manipulation*; Keim (2002) also uses a similarly definition of *zoom* in his operator-based taxonomy. The *zoom* operator is integral to Shneiderman's ***visual information seeking mantra***, combining with the *filter* operator (see below) to allow users to navigate between an overview and detail view. Example cards representing the *zoom* operator include "zoom in to see what is around the point source," "gain an overview of the entire collection of map features," and "display the map feature in more detail" (**Figure 5.5e**).

(9) ***Filter*****:** The *filter* operator describes cartographic interactions that alter the cartographic representation, and information views linked to the cartographic representation, to indicate map elements that meet one or a set of user-defined conditions. The *filter* primitive is included in the Shneiderman (1996) and Keim (2002) operator-based taxonomies and is synonymous with the MacEachren et al. (1999) and Masters and Edsall (2000) description of *focusing* (see the **Section 3.4** description of the prevalent *focusing* operator primitive for alternative definitions) and Edsall et al.'s (2008) description of *conditioning*. Application of the *filter* operator often results in the removal of the map features that do not meet the user-definite criteria (i.e., Becker and Cleveland's, 1987, *delete* operator), but also may emphasize the matching map features (Becker and Cleveland's *highlight* operator), deemphasize non-matching map features (Becker and Cleveland's *shadow highlight* operator), or, infrequently, add labels to the matching map features (Becker and Cleveland's *label* operator); the similarity of an outcome of a *filter* and Becker and Cleveland's 'brushing operations' perhaps explains why participants grouped cards denoting instances of brushing multiple map features along with the *filter* operator. Example cards representing the *filter* operator include "perform a query that specifies the range of contaminant concentration levels to be shown on the map," "select all apprehensions that fall within a mile of the address," and "change the temporal extent from seven to fourteen days" (**Figure 5.5n**).

(10) ***Search*****:** The *search* operator describes cartographic interactions that alter the cartographic representation, and information views linked to the cartographic representation, to indicate a particular location or map feature of interest. The *search* operator is conceptually similar to the *filter* operator, with the former typically returning a single map feature of interest and the latter typically returning a potentially large set of unknown map features that match a set of imposed constraints; however, application of *filter* can lead to isolation of a single map feature (i.e., if only one feature matches the user-defined constraints) and application of *search* may lead to retrieval of multiple features (i.e., if multiple map features have the same identifier). A key difference between the two is that the *search* operator looks for a direct match on a single identifier (typically the name, address, or timestamp of the feature), while the *filter* operator looks for matches within a subset of values (for categorical variables) or across a range of values (for numerical variables) in one or more facets of the represented geographic dataset. Thus, *search* directly enters the cartographic representation to locate a map feature of interest that is already known, while *filter* is a top-down approach to narrowing the cartographic representation to identify potential map features of interest. Most participants isolated a set of seven cards that denote the *search* objective from the larger set of cards constituting the *filter* operator, indicating that there is a salient difference between the two operators and that this difference should be considered when designing cartographic interfaces. Example cards representing the *search* operator include "search for a specific geographic place," "type in the address where a toxic chemical was released," and "enter search words into Google Maps to find target communities in Pittsburgh" (**Figure 5.5m**).

(11) ***Retrieve*****:** The *retrieve* operator describes cartographic interactions that request specific details about a map feature or map features of interest. The *retrieve* operator is synonymous with Shneiderman's (1996) *details-on-demand*, Dix and Ellis's (1998) *accessing extra information*, and Edsall et al.'s (2008) *accessing exact information*. The *retrieve* operator commonly is implemented using the direct manipulation interface style, perhaps explaining why most card examples illustrating *brushing* of a single map feature were sorted by participants into the *retrieve* category; *retrieve* is not specific to a single interface style—like all of the primitives identified through the operator card sorting study—and can be implemented through all other, non-direct interface styles. Example cards representing the *retrieve* operator include "brush over the first district of California to see how people voted," "click on a placemark for a bubble pop up with text, photos, and a link to the website," and "reveal extra information about a map feature on demand" (**Figure 5.5l**).

(12) ***Calculate*****:** Finally, the *calculate* operator describes cartographic interactions that derive new information about a map feature or map features of interest. The *calculate* operator may be performed to generate simple descriptive statistics as well as more complex spatial measurements and statistics. The *calculate* operator also includes the configuration and steering of advanced spatial models and geocomputational routines. Such a definition of *calculate* is most similar to Amar et al.'s (2005) *compute derived value* primitive, which is found in an objective-based taxonomy (**Section 3.3**). The category in the **Figure 5.5** matrix representing the *calculate* operator is small, comprising only three of cards. However, the *calculate* operator is maintained in the interaction primitive taxonomy given the **Chapter 4** finding that cartographic interfaces are used most commonly in support of the analysis stage (**Figure 2.2**), yet tighter integration is needed between interactive cartographic representations and spatial statistics, spatial modeling, and geocomputational routines (i.e., moving from Geovisualization towards Geovisual Analytics); that there are only three cards in the *calculate* category is an additional indication that such integration between visual interface and computation is not currently adequate. Example cards representing the *calculate* operator include "draw a polygon and retrieve an average for the area selected," and "select two cities and calculate the distance between them" (**Figure 5.5o**).

5.5 Conclusion: An Evolving Interaction Primitive Taxonomy

The pair of card sorting studies reported in this chapter resulted in an interaction primitive taxonomy with four dimensions (**Figure 5.3**): goals, operands, objectives, (all three treated together in **Section 5.3**) and operators (further sub-divided according to enabling operators and work operators; **Section 5.4**). Importantly, both the examples of each primitive (i.e., the cards) and the structures organizing the primitives (i.e., the categories) were derived empirically using input from expert mapmakers and map users, while remaining informed by extant theory and general logic. Thus, the **Figure 5.3** interaction primitive taxonomy affords a greater degree of ecological validity than other, extent taxonomies. Despite this increased validity, however, it is important to note that any taxonomy of cartographic interaction primitives—like existing taxonomies of visual variables—requires additional empirical examination to tweak the included primitives and their definitions and also must remain malleable to changes in cartographic interaction use and technological capabilities. This is particularly true for primitives established through the objective card sorting study, which exhibited a great degree of variation across participants due, at least in part, to application of three competing sorting criteria (goals, operands, and objectives). As described in **Section 7.2.1**, a series of open and/or closed card sorting studies with a new trio of card sets, focused to address each of the three aforementioned criteria, would be a particularly informative follow-up study allowing for validation and refinement to the interaction primitive taxonomy reported in **Figure 5.3**. While the insights generated from the operator card sorting study can be used with a greater degree of confidence for future research and practice given the higher reliability, a follow-up closed sort requiring participants to sort the operator cards into these categories would allow for additional refinement to the operator dimension of the interaction primitive taxonomy. Thus, the taxonomy resulting from the card sorting studies should be interpreted as a useful, initial structure for designing cartographic interaction studies to generate insights about prototypically successful cartographic interaction strategies and useful and usable cartographic interface designs (i.e., for investigating the *how?*), but not as the final structure. The empirically derived taxonomy of cartographic interaction primitives described in this chapter therefore is a substantive step towards accomplishing the second goal of the dissertation (**Section 1.5.2**), while **Chapter 6** applies this taxonomy as the theoretical foundation of a cartographic interaction study, accomplishing the third goal of the dissertation (**Section 1.5.3**).

Chapter Six: Cartographic Interaction Study
Prototypically Successful & Unsuccessful Interaction Strategies

Overview:

This chapter reports on a cartographic interaction study investigating the taxonomy of cartographic interaction primitives generated by the **Chapter 5** card sorting studies. The chapter begins with an introduction to the ongoing research goal of establishing a syntactics of cartographic interaction primitives (**Section 6.1**). To this end, a cartographic interface—referred to as *GeoVISTA CrimeViz*—was used as a 'living laboratory' for generating initial insight into the interaction primitive taxonomy. Background is provided on *GeoVISTA CrimeViz* itself as well as the user-centered design and development approach completed in collaboration between the Penn State GeoVISTA Center and the Harrisburg (PA, USA) Bureau of Police (**Section 6.2**). Following this background, the cartographic interaction study leveraging *GeoVISTA CrimeViz* is described (**Section 6.3**). Ten law enforcement personnel from the Harrisburg Bureau of Police completed fifteen user tasks with *GeoVISTA CrimeViz* representative of the objective and operand pairings listed in **Table 5.2**. The operators applied by participants during the study to complete each task were logged, with subsequent analysis and reporting emphasizing the successful and unsuccessful interaction strategies taken by participants to accomplish each task (**Section 6.4**). The chapter closes with concluding remarks (**Section 6.5**).

6.1 Design and Use Guidelines for Cartographic Interaction

The ultimate promise of a taxonomy of interaction primitives, and the associated *how?* question of a science of cartographic interaction, is the generation of design and use guidelines for cartographic interaction. As introduced in **Section 1.5.3**, the visual variables are groundbreaking as a theoretical framework in Cartography and related fields not only because they enumerate the basic building blocks that constitute a graphic, but also because they provide a systematic way of conceptualizing and investigating how cartographic representations work. The visual variable framework affords academic and professional cartographers alike the opportunity to explore competing map designs in a structured way; this effort ultimately resulted in the formulation of a ***syntactics*** for the visual variables that prescribes the appropriate representation choice given the level of measurement of the represented information (Bertin, 1967|1983, Morrison, 1974, Caivano, 1990, MacEachren, 1992).

Similarly, a taxonomy of cartographic interaction primitives affords the possibility to compare competing ***interaction strategies***, or sequences of operator primitives applied in a specific objective and operand context (Edsall et al., 2008). Such a syntactics of cartographic interaction primitives has the potential to inform both the design (i.e., from a mapmaker perspective) and use (i.e., from a map use perspective) of cartographic interfaces. However, the development of a syntactics of cartographic interaction is a research goal that is ongoing, requiring a series of controlled experiments to triangulate empirical findings and constant reevaluation as technology and practice evolves. Therefore, the third goal of the dissertation is limited to the identification of prototypically successful and unsuccessful cartographic interaction strategies with a single cartographic interface of interest. The resulting empirical findings can be used to inform the design of future scientific research studies on cartographic interaction, with the ultimate goal of formalizing a syntactics of cartographic interaction primitives.

To this end, this chapter reports on a cartographic interaction study using the taxonomy of cartographic interaction primitives reported in **Chapter 5** as the underpinning theoretical framework for evaluating the competing interaction strategies exhibited by participants. The study leveraged a cartographic interface called *GeoVISTA CrimeViz* as a 'living laboratory' to identify the most effective and efficient application of interaction operators according to the objective and operand context. *GeoVISTA CrimeViz* is an ongoing, collaborative project between the Penn State GeoVISTA Center and the Harrisburg (Pennsylvania, USA) Bureau of Police following a user-centered design approach. The interest and buy-in fostered during this collaborative case study was integral not only for improving the usability and enhancing the utility of *GeoVISTA CrimeViz*, but also for recruiting representative and highly motivated targeted end users for the subsequent cartographic interaction study; additional details about *GeoVISTA CrimeViz* and the collaboration with the Harrisburg Bureau of Police are provided in **Section 6.2**. As part of the collaboration, ten law enforcement personnel at the Harrisburg Bureau of Police participated in the cartographic interaction study using *GeoVISTA CrimeViz*, resulting in identification of a set of prototypically successful and unsuccessful interaction strategies with the cartographic interface. The cartographic interaction study achieves the third research goal of the dissertation (see **Section 1.5.3**), offering initial insight that can be used to inform future scientific research regarding the syntactics of cartographic interaction primitives.

6.2 Case Study: Crime Analysis and *GeoVISTA CrimeViz*

6.2.1 The *GeoVISTA CrimeViz* Cartographic Interface

Before reporting on the cartographic interaction study, it first is necessary to introduce the cartographic interface used as the platform for the study (*GeoVISTA CrimeViz*; detailed in this subsection) and important details about its design and development relevant to the cartographic interaction study (the collaboration with the Harrisburg Bureau of Police; detailed in the following subsection). The *GeoVISTA CrimeViz* cartographic interface was leveraged as an experiment tool for collecting insight about the empirically derived taxonomy of interaction primitives described in **Chapter 5**. ***GeoVISTA CrimeViz***[33] is an extensible, web-based geovisualization application built using Adobe Flash and PostGreSQL that supports spatiotemporal exploration, analysis, and sensemaking of criminal activity (Roth and Ross, 2009, Ross et al., 2009). *GeoVISTA CrimeViz* represents the second iteration of the *CrimeViz* concept, extending and refining an initial proof-of-concept interface described as ***DC CrimeViz*** to meet the needs of the Harrisburg Bureau of Police; the user-centered approach to design and development of the *DC CrimeViz* prototype, which plotted a publicly available crime incident data feed maintained by the District of Columbia, is described in Roth et al. (2010b). Except where otherwise noted, *GeoVISTA CrimeViz* is available openly under a Lesser General Public License (LGPL) through the project website (http://www.geovista.psu.edu/CrimeViz/). *GeoVISTA CrimeViz* provides a suite of easy-to-use and flexible spatiotemporal cartographic interactions to law enforcement agencies that do not have the resources to perform more robust analyses regularly. Specifically, it was our goal to implement a light-weight cartographic interface using common web mapping services to support crime analysis.

Crime analysis describes the systematic collection, preparation, interpretation, and dissemination of information about criminal activity to support the mission of law enforcement (Boba, 2005). Crime analysis, when successful, can characterize the pattern of crime incidents in a community in order to identify areas requiring immediate intervention by law enforcement. Beyond support for the practice of law enforcement, crime analysis draws heavily from the discipline of ***Criminology***, or the scientific study of the causes and control of crime and other delinquent behavior (Sutherland et al., 1992). In this context, crime analysts attempt to understand the etiology of persistent crime patterns in a community by

[33] *GeoVISTA CrimeViz* is a collaborative project completed at the Penn State GeoVISTA Center. See the **Acknowledgements** section for details on the complete project team.

considering its demographic and environmental characteristics, with the end goal of improving the quality of life for all individuals within the community. Thus, crime analysis tools, such as the one introduced here, must serve both tactical and strategic policing functions (O'Shea and Nicholls, 2003).

There is great and largely untapped potential for Interactive Cartography and Geovisualization to support crime analysis, as a primary goal of crime analysts is identification of structure and deviation in complex, spatiotemporal information (Harries, 1999); law enforcement personnel simply call the *hypotheses* generated from visual exploration by a different name: *hunches*. Such insights, or hunches, into crime patterns then are leveraged to make informed tactical, strategic, and administrative policing decisions; according to Ratcliffe's (2009b) mantra, 'prevention requires proactivity requires predictability requires patterns.' The field of ***crime mapping*** describes the analysis of the spatial component of crime (Eck et al., 2005) and includes the full suite of GIScience techniques and technologies to criminology, including data assembly, spatial statistics, and geocomputation, as well as cartographic representation and cartographic interaction (Harries, 1999). Researchers have identified the development and transition of new techniques for treating the spatial and temporal components in conjunction as a principal challenge facing the domain of crime analysis (Ratcliffe, 2009a).

Despite the potential for cartographic interfaces to identify and explicate clusters and trends in crime, many law enforcement agencies lack adequate analytical tools and training to explore and make sense of their crime incident datasets. Such techniques often are not applied in small- to intermediate-size municipal law enforcement agencies due to the lack of dedicated crime analysts on staff and to a general focus on tactical rather than strategic crime analysis (Mamalian and La Vigne, 1999). Thus, spatiotemporal analysis and visualization often is limited to the generation of one-off, static maps showing crime over a given period of time, usually the past 7 or 30 days (Lodha and Verma, 1999). The practical goal of *GeoVISTA CrimeViz* is to fulfill this key unmet need, providing understaffed departments with an extensible, easy-to-use tool for conducting spatiotemporal crime analysis and mapping. The targeted end user group of *GeoVISTA CrimeViz* is law enforcement personnel (analysts, officers, detectives, administrators, and decision makers) who have little experience and training applying interactive maps and map-based systems for crime analysis.

The overall *GeoVISTA CrimeViz* concept includes three primary interface panels (**Figure 6.1**), each of which house interface controls for manipulating one of the three operand primitives identified in the **Chapter 5** taxonomy of interaction primitives; the **Appendix E** user guide provides a more complete overview of features included in *GeoVISTA CrimeViz* as delivered to the Harrisburg Bureau of Police:

(1) ***The Map Panel*** **(*space-alone*)***:* The Map Panel provides the interface controls for spatial exploration, analysis, and sensemaking of criminal activity. The Google Maps API for Flash is leveraged to integrate the Google Maps multiscale basemap design and direct manipulation capabilities into the Map Panel (e.g., the *pan*, *zoom*, and *retrieve* operators). Crime incidents are cleaned and plotted atop the Google Maps basemap in near real-time (updates are processed every 24 hours). Two cartographic representations are provided based on the map scale: an overview aggregating crime incidents to an arbitrary hexagon grid and a details view representing crime incidents as individual points, colored by the broader category of crime and numbered according to the ***uniform crime reporting (UCR) code***, a set of numerical codes used to identify and index crime incidents by type. An individual point can be selected to *retrieve* details about the associated crime incident and an interactive Google Street View image of the location of the crime.

(2) ***The Data Panel*** **(*attributes-in-space*)*:*** The Data Panel provides the interface controls for attribute exploration, analysis, and sensemaking of criminal activity. The Basic Data Panel provides a form fill-in interface to *search* for unique crime incidents or addresses as well as a series of hierarchical menu selection interfaces to *filter* crime incidents by UCR and ***modus***

operandi (MO), or method of committing the crime. The Advanced Data Panel provides direct manipulation numerical steppers to *filter* by police district and police grid as well as a form fill-in interface to *search* for specific keywords or phrases. The Advanced Data Panel also includes a series of checkboxes to *overlay* contextual data layers that may assist in the interpretation of the spatiotemporal crime patterns.

(3) ***The Temporal Panel*** **(*space-in-time*):** The Temporal Panel provides interface controls for temporal exploration, analysis, and sensemaking of criminal activity. The Basic Temporal Panel includes a direct manipulation histogram in which the crime incidents are aggregated into a set of mutually exclusive and collectively exhaustive ***temporal bins***, or equivalent intervals of time, with the height of the histogram bin indicating the frequency of crimes during the associated time period. The Map Panel can be animated across the bins using the VCR-like controls in the Basic Temporal Panel, with the histogram doubling as an interactive temporal legend. The Advanced Temporal Panel includes a pair of menu selection interfaces to *reexpress* and *sequence* the crime incident dataset temporally, allowing for the generation of linear and composite views as well as the manipulation of the binning interval. In a ***temporal composite***, the frequencies for each individual instance of a finite set of cyclical temporal units (e.g., Sunday, Monday, Tuesday, etc.) are averaged or summed to calculate a single, representative value for each of the cyclical temporal units (Moellering, 1976). The Advanced Temporal Panel also provides a set of direct manipulation numerical steppers for

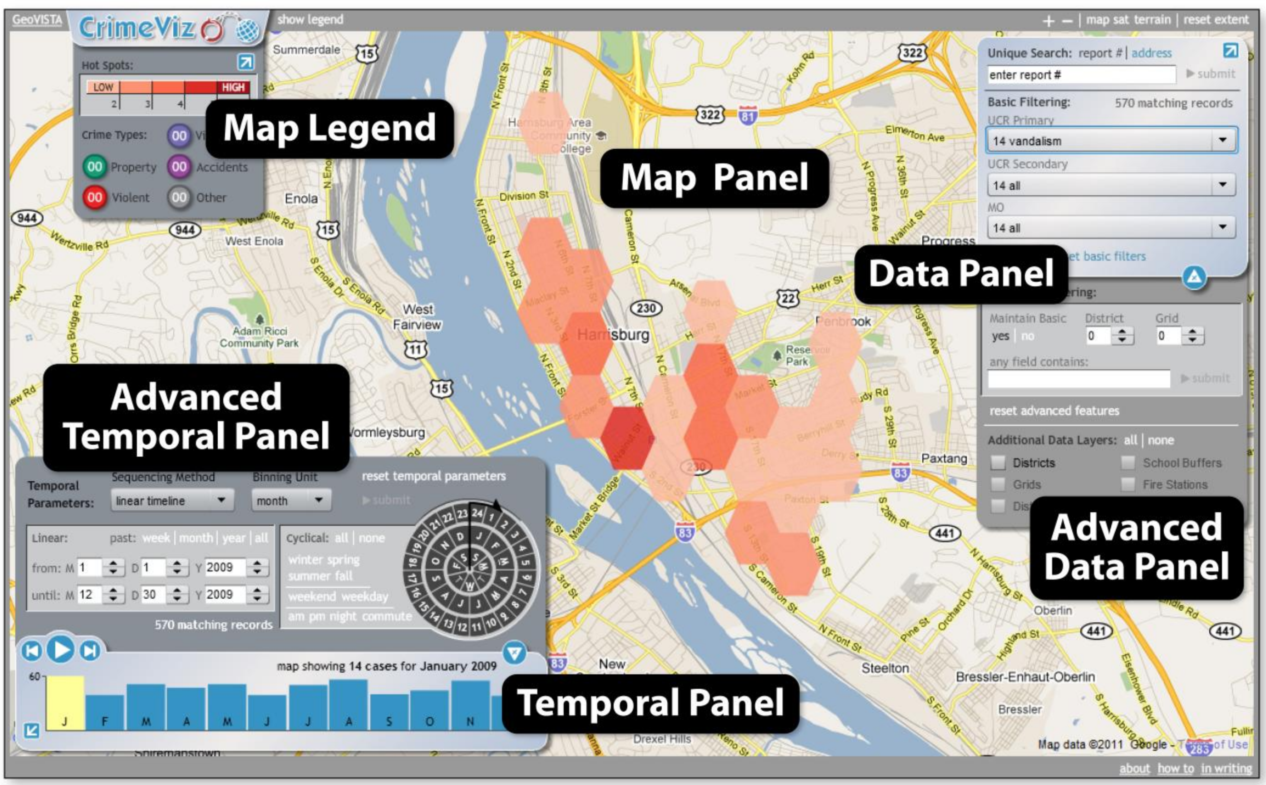


Figure 6.1: The *GeoVISTA CrimeViz* Cartographic Interface. *GeoVISTA CrimeViz* comprises three interface panels for geographic (the Map Panel), attribute (the Data Panel), and temporal (the Temporal Panel) exploration, analysis, and sensemaking. Additional features are located in advanced panels. Details about the *GeoVISTA CrimeViz* project, including code, videos, tutorials, and a public version of the cartographic interface, are available at: http://www.geovista.psu.edu/CrimeViz/

linear temporal filtering (adjusting the temporal extent or range of the temporal histogram and associated cartographic animation), as well as a direct manipulation ***time wheel*** interface for ***cyclical temporal filtering*** (adjusting which cyclical temporal units are included in the temporal aggregation, e.g., hours of the day, days of the week, and months of the year).

6.2.2 Collaboration with the Harrisburg Bureau of Police

The collaboration between the Penn State GeoVISTA Center and Harrisburg Bureau of Police grew out of the work domain analysis stage of design and development of the original *DC CrimeViz* proof-of-concept interface (Roth et al., 2010b), which at the time existed only as a partially functional prototype. Following the work domain analysis, an inquiry was sent by stakeholders at the Harrisburg Bureau of Police to ascertain if *DC CrimeViz* could be reconfigured for use at their law enforcement agency. Because design and development of *DC CrimeViz* was only at the early stages at the time of the inquiry, an agreement instead was made to collaborate with the Harrisburg Bureau of Police for the remainder of the project. Such collaboration with the Harrisburg Bureau of Police represented a welcomed opportunity for the Penn State GeoVISTA Center, as it held the dual benefits of increased access to *actual* end users (not just representative end users) for completing the applied user-based interface evaluations. This in turn results in both a cartographic interface that more closely meets the needs of the general targeted user community and an interested and motivated sample pool of participants from which to draw for cartographic interaction study. It also greatly increased the potential that the application, once operational, would be put to real world use.

The Harrisburg Bureau of Police is an Internationally Accredited law enforcement agency serving a municipal population of approximately 50,000 citizens. Harrisburg, the Capitol of Pennsylvania, is the largest city within the Harrisburg-Carlisle Metropolitan Statistical Area, which covers a population of approximately 510,000 people; the work day population within the Harrisburg city limits is estimated at approximately 120,000. Harrisburg experiences a relatively larger number of crime incidents and ordnance violations within the city compared to its population, ranging between 10,000-15,000 incidents annually during 2006-2010. The Harrisburg Bureau of Police employs over 200 sworn and civilian personnel and is organized into three divisions: the Uniformed Patrol Division (primarily officers and supervisors responsible for first response, traffic control, parking enforcement, and animal control), the Technical Services Division (primarily administrative and service personnel that support the functions of law enforcement and courtroom proceedings), and the Criminal Investigative Division (primarily detectives, supervisors, and forensic agents responsible for criminal investigations of adult and juvenile violent and vice crime incidents). The *GeoVISTA CrimeViz* cartographic interface primarily is designed for use by the Criminal Investigative Division, but is extendable to the others.

Collaboration with the Harrisburg Bureau of Police was organized according to Shneiderman and Plaisant's (2006) ***multi-dimensional, in-depth, long-term case study (MILC)*** approach. The MILC approach recommends administration of numerous interface evaluations (*multi-dimensional*) through intense engagement with a small number of actual end users (*in-depth*) over a long period of time (*long-term*) in order to build a comprehensive, yet evolving, understanding of the user's needs with regard to a single interface (*case study*). Because of the close engagement between designers/developers and users during a case study collaboration, Shneiderman and Plaisant indicate that the MILC approach often results in increased credibility of the project team and increased trustworthiness in the team by the user community; both credibility and trustworthiness act to improve user ***motivation***, described in **Section 2.5** as the desire one has to use the cartographic interface either out of necessity (i.e., to complete a work task) or out of interest (e.g., curiosity, entertainment, popularity, recommendation) (Greif, 1991, Roth and Harrower, 2008). Applied research associated with the MILC spanned approximately 18 months from the initial, in-person meeting at the Harrisburg Bureau of Police to the formal cartographic interaction study directly preceding transition of the first fully-featured version *GeoVISTA CrimeViz*, although interface evaluation and revision remains ongoing as noted above.

Shneiderman and Plaisant (2006) particularly emphasize participant observation in their description of the MILC method, as the long hours of direct contact strengthen the collaborative relationship between the design/development team and the targeted end users. As discussed in **Appendix E**, the participant observation is less than ideal for the evaluation and revision of cartographic interfaces, as such interfaces are typically a single step in a larger workflow that includes other, non-cartographic applications; this issue was compounded by the distance between the Penn State GeoVISTA Center and the Harrisburg Bureau of Police (approximately 90 miles). Instead, the schedule of collaborative interface evaluations constituting the MILC with the Harrisburg Bureau of Police took three primary forms:

(1) ***Synchronous, Same-Place Interface Evaluation*****:** The keystone of the case study were in-person, group meetings held approximately every four months, resulting in five visits total. In the early meetings, this in-person contact was used for ***formative*** round-table discussion (i.e., very informal focus group sessions) between Penn State GeoVISTA Center researchers and Harrisburg Bureau of Police stakeholders, which included a core set of 6-8 officers and IT personnel that were instrumental in initiating the collaboration, their supervisors (when available), and, in one of the meetings, the Chief of Police. In the initial sessions, discussion was organized around the set of open questions that the GeoVISTA design/development team had about the revised *GeoVISTA CrimeViz* concept, as tailored for Harrisburg Bureau of Police. Discussion topics included user needs requiring further explication, potential interface design ideas (presented first as static mockups and later as partially functional interactive mockups; e.g., **Figure 6.2**), and logistical considerations regarding the collaboration. Initial meetings also were used to observe how existing digital interfaces were employed by the Harrisburg Bureau of Police, specifically their record management system (RMS) indexing all crime reports. In the latter meetings, these round-table discussions with key stakeholders were appended to include formal and informal training sessions (described below) and ***summative*** interface evaluations, namely the cartographic interaction study (see **Section 6.3**). Initial in-person meetings lasted approximately one-half of a day, while the later meetings stretched between three and five days.

(2) ***Synchronous, Different-Place Interface Evaluation*****:** Conference calls were scheduled every two-to-four weeks between the in-person meetings in Harrisburg. As with Shneiderman and Plaisant's (2006) description of the MILC method, these meetings followed a regular schedule at the start of the collaboration when formative information was needed on the *GeoVISTA CrimeViz* concept and interface design (approximately the first four months, or between the first two in-person meetings), but later were scheduled flexibly only as issues arrived or milestones were reached. The conference calls generally included only a subset of the aforementioned key stakeholders and lasted between 30 and 60 minutes, both to compensate for the demands on the time of the Harrisburg Bureau of Police personnel. When possible, a set of discussion topics was distributed prior to the conference call, which often included follow-up prompts about topics first introduced during the in-person meetings in order to continue discussion. The calls were facilitated by Adobe Connect, a web conferencing application used for synchronous, different-place audio/visual collaboration. Using the desktop sharing capabilities of Adobe Connect, the GeoVISTA team was able to demonstrate newly operational functionality included in *GeoVISTA CrimeViz*, while the Harrisburg team was able to demonstrate usability and utility issues uncovered through their own use of the cartographic interface.

(3) ***Asynchronous Interface Evaluation*****:** Finally, email was used to maintain contact between the conference calls. Stakeholders at the Harrisburg Bureau of Police were encouraged to forward descriptions of usability and utility issues as they occurred, along with a screenshot illustrating the issue, if informative (see Haklay and Zafiri, 2008, for details on using screenshots for cartographic interface evaluation). Although email is a restrictive form of communication when compared to other, synchronous methods, many of the usability and utility issues first were reported through email (i.e., immediately after being identified when using a partially-functioning version of *GeoVISTA CrimeViz*) and then logged for follow-up discussion during the in-person meetings or conference calls. Additional methods of collecting asynchronous feedback, such as a discussion board or wiki, were not deemed necessary given the small number of stakeholders involved in the case study (whose feedback could be managed via email) and restrictions on Internet use at the Harrisburg Bureau of Police.

Information elicited through synchronous and asynchronous methods was collected informally as a running list of notes about the cartographic interface, with the exception of the cartographic interaction study. Notes emphasized ***critical incidents*** with the interface, particularly key impediments to use (usability issues) or missing core functionality (utility issues). Usability and utility issues were logged as individual ***tickets*** in the *GeoVISTA CrimeViz* ***action list***, along with the date submitted, the date revised, a priority ranking, the ***owner*** of the ticket (i.e., the project team member responsible for fixing the issue in the interface), and a short description. The action list was first maintained as a collaborative spreadsheet in Google Documents, but later was moved to Assembla (http://www.assembla.com/) for easier tracking of outstanding tickets and overall cartographic interface improvement.

Figure 6.2: A Static Mockup of *GeoVISTA CrimeViz*. Both static and interactive mockups of the *GeoVISTA CrimeViz* cartographic interface were generated to facilitate discussion during the in-person meetings and conference calls between the Penn State GeoVISTA Center and the Harrisburg Bureau of Police. The above mockup, produced in Adobe Illustrator, represents a major update to the *GeoVISTA CrimeViz* concept according to the input collected from the work domain analysis and the first in-person meeting with the Harrisburg Bureau of Police. The mockup was presented to stakeholders during the second in-person meeting in order to elicit a final round of input into the cartographic interface design prior to exporting to Adobe Flash for development.

A final, noteworthy component of the collaborative partnership was the provision of training to personnel at the Harrisburg Bureau of Police. Shneiderman and Plaisant (2006) cite Lewin's (1951) ***action research*** as an important influence on the MILC approach, which describes a form of field study in which the researcher plays an active role in improving practice, rather than simply observing and recording it. The provision of training therefore is an important part of the MILC approach, effectively improving the usability and utility of the cartographic interface by improving the ability of actual end users to manipulate and make sense of it (Roth et al., 2009). Stakeholers participating in the in-person meetings and conference calls were encouraged to ask questions about the use of *GeoVISTA CrimeViz* specifically and the utility of Interactive Cartography and Geovisualization broadly; the expertise acquired by stakeholders through this informal training added a second and equally critical layer of buy-in within the Harrisburg Bureau of Police, as the individuals participating in the MILC acted as the early adoptors of the cartographic interface and encouraged the use of the interface by their colleagues. As *GeoVISTA CrimeViz* was nearing the initial transition, a formal, 60-minute training presentation was provided during an 'all-hands' meeting, which was attended by 30-40 of the higher ranking officers and supervisors in the Harrisburg Bureau of Police, as well as all Police Captains and the Chief of Police. Both an overview of the collaborative project and a demonstration of the *GeoVISTA CrimeViz* cartographic interface were provided during this meeting; following the presentation, supervisors were provided one-page summaries of the interface and business cards containing the test link and password to disseminate to the officers in their respective units. As described in **Section 6.3.3**, a condensed review of this training presentation was provided to participants at the beginning of the cartographic interaction study, presenting the unusual, but advantageous recruiting situation in which there were many more willing participants than project resources for testing. As mentioned above, a ***user guide*** (**Appendix E**) describing the functionality of *GeoVISTA CrimeViz* also was generated for use as a reference for existing personnel and an introduction for new personnel.

6.3 Method: Cartographic Interaction Study and User Satisfaction Survey

6.3.1 Review of Cartographic Interaction Studies

A cartographic interaction study was administered for the dual goals of empirical evaluation of the **Chapter 5** taxonomy of cartographic interaction primitives (basic research goal) and summative evaluation of *GeoVISTA CrimeViz* (applied research goal). An ***interaction study*** is a method that requires participants to complete a set of benchmark tasks with an interface in a controlled setting while their interactions are capture in an interaction log (MacEachren et al., 1998). The interaction study method was superior to other user-based interface evaluation methods that investigate user interactions—such as the talk aloud or think aloud study—because the scientific rigor imposed both in the experimental procedure and data collection facilitates investigation of basic research goals in addition to the applied research goals typical of a user-centered design.

There is a small, yet important set of interactions studies reported in the cartographic literature. The term itself is borrowed from Robinson et al. (2005: 245), who use it to describe "Formal assessment efforts [that] take place in a usability laboratory where audio and video can be captured while users attempt to work with an application." Although interaction studies were among the earliest empirical approaches for evaluating the usability and utility of interfaces (Marsh and Haklay, 2010), only several applications to cartographic interfaces have been reported, including MacEachren et al. (1998), Andrienko et al. (2002), Edsall (2003), and Robinson (2008a, 2008b). Interestingly, a purpose-driven operator-based taxonomy (see the discussion at the end of **Section 3.4**) was developed as part of each of these cartographic interaction studies in order to analyze the collected information on user interactions. Thus, these studies provide important examples of employing an interaction primitive taxonomy (primarily operator-based taxonomies in the reported examples) to codify user interactions to the end both of improving the evaluated cartographic interface as well as identifying prototypically successful interaction strategies that may be generalizable beyond the evaluated cartographic interface. The applied and basic insights generated from each cartographic interaction study are summarized in the following, as they were used to inform the design of the cartographic interaction study with *GeoVISTA CrimeViz* described in the following sub-sections.

MacEachren et al. (1998) conducted a cartographic interaction study to evaluate HealthVisB, a geovisualization application supporting multivariate analysis of the disease burdens and potential risk factors through dynamically linked map and scatterplot views. The primary advancement in the 'B' version of the HealthVis application is provision of cartographic animation to investigate spatiotemporal patterns (see Haug et al., 1997, for a description of the original cartographic interface). Five experts in epidemiology and four experts in population science completed three spatiotemporal tasks that generally translate to the objective-operand pairings of *rank* by *attributes-in-space*, a combination of *associate* by *space-in-time* (Part A: Trend) and *delineate* by *space-in-time* (Part B: Cluster), and *compare* by *space-in-time*. An eighteen-part purpose-driven operator-based taxonomy of 'key actions' was developed to analyze the interaction logs, which included: (1) enabling interactions such as *program:execute*, *module:start*, and *module:exit*, (2) visualization manipulations such as *boundary:change*, *scatterplot:turn*, and *class:select*, (3) variable selection changes such as *cause:select*, *cause:move*, *risk:select*, and *risk:move*, and (4) time series changes such as *cause:step*, *risk:step*, *date:move*, *date:step*, *animate:start*, *animate:pace*, *animate:rewind*, and *animate:stop*. Findings from the MacEachren et al. cartographic interaction study include a general reliance on and satisfaction with the interface controls implemented with the direct manipulation interface style, a primary use of the default map for the *rank* objective by *attributes-in-space* (i.e., there were only modest amounts of interaction when the temporal component was not included in the task), two competing, yet equally successful interaction strategies for accomplishing the *associate* and *delineate* objectives by *space-in-time* (i.e., users either solely applied the *sequence* operator to loop through the animation feature or used the *sequence* operator together with the *filter* operator), and overall reliance on manual time-stepping (i.e., a temporal *pan* operator rather than the interactive application of the *sequence* operator) for the final *compare* objective by *space-in-time*.

Andrienko et al. (2002) conducted a multiple-round cartographic interaction study to evaluate the usability of the interactive choropleth map provided in their CommonGIS application (formerly Descartes; see Andrienko and Andrienko, 1999a). Participants were required to answer a series of questions that varied according to Bertin's (1967|1983) levels of map reading; the complete protocol was not published, although the provided examples primarily represent the *identify* objective. The first two rounds of testing were conducted with the same set of nine experts in software usability to test ***memorability*** (i.e., how well a user can return to an interface and pick up where he or she left off), while the final round was conducted online with 102 student participants. Each question was accompanied by a description of the 'interactive techniques', or operators, that should be applied to answer the question (i.e., the appropriate interaction strategy was provided by the investigators as part of the experiment protocol), with operators organized into five categories: (1) *outlier removal* (the *filter* operator, when applied to isolate extreme values in the map), (2) *visual comparison* (the *resymbolize* operator, implemented as a change to the middle point of a diverging color scheme), (3) *dynamic classification* (the *resymbolize* operator, implemented as an adjustment to the classification scheme or the class break positions), (4) *dynamic query* (the *filter* operator using direct manipulation of interface widgets to impose constraints on the displayed map features), and (5) *dynamic linking* (the *retrieve* operator, applied to *retrieve* specific information about a brushed map feature in linked information views). Because Andrienko et al. provided instructions on the proper interaction strategy, the primary empirical data collected was the correctness of the question responses (i.e., which operators led to the highest ***error frequency***). From the first round of testing, Andrienko et al. found that their *dynamic query* operator caused the highest error frequency, that participants made fewer errors at the elementary reading level than at the general, and that user satisfaction generally corresponded to user performance. From the second round, the authors found that performance was much better the second time around (pointing to high memorability) and that performance and satisfaction increased the most for the *dynamic classification* and *dynamic query* tools. From the third round, the authors found that the students performed much worse than the experts (somewhat expectedly), that the students varied much more widely in their performance and interaction technique usage, and that the *dynamic query* tool remained the most difficult to use.

Edsall (2003) conducted a cartographic interaction study to evaluate HealthVisPCP, an additional extension to the HealthVis tool that included a dynamically linked parallel coordinate plot (PCP) view in addition to the map and scatterplot views. 31 students and six expert epidemiologists completed 16 closed-ended tasks and one open-ended task; although the complete protocol was not included in the paper, Edsall indicated that the closed-ended tasks varied according to three characteristics: (1) the number of variables involved in the task, (2) the spatial extent or scale of the task (#1 and #2 together are related to search level), and (3) the task complexity and difficulty (which may be related to the level of ***sophistication*** exhibited in the **Chapter 5** objective-based taxonomy). The coding scheme includes specific pairings across the view (question view, map, PCP, scatterplot, legend), the type of interaction, and, in several cases, the specific interface style implementing the interaction. Unique interactions in the coding scheme include: (1) *answer* (an enabling interaction specific to the experiment), (2) *open* (a second enabling interaction specific to the experiment), (3) *reset/restore* (used to return to the default or original configuration, related to the *save* enabling operator described in **Chapter 5**), (4) *apply* (adjusting the variables displayed in the views, which is included as part of the *overlay* operator, and the number of classes for each variable using a menu selection, which is included as part of the *resymbolize* operator), (5) *brushing* (in order to *retrieve* specifics), (6) *zoom* (as defined in **Chapter 5**) (7) *pan* (as defined in **Chapter 5**), (8) *reorder* (specific to the PCP axes, which falls under the *arrange* operator), and (9) *reclassify/focus* (different codes were used for applying a new classification scheme and adjusting the break between a pair of classes; both examples fall under the *resymbolize* operator described in **Chapter 5**, despite Edsall's use of the term *focus* for the latter). From analysis of the user interactions and question responses, Edsall found that there was no significant difference in accuracy when reading from the scatterplot and PCP, that there was a significant difference in accuracy according to the spatial extent of the task, that low scorers (by accuracy) tended not to interact with the scatterplot or PCP (i.e., the linked views) when available, that high scorers generally interacted with the system more often than low scorers, that temporal trends (i.e., *associate* by *space-in-time*) were observed only by subjects that interacted with the PCP, and that the most complex and comprehensive user commentaries came from participants that made extensive use of the interface.

Finally, Robinson (2008a, 2008b) offers an analog cartographic interaction study focusing upon the synthesis stage of science (**Figure 2.2**). Although the collaboration sessions used paper analysis artifacts (i.e., pieces of evidence related to the disease outbreak) and pen/post-it annotation devices, the experiment was designed with the goal in mind of understanding how to design an interactive environment to support collaborative synthesis. Five pairs (n=10) of expert epidemiologists were walked through a synthetic infectious disease outbreak scenario and asked to synthesize evidence artifacts describing the outbreak in order to establish competing hypotheses about the origin of the outbreak. The collaborative sessions were video recorded and coded according to a multi-level taxonomy of twenty-eight 'low-level synthesis events'. Eight high-level categories were included in the taxonomy: (1) *annotate* (as defined in **Chapter 5**), (2) *group artifacts* (by hypothesis, by category, by type, by time, by read/unread, unknown reason), (3) *collapse/expand group of artifacts*, (4) *link artifacts* (by hypothesis or by network; such a definition was noted in **Chapter 5** as a potential interpretation of *linking* as an operator), (5) *sort* (by category, by type, or by time), (6) *search* (as defined in **Chapter 5**), (7) *tag* (by hypothesis, by category, by time, by network, by certainty, by follow-up, or by place; this may fall under the *edit* enabling operator), and (8) *zoom* (as defined in **Chapter 5**). Overall, the five most common events were *zoom* to a single item, *annotate* text, *group* by category, *group* by timeline, and *tag* hypothesis; the most common collaborative event (i.e., completed jointly) was *search* for artifacts. Digging more deeply into the individual interaction sessions, Robinson also found that sessions began by using 2-3 to even 15 minutes to establish common ground, that roles were quickly assigned to each group member with one participant being the leader and one being the recorder (i.e., annotator), that two interaction strategies for performing the *rank* objective on hypotheses emerged (a first ranking individually and then negotiating final rankings and a second not coming to final rankings formally), that one instance of collaborative deadlock emerged when one participant was unwilling to consider the complete set of evidence, that multiple interface metaphors are necessary, as participants work in many ways and commonly switched their strategies mid-stream, and that it is essential to preserve prior work when moving from an individual to a collaborative setting (i.e., to support the *save*, *import*, and *export* enabling operators). The experimental parameters of these four existing studies (MacEachren et al., 1998, Andrienko et al., 2002, Edsall, 2003, Robinson, 2008a) were used directly to inform the design the cartographic interaction study, as introduced in the following subsections.

6.3.2 Participants

Ten participants were sampled purposively from the Harrisburg Bureau of Police to participate in the cartographic interaction study using *GeoVISTA CrimeViz* as an experimental platform. As introduced in **Section 4.2.2**, ***purposive sampling*** describes the recruitment of participants according to their fitness to a small set of predefined criteria regarding the research (Patton, 1990). The primary criteria for participation in the cartographic interaction study included work responsibilities that would be supported by *GeoVISTA CrimeViz* once transitioned (i.e., participants were actual end users) and general familiarity with the *GeoVISTA CrimeViz* beta version (i.e., existing use of partially-featured versions made available to the Harrisburg Bureau of Police). Training and experience in crime analysis and crime mapping were not required for participation, as *GeoVISTA CrimeViz* explicitly was designed for use by law enforcement personnel that do not have access to advanced crime mapping tools or that lack access to educational resources needed to learn how to use such tools. The sample size of ten was determined according to the expert involvement of existing cartographic interaction studies (**Section 6.3.1**), which range from 6-10 experts.

Participants were identified by the key stakeholders at the Harrisburg Bureau of Police, who themselves participated in the in-person meetings and conference calls during formative evaluation of *GeoVISTA CrimeViz* mockups (**Section 6.2.2**). Because of the buy-in generated through the MILC—and the training component included at the start of the experimental session (see **Section 6.3.3**)—many more participants volunteered for the cartographic interaction study than could be tested given available project resources. Abbreviated, informal training sessions were provided to the additional volunteers that could not be scheduled in a formal testing session, but were interested in learning more about *GeoVISTA CrimeViz*. The participant sample therefore was characterized by high levels of user motivation. As discussed in **Section 2.5**, while domain experts are highly motivated to use a cartographic interface in order to complete their work for real-world situations, they may be much less motivated to use a cartographic interface during an *in vitro* study, as their cartographic interactions result in no work-related products and have no real-world consequences (Harrower, 2002). This situational variation in motivation may cause experts to perform more similarly to novices during controlled experiments, and is an argument for promoting user motivation for basic research in addition to applied research.

A background survey was administered to establish several characteristics of the cartographic interaction study participants. Four participants had no post-secondary degrees (although all indicated that they had taken training courses through the Harrisburg Area Community College), two participants held an Associates degree, and four participants held a Bachelors degree; all Associates and Bachelors degrees were in Criminal Justice. All participants were sworn officers and thus were trained in law enforcement and policing. The majority (9 of 10) of participants reported making maps either yearly or rarely, with only one participant making maps daily (**Table 6.1**); the *GeoVISTA CrimeViz* cartographic interface therefore fills a key unmet need at the Harrisburg Bureau of Police. The majority (7 of 10) of participants reported using maps at least monthly, with half (5 of 10) using maps weekly or daily. User motivation therefore was prioritized over user expertise in the cartographic interaction study, although it should be noted that all participants did have familiarity with the specific *GeoVISTA CrimeViz* tool, if not crime analysis and crime mapping broadly.

Regularity of Action	*Mapmaking*	*Map Use*
Daily	1	1
Weekly		4
Monthly		2
Yearly	2	1
Rarely	7	2
Total	**10**	**10**

Table 6.1: Regularity of Making and Using Crime Maps. Overall, participants in the cartographic interaction study made maps less frequently than they used them, an indication that *GeoVISTA CrimeViz* fills a key unmet need at the Harrisburg Bureau of Police.

6.3.3 Materials and Procedure

The cartographic interaction study was conducted in a private interview room, located in the Harrisburg Police Headquarters, with wireless Internet access and that otherwise is used for depositions and interrogations. A 'mobile' usability laboratory was set up in the interview room for testing, which consisting of a laptop computer used by the investigator and external monitor, keyboard, and mouse used by the participant; the laptop and external monitor were set opposite of each other on the central table in the interview room such that the investigator and participant were facing one another. Both the laptop screen and external monitor displayed the same web browser, with *GeoVISTA CrimeViz* loaded, and both the investigator and participant had control over the browser through their respective input devices. As described below, the mobile usability laboratory allowed the investigator to provide an initial demonstration, with the participant watching the investigator's cartographic interactions, and then for the participant to complete the cartographic interaction study, with the investigator watching the participant's cartographic interactions. Cartographic interactions with *GeoVISTA CrimeViz* were logged using Camtasia Studio, a video recording application that records screen interactions; audio backups of the sessions were captured using a voice recorder. Testing was completed over five days, with the mobile usability lab remaining set up throughout the period.

The cartographic interaction study proceeded in three sections (**Appendix F**). Each session began with a review of the Penn State GeoVISTA Center collaboration with the Harrisburg Bureau of Police as well as an overview of the goals of the summative evaluation. The introduction period was followed with a demonstration and opening exploration period of *GeoVISTA CrimeViz*, constituting the training session that personnel at the Harrisburg Bureau of Police received as a benefit to participation. Because it was expected that participants were familiar with *GeoVISTA CrimeViz*, the interactive demonstration provided by the investigator focused on explanation of features that recently were added into the cartographic interface, or only were fully functional at the time of the cartographic interaction study (i.e., features that the participants may be aware of, but may not be aware are working). Following the demonstration, the participant was given control of *GeoVISTA CrimeViz* and encouraged to ask questions about the cartographic interface while interacting with it. Approximately 15 minutes were budgeted for the demonstration and opening exploration, although participants were consistent in desiring 30 minutes for the training session in order to work through all questions generated through the initial demonstration and their own prior use of *GeoVISTA CrimeViz*.

Following the demonstration and opening exploration, the participants were asked to answer a set of 15 close-ended questions using *GeoVISTA CrimeViz*. The questions were based on the **Chapter 5** taxonomy of cartographic interaction primitives, with one question generated for each objective (*identify*, *compare*, *rank*, *associate*, and *delineate*) and operand (*space-alone*, *attributes-in-space*, *space-in-time*) pairing. The questions were worded so that participants could respond with a brief answer containing only a single term or set of terms. The questions also were generated so that the answer was not apparent in the default overview provided when first entering *GeoVISTA CrimeViz*, avoiding the issue that occurred in the MacEachren et al. (1998) study in which participants did not need to interact with the cartographic interface to accomplish a subset of the objectives. A pilot study was administered in order to revise questions that were unclear or poorly worded, that potentially had more than one correct or partially correct answer, and that had answers that participants would be able to recall from experience without first interacting with *GeoVISTA CrimeViz*.

During the cartographic interaction study, each question was read aloud by the investigator and then a print of the question was handed to the participant for reference. The order of the questions was randomized, with no two participants receiving the same question order. Unlike the training session, participants were not allowed to ask for clarification about *GeoVISTA CrimeViz* during the cartographic interaction study. They instead were directed to limit their verbalizations in order to focus upon the question at hand. Once the participants believed they had found the answer to the question, they were instructed to state it aloud for audio recording. Participants were provided a maximum of three minutes to answer each question in order to ensure the complete set of 15 questions was completed in 45 minutes or less; only four of the total 150 questions (15 questions by 10 participants) exceeded the three minute limit, with all participants completing the formal testing component of the cartographic interaction study in 20-25 minutes. In the event that the three minute limit was reached, participants were given the opportunity to provide a best guess before moving to the next question, although the participants also were allowed to answer "I don't know". After an answer was verbalized for a question, or after the three minute time limit expired, the browser containing *GeoVISTA CrimeViz* was refreshed by the investigator to make the participant start from the default overview when answer the subsequent question. All sessions—including the introduction, training, and formal testing—lasted between 60 and 75 minutes.

6.3.4 Interaction Analysis

Participant interactions with *GeoVISTA CrimeViz* were recorded using Camtasia Studio for subsequent distillation into interaction logs. As introduced in **Section 3.4**, an ***interaction log*** is a document listing every interaction employed during an experimental or real-world interaction session, along with a timestamp indicating when the interaction was performed. With regard to the interpretation of empirical information, an interaction log and its associated listing of operators are analogous to a unitized transcript and its associated frequency of codes in qualitative data analysis (see **Section 4.2.4**), although the ordering of the operators in an interaction log often is as important as the operators themselves. To examine the **Chapter 5** taxonomy of cartographic interaction primitives, the specific *GeoVISTA CrimeViz* cartographic interface components available during the cartographic interaction study were translated according to the operator and operand dimensions of the taxonomy; **Table 6.2** provides a listing of each individual cartographic interface component in the experimental version of *GeoVISTA CrimeViz* and the associated operator and operand primitives it supports. In total, 8 of the 12 work operators (**Section 5.4.3**) are supported by *GeoVISTA CrimeViz*, as these operators were identified during the MILC with the Harrisburg Bureau of Police (**Section 6.2.2**) as essential for supporting end user needs. Sweeney et al. (1993) describe an additional set of performance measures that characterize the overall success and diversity of the interaction strategies applied to accomplish an objective, which include: (1) the percentage of the questions that were completed (i.e., questions answered prior to reaching the three minute time limit), (2) the accuracy level or error rate of the answers, (3) the time taken to answer each question, (4) the number of operators used to answer the question (i.e., ***frequency***), and (5) the range of operators used to answer the question (i.e., ***diversity***); the summary metrics by objective-operand pairings are provided in **Table 6.3**. In addition to the objective-operand measures, summary measures by operator-operand pairings are provided in **Table 6.4**, which includes each pairing's overall frequency and ***extensiveness***, or the number of interaction sessions in which a specific combination was employed.

Interaction logs often are expressed as ***timeline graphics*** to facilitate interpretation of individual interaction strategies and comparison of competing interaction strategies (Haug et al., 2001). At times, interpretation of these timeline graphics can be as difficult as interpreting a text-based table listing the interactions, particularly when interactions performed during a session are both frequent and diverse. To improve interpretation of the interaction logs, the timeline graphics provided in **Section 6.4** (**Figure 6.3-6.17**) aggregate the logs to the temporal resolution of five seconds and align all 10 interaction strategies performed for each objective-operand combination. Each applied interaction operator is indicated by a one-letter code (the codes are included in **Table 6.2**) and each manipulated interaction operand is indicated by the color (*space-alone* in green, *attributes-in-space* in blue, and *space-in-time* in red). The timestamp of the participant's response also is represented in the timeline graphics, indicated in black with a 'yes' (correct) or 'no' (incorrect). When multiple operators were performed within a five second timeframe, they are stacked horizontally using the same ordinal-level metaphor employed by a stem-and-leaf information graphic (although it is important to note that interaction codes are not conceptual 'leaves' to the timeline's 'stem'). For each timeline graphic, the individual participant interaction strategies were sorted from 'successful' to 'unsuccessful' according to the following criteria: (1) correct versus incorrect, (2) completed within three minutes or not, (3) time taken to respond, and (4) number of interactions (applied only when two or more participants took the same amount of time to answer a question).

6.4 Results and Discussion

6.4.1 Interacting with *GeoVISTA CrimeViz*

Table 6.3 provides a summary of participant interactions performed to answer each of the 15 questions included in the cartographic interaction study protocol (**Appendix F**), which again are representative of every possible objective and operand pairing; composite metrics also are provided for each objective or operand primitive, as well as all questions in total. Participants performed well overall, answering 123 of the 150 total questions correctly (82%); the high accuracy rating perhaps is a reflection on the training—and associated increased levels of user motivation—completed as part of the MILC approach (**Section 6.2.2**). As stated above, only four of the 150 total questions required the full three minutes; participants were able to provide the correct answer after time had expired in two of these four instances. On average, participants required 1:00 (one minute) and employed 3.4 different operators a total of 7.4 times to answer each question.

The **Table 6.3** metrics generally indicate an increasing level of difficulty across the objective primitives according to their level of sophistication. The *identify* objective (i.e., the least sophisticated) required the least amount of time overall (0:31) and the fewest interactions (3.1), while the *delineate* objective (i.e., the most sophisticated) required the most amount of time overall (1:27) and the most interactions (9.8); the *delineate* operator also resulted in the most incorrect answers (only 67% accuracy). There is some overlap in the metrics for the operators of intermediate sophistication. While the *compare* objective overall took slightly longer to complete and resulted in more mistakes than the *rank* objective (which is counter to the proposed level of sophistication), the *rank* objective required more frequent and diverse interactions than the *compare* objective (which follows the proposed level of sophistication). Similarly, the *rank* objective required more frequent and diverse interactions than the *associate* objective (which is counter to the proposed level of sophistication), the *associate* operator took longer to complete and resulted in more errors (which follows the proposed level of sophistication). The *associate* operator proved to be equally or more sophisticated than the *compare* operator across all five metrics, suggesting that the ordering of *identify-compare-rank-associate-delineate* still holds overall, but that the categories themselves exhibit partial overlap along a continuum of sophistication.

Regarding the operand component of the questions, participants most easily responded to questions regarding the *space-alone* operand; this finding holds across all five metrics. Summary metrics regarding the *attributes-in-space* and *space-in-time* operands were similar, with participants requiring slightly more time to respond to questions including the *attribute-in-space* operand and slightly more frequent and diverse interactions to respond to questions including the *space-in-time* operand. Interestingly, participants only had problems answering questions about the *attribute-in-space* operand within the allotted three minute time limit, but were considerably less accurate in their responses to questions about the *space-in-time* operand.

In contrast, **Table 6.4** provides a summary of the operators employed to answer each of the 15 questions (rather than performance on the questions themselves), discriminated according to the operand on which they were performed. The *retrieve* operator was the most frequently and extensively applied operator primitive (frequency=395, extensiveness=71%), followed by the *filter* (frequency=240, extensiveness=60%) and *zoom* (frequency=127, extensiveness=44%) operators respectively; no other operators were used in more than one-third of the 150 interaction strategies. Such an emphasis of *retrieve*, *filter*, and *zoom* supports Shneiderman's (1996) ***visual information seeking mantra***, in which the *filter* and *zoom* operators are used to transition from an overview to a details view, with the *retrieve* operator then applied to extract specific information from the details view. As discussed in the **Section 6.4.2** description of prototypically successful interaction strategies, however, the *filter*, *zoom*, and *retrieve* operators (as well as the *pan* operator, which typically is applied in tandem with *zoom*) often are not employed productively, and instead may be an indication that the user does not know how to find the answer to his or her question.

Regarding the operand on which the operator is applied, participants least commonly interacted with the *space-alone* operand (frequency=175, extensive=33%); several of the cartographic interfaces provided to manipulate the *space-alone* operand were ignored altogether (e.g., *search* and *overlay* by *space-alone*). This perhaps is explained by the increased difficulty in answering protocol questions regarding the *attributes-in-space* and *space-in-time* operands, as many more interactions were performed to answer questions about either of these two operands (**Table 6.3**). However, this may be true about all cartographic interactions generally, as a map first and foremost is a spatial representation and thus ostensibly supports many spatial map reading questions without digital cartographic interaction. Therefore, it may be more important to provide (and design well) cartographic interfaces to manipulate the *attributes-in-space* and *space-in-time* operands than the *space-alone* operand, given the intrinsic spatial quality of a cartographic representation. Finally, an interesting distinction between cartographic interactions with the *space-in-space* and *space-in-time* operands was observed; while the participants most frequently interacted with the *space-in-time* operand (frequency=543, extensiveness=63%), they most extensively interacted with the *attributes-in-space* operand (frequency=248, extensiveness=78%).

#	*Operator-Operand*	*Description of Features in GeoVISTA CrimeViz*
1	**Reexpress (X)**	
	Space-Alone	*<none>*
	Attributes-in-Space	*<none>*
	Space-in-Time	Menu Selection for Linear versus Composite Time
2	**Arrange**	
	Space-Alone	*<none>*
	Attributes-in-Space	*<none>*
	Space-in-Time	*<none>*
3	**Sequence (Q)**	
	Space-Alone	*<none>*
	Attributes-in-Space	*<none>*
	Space-in-Time	Direct Manipulation Click of the 'Play' (Loop) and 'Pause' VCR Controls
4	**Resymbolize**	
	Space-Alone	*<none>*
	Attributes-in-Space	*<none>*
	Space-in-Time	*<none>*
5	**Overlay (O)**	
	Space-Alone	Menu Selection for Basemap Type ('Map', 'Sat', 'Terrain')
	Attributes-in-Space	Menu Selection Checkboxes for Point/Line Data Layers ('Schools', etc.)
		Menu Selection Radio Buttons for Polygonal Data Layers ('Districts', etc.)
		Menu Selection 'Reset' Additional Data Layers
	Space-in-Time	*<none>*
6	**Reproject**	
	Space-Alone	*<none>*
	Attributes-in-Space	*<none>*
	Space-in-Time	*<none>*
7	**Pan (P)**	
	Space-Alone	Direct Manipulation Click+Drag on Map
		Direct Manipulation 'Resent Extent' Control
	Attributes-in-Space	*<none>*
	Space-in-Time	Direct Manipulation Click on Histogram Bin
		Direct Manipulation Click on 'Back' and 'Step' VCR Controls
		Direct Manipulation of Histogram Slider Bar (When Entirety is Not Displayed)

Table 6.2: Operator and Operand Primitives Supported by *GeoVISTA CrimeViz*. The individual cartographic interface components constituting *GeoVISTA CrimeViz* were translated into the operator and operand dimensions included in the **Chapter 5** taxonomy of cartographic interaction primitives. In total, *GeoVISTA CrimeViz* supports eight interaction operators: **(this page)** *reexpress* (X), *sequence* (Q), *overlay* (O), and *pan* (P) **(next page)** *zoom* (Z), *filter* (F), *search* (S), and *retrieve* (R).

#	*Operator-Operand*	*Description of Features in GeoVISTA CrimeViz*
8	**Zoom (Z)**	
	Space-Alone	Direct Manipulation Double-Click on Map
		Direct Manipulation Click on Hexagon Grid
		Direct Manipulation Click on Data Layer Element
		Direct Manipulation '+' and '-' Controls
		Direct Manipulation 'Resent Extent' Control
	Attributes-in-Space	*<none>*
	Space-in-Time	Menu Selection for Binning Unit
9	**Filter (F)**	
	Space-Alone	Menu Selection Numerical Stepper by 'District'
		Form Fill-in by 'District'
		Menu Selection for 'Reset Advanced Features'
	Attributes-in-Space	Menu Selection by 'UCR Primary,' 'UCR Secondary' and 'MO'
		Form Fill-in by 'UCR Primary,' 'UCR Secondary' and 'MO'
		Menu Selection for 'Reset Basic Filters'
	Space-in-Time	Menu Selection Numerical Stepper for 'From' and 'To' Linear Filtering
		Form Fill-in 'From' and 'To' Linear Filtering
		Menu Selection Shortcuts for Linear Filtering ('Week', 'Month', 'Year', 'All')
		Direct Manipulation of 'Hours', 'Months', and 'Days' Widgets for Cyclical Filtering
		Menu Selection Shortcuts for Cyclical Filtering ('All', 'None', 'Winter', etc.)
		Menu Selection for 'Reset Temporal Parameters'
10	**Search (S)**	
	Space-Alone	Form Fill-in Search by 'Address'
	Attributes-in-Space	Form Fill-in Search by 'Report #'
	Space-in-Time	*<none>*
11	**Retrieve (R)**	
	Space-Alone	*<none>*
	Attributes-in-Space	Direct Manipulation Mouse-Over of Hexagon Bin
		Direct Manipulation Mouse-Over of Crime Incident
		Direct Manipulation Click of Crime Incident
		Menu Selection to Activate Street View
		Direct Manipulation Mouse-Over of Data Layer Element
	Space-in-Time	Direct Manipulation Mouse-Over of Histogram Bin
12	**Calculate**	
	Space-Alone	*<none>*
	Attributes-in-Space	*<none>*
	Space-in-Time	*<none>*

Objective-Operand	*Complete*	*Correct*	*Avg Time*	*Frequency*	*Diversity*
Identify by Space-Alone	10 (100%)	10 (100%)	0:18	1.3	1.2
Identify by Attributes-in-Space	10 (100%)	10 (100%)	0:32	1.6	1.5
Identify by Space-in-Time	10 (100%)	6 (60%)	0:43	6.5	3.6
All Identify	**30 (100%)**	**26 (87%)**	**0:31**	**3.1**	**2.1**
Compare by Space-Alone	10 (100%)	9 (90%)	0:25	7.6	3.0
Compare by Attributes-in-Space	10 (100%)	10 (100%)	0:57	3.5	1.6
Compare Space-in-Time	10 (100%)	6 (60%)	1:32	11.2	3.4
All Compare	**30 (100%)**	**25 (83%)**	**0:58**	**7.4**	**2.7**
Rank by Space-Alone	10 (100%)	9 (90%)	0:42	8.9	3.9
Rank by Attributes-in-Space	9 (90%)	10 (100%)	1:11	11.2	5.1
Rank by Space-in-Time	10 (100%)	9 (90%)	0:53	7.1	3.8
All Rank	**29 (96.7%)**	**28 (93%)**	**0:56**	**9.1**	**4.3**
Associate by Space-Alone	10 (100%)	10 (100%)	0:18	3.0	1.6
Associate by Attributes-in-Space	10 (100%)	8 (80%)	1:24	10.5	5.0
Associate by Space-in-Time	10 (100%)	6 (60%)	1:36	9.2	3.4
All Associate	**30 (100%)**	**24 (80%)**	**1:06**	**7.6**	**3.2**
Delineate by Space-Alone	10 (100%)	9 (90%)	1:08	8.8	4.8
Delineate by Attributes-in-Space	7 (70%)	3 (30%)	2:13	13.6	4.9
Delineate by Space-in-Time	10 (100%)	8 (80%)	1:02	7.0	4.2
All Delineate	**27 (90%)**	**20 (67%)**	**1:27**	**9.8**	**4.6**
All Space-Alone	**50 (100%)**	**47 (94%)**	**0:34**	**5.9**	**2.9**
All Attributes-in-Space	**46 (92%)**	**41 (82%)**	**1:16**	**8.1**	**3.5**
All Space-in-Time	**50 (100%)**	**35 (70%)**	**1:09**	**8.2**	**3.7**
Total	**146 (97%)**	**123 (82%)**	**1:00**	**7.4**	**3.4**

Table 6.3: A Summary of Participant Interactions by Objective and Operand Pairings. Following the recommendations of Sweeney et al. (1993), five summary scores are provided for each question in the cartographic interaction study protocol (i.e., each objective-operand pairing): (1) number and percentage answered within three minutes, (2) number and percentage answered correctly, (3) average time per question, (4) average operator frequency, and (5) average operator diversity. Totals also are provided by individual operator primitive, individual operand primitive, and the study as a whole.

Operand-Operand	*Frequency*	*Extensiveness*
Space-in-Time (X)	78	50 (33%)
All Reexpress (X)	**78**	**50 (33%)**
Space-in-Time (Q)	32	14
All Sequence (Q)	**32**	**14 (9%)**
Space-Alone (O)	0	0 (0%)
Attributes-in-Space (O)	57	46 (31%)
All Overlay (O)	**57**	**46 (31%)**
Space-Alone (P)	81	28 (19%)
Space-in-Time (P)	40	17 (11%)
All Pan (P)	**121**	**41 (27%)**
Space-Alone (Z)	82	39 (26%)
Space-in-Time (Z)	45	34 (23%)
All Zoom (Z)	**127**	**66 (44%)**
Space-Alone (F)	12	12 (8%)
Attributes-in-Space (F)	90	31 (21%)
Space-in-Time (F)	138	74 (49%)
All Filter (F)	**240**	**90 (60%)**
Space-Alone (S)	0	0 (0%)
Attributes-in-Space (S)	42	29 (19%)
All Search (S)	**42**	**29 (19%)**
Attributes-in-Space (R)	185	59 (39%)
Space-in-Time (R)	210	58 (39%)
All Retrieve (R)	**395**	**106 (71%)**
All Space-Alone	**175**	**49 (33%)**
All Attributes-in-Space	**248**	**117 (78%)**
All Space-in-Time	**543**	**94 (63%)**
Total	**1092**	**150 (100%)**

Table 6.4: A Summary of Participant Interactions by Operator and Operand Pairings. Two summary metrics are provided across operator-operand pairings: (1) frequency (total number of applications across all participants; no maximum) and (2) extensive (total number and percentage of interaction strategies in which the operator was applied; maximum of 150).

6.4.2 Prototypically Successful and Unsuccessful Interaction Strategies

Table 6.3 and **Table 6.4** describe the cumulative application of operator primitives according to the objective and operand context (i.e., the question from the protocol). In the following, individual interaction strategies are compared for each objective and operand pairing to identify common patterns and prototypically successful interaction strategies. For each objective-operator pairing, a brief summary of the variation across participants and a timeline representation of the interaction logs (see **Section 6.3.4**) are provided. Equal emphasis is given to successful and unsuccessful strategies, as key bottlenecks and missteps constituting the latter are important for understanding why one strategy is more effective (i.e., led to a correct answer) or more efficient (i.e., led to a correct answer more quickly) than others. Where possible, ***personas*** are developed to characterize chronic issues in applying operators that occurred across participants and across tasks; in most cases, there are equivalent positive personas performed during successful interaction strategies that represent the inverse of associated the negative personas.

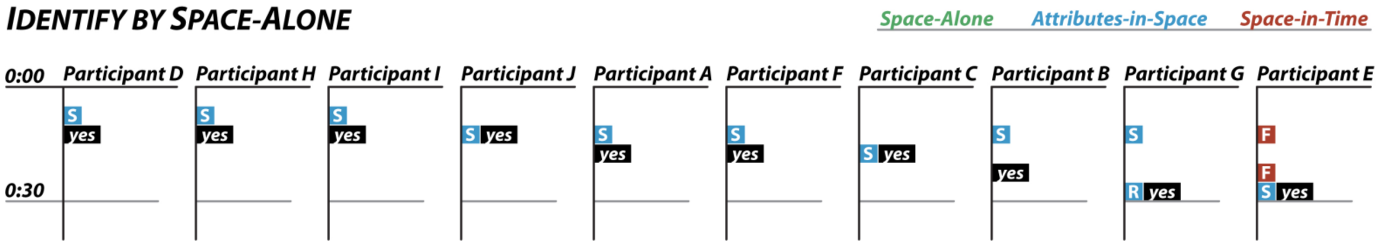


Figure 6.3: Interaction Logs for *Identify* by *Space-Alone* (#1):

#1. *Identify* by *Space-Alone*: On what street did incident #20101100945 occur? (*space-alone*)

There was little variation across participants in the operators employed to answer the *identify* by *space-alone* question (#1; **Figure 6.3**); all participants were able to answer this question correctly and within 30 seconds. The prototypically successful interaction strategy consisted entirely of the *search* operator, specifically the *GeoVISTA CrimeViz* form fill-in interface for searching by the crime incident report number that is included in the Data Panel. Generally, the faster the participant could type the crime incident report number into the *search* interface, the sooner he or she answered the question. The least efficient strategies were those that included additional operators (e.g., *retrieve* by Participant G and *filter* by Participant E), although this resulted in only a minimal loss of efficiency for the *identify* by *space-alone* question (#1).

#2. *Identify* by *Attributes-in-Space*: What type of crime (by UCR code) is incident #20101100894, which occurred at 200 Herr Street?

As with the *identify* by *space-alone* question (#1), there was little variation across participants in the operators employed to answer the *identify* by *attributes-in-space* question (#2; **Figure 6.4**). Again, all participants were able to answer the question correctly, although four participants required more than 30 seconds (and one required more than a minute). Interestingly, all participants chose to apply the *search* operator, although a response did not immediately follow application of the operator in all cases, perhaps indicating a greater difficulty in extracting the attribute information from the *GeoVISTA CrimeViz* information window design, as compared to the spatial information extracted during the *identify* by *attributes-in-space* question (#2). All participants searched by the crime incident report number (i.e., *search* by *attributes-in-space*, or a blue 'S' in the interaction log) rather than searching by the street address (i.e., *search* by *attributes-in-space*, or a green 'S' in the interaction log), even though both components were included in the question (unlike the *identify* by *space-alone* question, #1, above, which included the crime incident report number only). Participants searched by the report number rather than the street address to answer all questions in the protocol (i.e., there were zero applications of *search* by *space-alone*, as shown in **Table 6.4**), despite opportunities to do otherwise (or to perform both). This perhaps is explained by the participants' familiarity in working with their own crime incident reports, but not with maps of these reports. Regardless, the clear reliance on the *search* operator for the *identify* by *space*-alone (#1) and *attributes-in-space* (#2) questions provides initial evidence that the *identify* objective should be supported by the *search* operator, when possible.

Application of additional operators for the *identify* by *space-alone* question (#1) did impose noticeable differences in efficiency; the three participants that performed operators other than *search* required 15-45 seconds longer to answer the question than their counterparts that applied *search* only. As with the *identify* by *space-alone* question (#1), Participant E curiously did not answer until after first narrowing into a specific time range using the *filter* by *space-in-time*, even when all information needed to answer a question was included in the display; such an application of the *filter* operator negatively impacts productivity and may be part of a routine (at least for Participant E) when moving from an overview to a details view (i.e., the ***excessive-filterer*** persona).

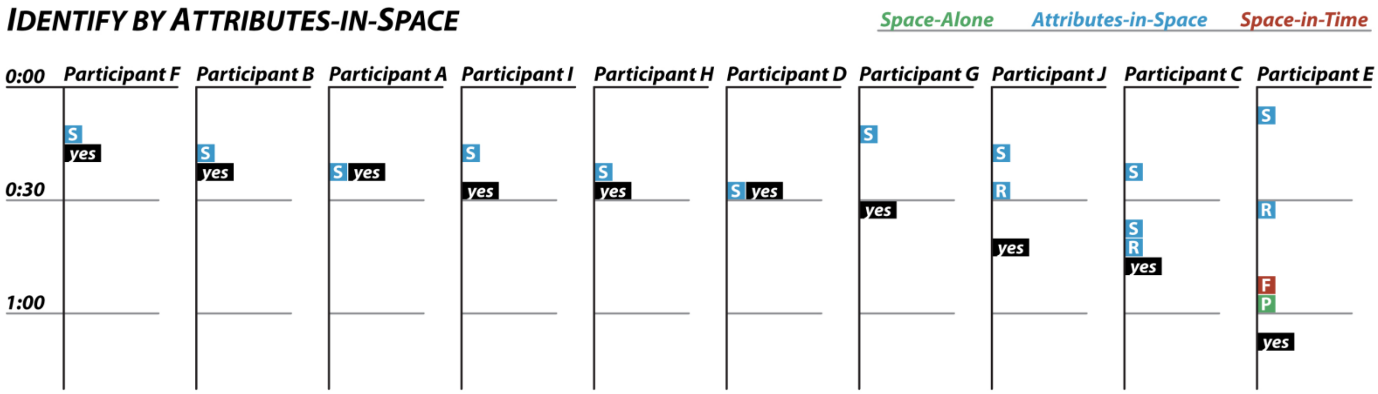


Figure 6.4: Interaction Logs for *Identify* by *Attributes-in-Space* (#2).

#3. *Identify* by *Space-in-Time*: How many total crime incidents occurred in District #5 on September 1st, 2010?

Unlike the other questions representative of *identify* objectives (#1 and #2), the *identify* by *space-in-time* question (#3) proved to be difficult (only 6 of 10 participants answered correctly) and resulted in several competing interaction strategies (**Figure 6.4**). Five of the six participants that correctly answered the question applied the *filter* operator to both the *space-alone* operand (i.e., numerical stepper to *filter* by Police District) and *space-in-time* operand (i.e., numerical steppers to *filter* linearly in time), appropriately moving from the overview map to a details view showing only the correct spatiotemporal extent. Participants were forced to use the *filter* operator for the *identify* by *space-in-time* (#3) question because a temporal *search* was not provided in the experimental version of *GeoVISTA CrimeViz* (**Table 6.2**). Participant I was able to answer the question correctly by substituting *filter* by *space-alone* with the *zoom* and *pan* operators (i.e., ***map browsing***), both in *space-alone*; participants were able to recover when applying this solution to objectives of lesser sophistication (e.g., *identify* and *compare*), but not for objectives of increased sophistication (resulting in the ***lost-browser*** persona); rapid application of *zoom* did not prove successful for Participant A regarding the *identify* by *space-in-time* question (#3).

Interestingly, Participant F did successfully apply the *filter* operator to both operands, but followed these operators with a rapid series of *retrieve* operators and ultimately failed to find the correct answer. The *retrieve* operator was applied by Participant G to answer the *identify* by *space-alone* question (#1) and Participants J, C, and E to answer the *identify* by *attributes-in-space* question (#2); in both cases, only a single *retrieve* operator was applied to confirm the correct answer, impacting efficiency by only 10-15 seconds. Thus, while a single, purposeful application of the *retrieve* operator decreases productivity slightly, it acts to acquire the correct answer or to improve the user's confidence in the answer, and therefore is not a suboptimal interaction strategy generally. However, the rapid application of the *retrieve* operator by Participant F did not lead to a correct answer. This rapid application of *retrieve* instead was indicative of anxious behavior applied when the *filter* operators did not result in an obvious answer in the cartographic representation, leading the participant to probe the representation in hope of finding the answer (i.e., the ***unsure-retriever*** persona). This behavior is most evident in *identify* objectives, for which the target is a single map feature. Such a suboptimal interaction strategy is prompted by a breakdown in Shneiderman's (1996) visual information seeking mantra, or when the application of the *filter* or *zoom* operators did not yield the expected details, thus indicating that navigation between an overview and details view is two-way and that strong orientation cues are needed in the cartographic interface design to maintain a portion of the overview or to indicate how to return to the overview (Harrower and Sheesley,

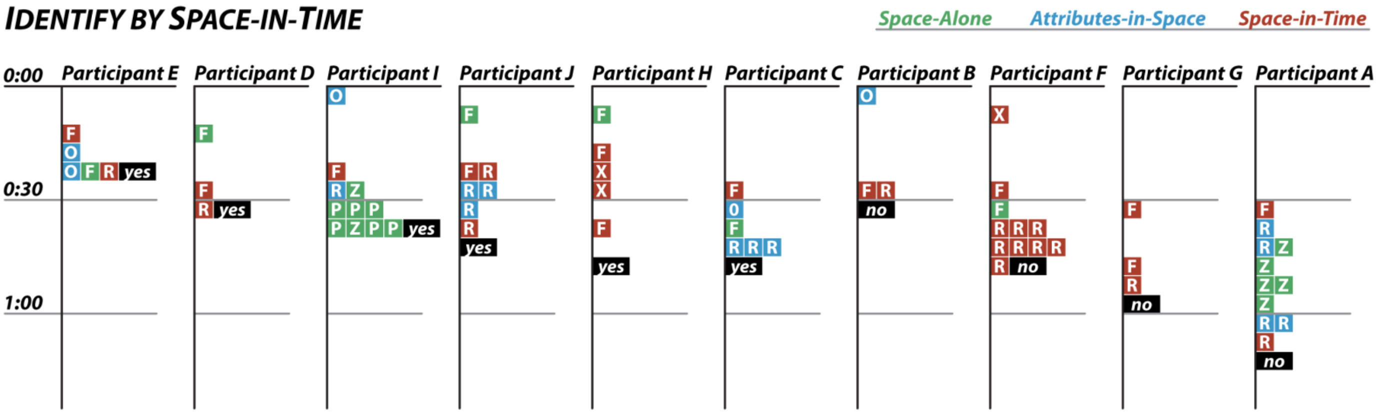


Figure 6.5: Interaction Logs for *Identify* by *Space-in-Time* (#3).

2005). That such a breakdown may happen is additional evidence for supporting the *search* operator over the *filter* (e.g., the misstep by Participant F) and *zoom* (e.g., the misstep by Participant A) operators for the *identify* objective. This specific example of the unsure-retriever persona was prompted by application of an incorrect visual isomorph using the *reexpress* operator (specifically, the use of a composite rather than a linear view of time), an issue described in more detail below.

#4. *Compare* by *Space-Alone*: Are Fire Station #2 and Fire Station #8 in the same police district?

Participants overall performed well on the *compare* by *space-alone* question (#4) with 9 of the 10 participants answering correctly and all participants answering within 45 seconds (Figure 6.6). The prototypically successful interaction strategy included application of the *overlay* and *retrieve* operators. All participants applied the *retrieve* operator three to six times, illustrating that rapid application of *retrieve* does not necessarily indicate the unsure-retriever persona when performed to answer a *compare* objective (or objectives at a higher level of sophistication); however, it is important to note that the number of applications of *retrieve* generally increases from three with an equal increase in response time, as some participants could not remember the initially retrieved values. Of the participants that applied the *zoom* operator, most participants applied it only following application of the *overlay* operator. Generally, it is recommended to apply the *overlay* operator prior to applying the *zoom* operator, rather than vice versa, as the initial application of *overlay* provides important contextual information for the subsequent

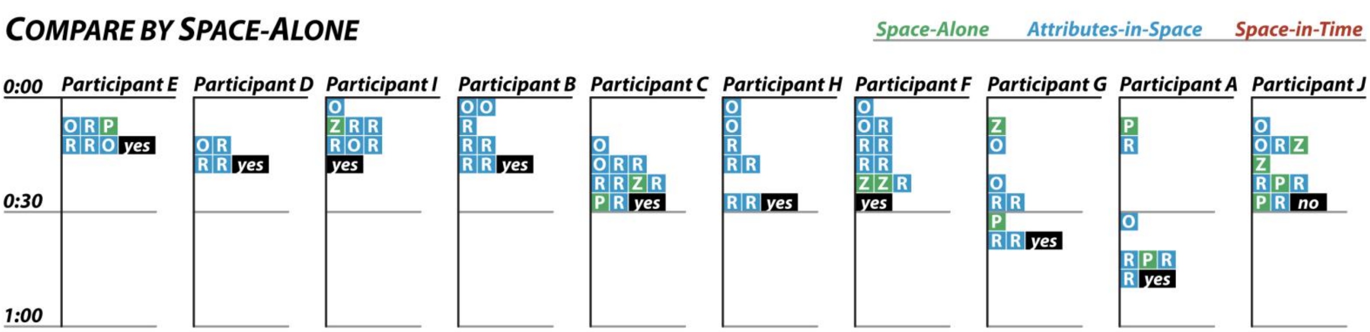


Figure 6.6: Interaction Logs for *Compare* by *Space-Alone* (#4).

application of *zoom*, ultimately supporting an informed transition from an overview to a details view; the only potential negative of such a strategy is the plotting of a voluminous contextual dataset, producing a cluttered view and a potential system response delay that together hinder the appropriate application of the *zoom* operator (cartographic design of an overview representation for the context layer alleviates this issue). Participant G illustrates the potential problems with applying *zoom* prior to *overlay* (i.e., the ***uninformed-zoomer*** persona), as he or she ultimately had to apply the *pan* operator to recenter the view on the compared map features, delaying the response. Curiously, Participant J answered incorrectly (to a yes/no question) despite performing the prototypically successful interaction strategy and extracting the information necessary to answer the question; it is possible he or she misunderstood the question or misread the information provided when applying the *retrieve* operator.

#5. *Compare* by *Attributes-in-Space*: Is incident #20101100945, which occurred on Market Street, the same type of crime (by UCR) as incident #20101100608, which occurred on 3rd Street?

As with the *compare* by *space-alone* question (#4), participants performed well on the *compare* by *attributes-in-space* question (#5), with all 10 participants answering the question correctly and 7 of 10 participants answering within 60 seconds (Figure 6.7). The prototypical interaction strategy included a pair of *search* operators, effectively resulting in the doubling of the prototypical interaction strategy for the *identify* by *attributes-in-space* (#2) question, which included only a single application of *search*; the relationship between the *identify* (#2) and *compare* (#5) interaction strategies, when applied to the *attributes-in-space* operator, indicates that a more sophisticated objective may be compartmentalized into a series of less sophisticated objectives to simplify the task or to make it easier to determine an optimal interaction strategy. Interestingly, Participants A and C applied the *search* operator three or more times, resulting in a response time 30-45 seconds longer than their counterparts applying the *search* operator only twice; this delay was caused by mistyping the crime incident report number into the form fill-in search interface, a productivity issue associated with the added flexibility of the form fill-in interface style. Both Participant I and Participant G behaved as excessive-filterers, starting the session with an unnecessary *filter* by *space-in-time*. Participant I followed the *filter* operator with a series of *zoom*, *pan*, and *retrieve* operators, behavior indicative of the lost-browser persona; Participant I was able to find the correct answer, but less quickly than participants applying the *search* operator twice without misspellings.

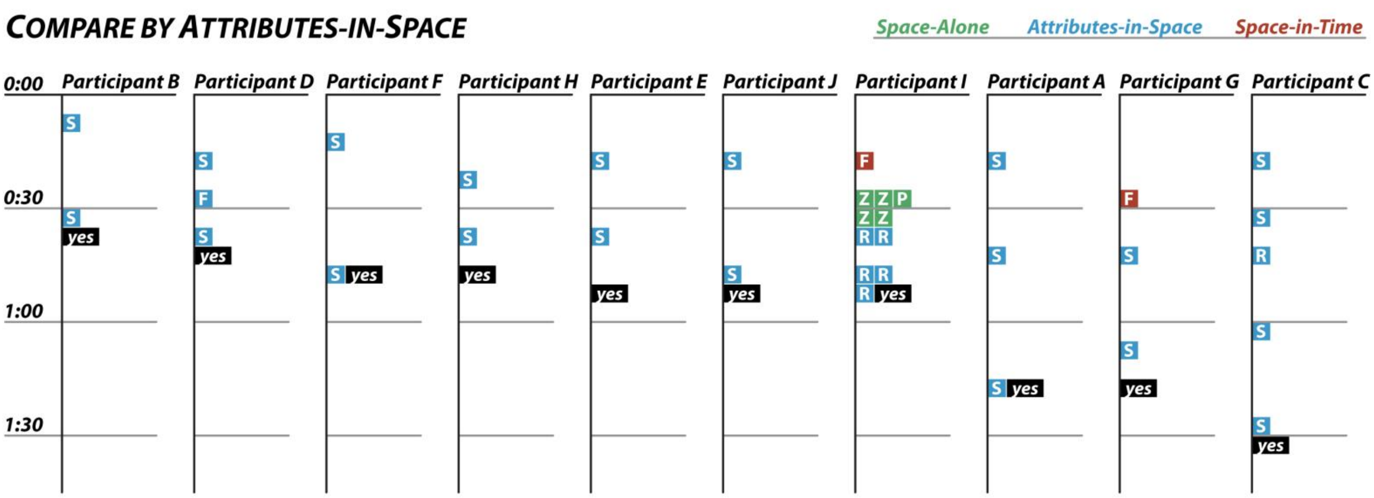


Figure 6.7: Interaction Logs for *Compare* by *Attributes-in-Space* (#5).

#6. *Compare* by *Space-in-Time*: In October 2010, how many more crime incidents occurred within Harrisburg on Sundays compared to Mondays?

Interaction strategies performed to answer the *compare* by *space-in-time* question (#6) were among the most complex exhibited during the cartographic interaction study (**Figure 6.8**); only 6 of 10 participants correctly answered the question (tied for the second lowest accuracy) and participants used on average 11.2 operators per session (tied for the second most), but not one operator was applied to the *space-alone* or *attributes-in-space* operand (as with most of the questions concerning the *space-in-time* operand). The key to completing the *compare* by *space-in-time* question was generation of the proper visual isomorph using the *reexpress* operator, in this case a composite week by day of the week. Overall, the more quickly the *reexpress* operator was performed to generate the appropriate visual isomorph, the more quickly the participant was able to respond; for instance, Participant H and G first applied several *filter* operators—again, likely out of habit, representing the excessive-filterer persona—which delayed response by 30-90 seconds compared to Participants I, B, D, and E. The four participants that answered incorrectly were not able to generate the appropriate visual isomorph (i.e., the ***mistaken-reexpresser*** persona); Participant A applied the incorrect visual isomorph and never changed it, Participants J and F changed the visual isomorph multiple times, but never evoked the composite week by day of the week visual isomorph, and Participant C never thought to change the visual isomorph from a linear timeline. The importance of identifying the appropriate visual isomorph for answering the *compare* by *space-in-time* question (#6) relates to Keehner et al.'s (2008) argument to constrain interaction in order to show only the optimal visual isomorphic view. In situations when multiple visual isomorphic views are needed to support a range of user objectives (as with *GeoVISTA CrimeViz* and geovisualization applications), strong affordances need to be incorporated into the cartographic interface design to inform selection of the appropriate visual isomorph using the *reexpress* operator. The overall difficulty in applying the *reexpress* operator to identify the optimal visual isomorph likely explains the poor accuracy levels exhibited by participants on questions concerning the *space-in-time* operand (70%), as compared to questions concerning the *space-alone* (94%) and *attributes-in-space* (82%) operands (**Table 6.3**), as the *reexpress* operator was only available for manipulation of the *space-in-time* operand.

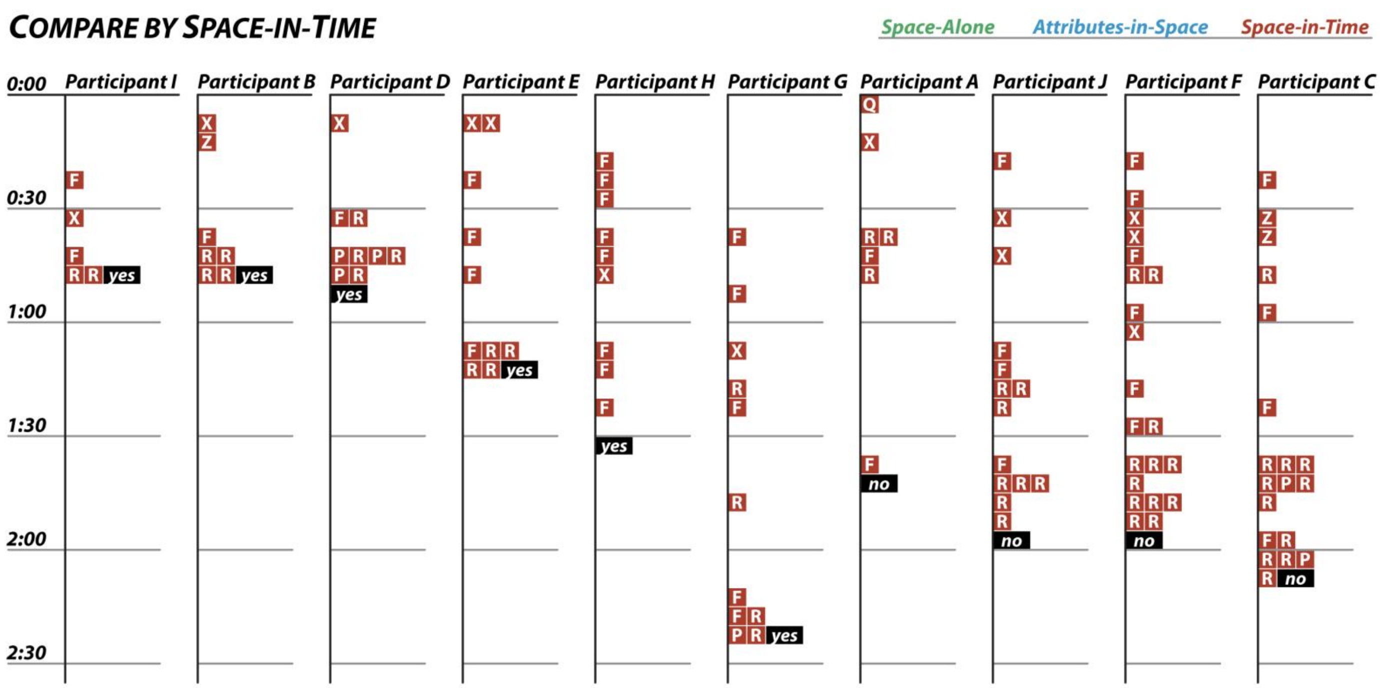


Figure 6.8: Interaction Logs for *Compare* by *Space-in-Time* (#6).

Following generation of the appropriate visual isomorph using the *reexpress* operator, participants then needed to apply the *filter* operator to limit the linear temporal extent and the *retrieve* operator to extract the frequency either in the temporal histogram or in the map view. As stated above, all participants interacted with the temporal histogram instead of the map view, the more efficient choice as participants would have had to add the frequencies of the hexagons using multiple applications of *retrieve* to *attributes-in-space*. The use of the *retrieve* operator between participants that answered the *compare* by *space-in-time* question (#6) correctly versus incorrectly demonstrates the difference between a targeted, informed use of *retrieve* and a anxious, unsure use of *retrieve* (i.e., the unsure-retriever persona; see Participants J, F, and C in particular).

#7. *Rank* by *Space-Alone*: What school in Harrisburg is closest to Interstate-83?

Performance on the *rank* by *space-alone* question (#7) overall was good, with 9 of 10 participants answering correctly and 7 of 10 participants answering within 45 seconds (**Figure 6.9**). Overall, the interaction strategies performed for the *rank* by *space-alone* question were very similar to the *compare* by *space-alone* question, again indicating the possibility of decomposing sophisticated objectives into a set of less sophisticated and more easily managed objectives. Successful participants first performed the *overlay* operator to display contextual information when subsequently applying the *zoom* operator. After applying the *overlay* operator, most participants zoomed to a specific area based on the overlaid context information, but then spent 5-10 seconds panning to neighboring areas to double-check their answer before responding. Participant A failed to apply the *overlay* operator at the start of the session, instead applying the *pan* and *retrieve* operators without context information; as a result, Participant A exhibited characteristics of the lost-browser persona for approximately one minute, as indicated by the continuous, but relatively slow application of *pan* and *zoom* operators. Interestingly, the lone incorrect response was caused by failure to zoom into a large enough cartographic scale; Participant H used the '+' button to *zoom* into the map, which only jumps one scale level, compared to the direct manipulation of a hexagon bin or map feature used by other participants, which jumps four scale levels. As a result, the overlaid context layer was occluded by the crime incident information in the area of interest, leading the participant to focus on a different area of the map. All participants completed their interaction strategy with a single *retrieve* operator, indicating a purposeful extraction of the map feature of interest.

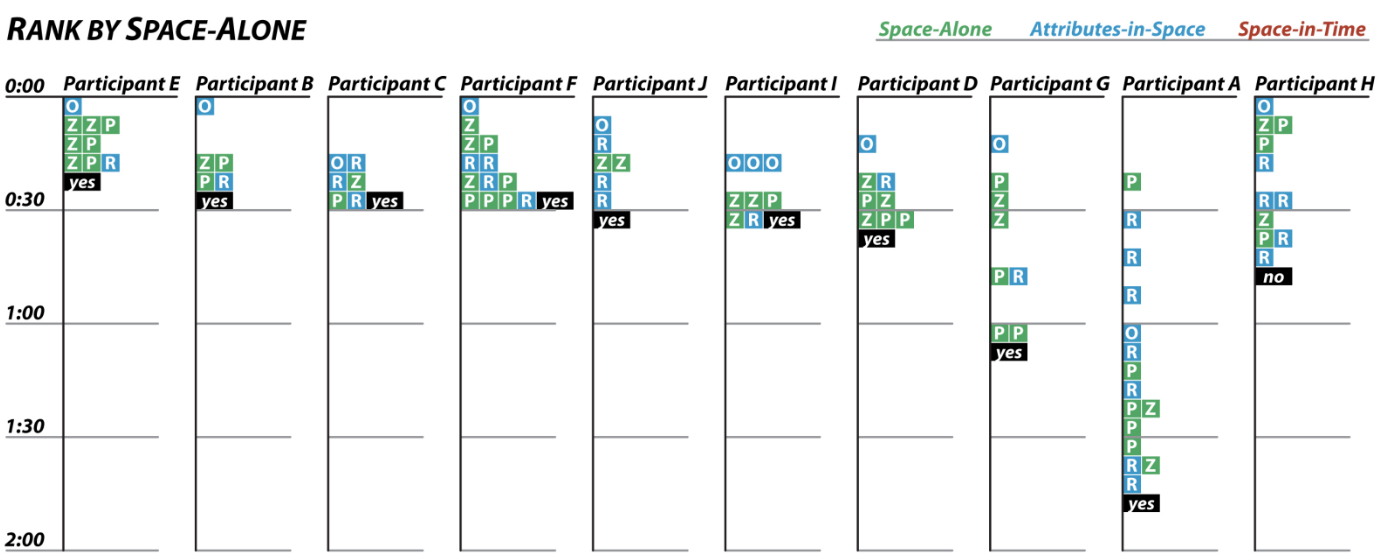


Figure 6.9: Interaction Logs for *Rank* by *Space-Alone* (#7).

#8. *Rank* by *Attributes-in-Space*: Which crime type (by UCR code) was the most common in District #1 on November 5th, 2010?

All 10 participants answered the *rank* by *attributes-in-space* question (#8) correctly, although the solutions were split between two competing strategies (**Figure 6.10**). A first subset of participants (Participant B, I, and G) relied on the *overlay* operator by *attributes-in-space* to determine the extent of each Police District, examining the crime incidents in comparison to this context layer, while a second subset of participants (Participants H, D, F, E, and C) relied on the *filter* operator by *space-alone* to isolate crime incidents only occurring within the Police District under investigation; Participant J applied both operators while Participant A succeed without applying either. Interestingly, and somewhat unexpectedly, the second strategy using the *filter* operator took approximately 60% longer compared to the first strategy using *overlay* (average of 0:54 seconds for Participants B, I, and G; average of 1:28 seconds for Participants H, D, F, E, and C). This difference in efficiency perhaps is explained by the fact that most participants followed either *overlay* or *filter* with a *zoom* in *space-alone* operator to inspect the details view of the crime incident dataset; participants first applying *overlay* only applied *zoom* once and did not apply *pan*, while the majority of the participants (although not all) that first applied *filter* were forced to apply *zoom* two or more times, as well as the *pan* operator. As discussed with regard to the *compare* by *space-alone* question (#4), the *overlay* operator provides the important context needed to apply the *zoom* operator appropriately. The application of the *filter* operator did not provide this context in this case, resulting in behavior indicative of the uninformed-zoomer persona and, ultimately, the lost-browser persona, as in the case of Participant C, the least efficient of the 10 participants.

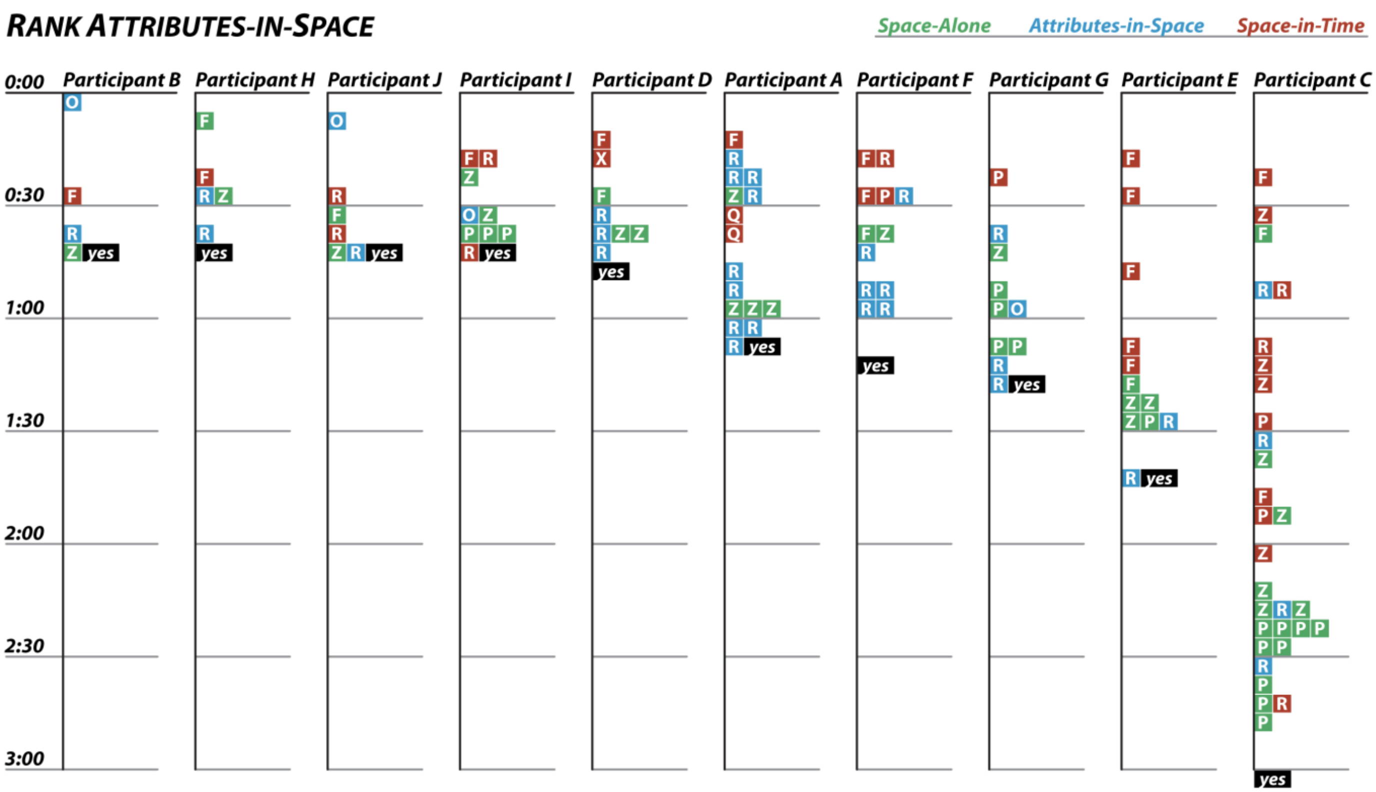


Figure 6.10: Interaction Logs for *Rank* by *Attributes-in-Space* (#8).

Interestingly, 9 of the 10 participants applied a temporal *filter* early in the interaction session, an unnecessary operator given that the date under consideration was viewable in the default histogram extent (i.e., November 5th was the fourth histogram bar in the default histogram, with November 2nd selected by default); only Participant G noticed that the *pan* by *space-in-time* (i.e., clicking on the associated histogram bar to advance the map to that date) could be applied more efficiently than a *filter* by *space-in-time*, although this did not lead to an overall improvement in speed for this participant given the time it took to apply the *overlay* operator. Across all questions, participants applied the *filter* operator rather than the *pan* operator when the latter could be used more efficiently, a behavior indicative of the excessive-filterer persona and also perhaps also related to the lack of a temporal *search* operator.

#9. *Rank* by *Space-in-Time*: From 2006 through 2010 (i.e., the complete time span), which month exhibited the highest frequency of crime incidents across Harrisburg?

Nine of the ten participants correctly responded to the *rank* by *space-in-time* question (#9; **Figure 6.11**), the highest accuracy rate exhibited across questions concerning the *space-time* operand. Successful interactions were contingent upon identification of the correct visual isomorph (here, a composite year by month) using the *reexpress* operator, as with the *compare* by *space-in-time* question (#6). Nine of the ten participants generated a composite year by month in either their first or second application of the *reexpress* operator; all six participants that applied the *reexpress* operator twice (Participants E, B, F, C, J, and D) first generated a composite month by day of the month, indicating the potential confusion between the overall composite being created (in this case, a year) and the binning unit within the composite (in this case, a month). Participant G also generated a composite month by day of the month with the first application of the *reexpress* operator, but did not appropriately apply the *reexpress* operator a second time to generate the correct visual isomorph, ultimately leading Participant G to provide an incorrect response; the rapid application of the *retrieve* and *pan* at the end of Participant G's session indicates behavior of the unsure-retriever persona, clearly caused by the generation of an unhelpful visual isomorph and the associated uncertainty in requesting the appropriate visual isomorph. It is important to note that 6 of the 10 participants first applied the *filter* operator to adjust the linear extent, despite the *reexpress* operator adjusting the extent by default when requesting a composite year by month; this behavior again is indicative of the filter-first attitude of the excessive-filterer persona.

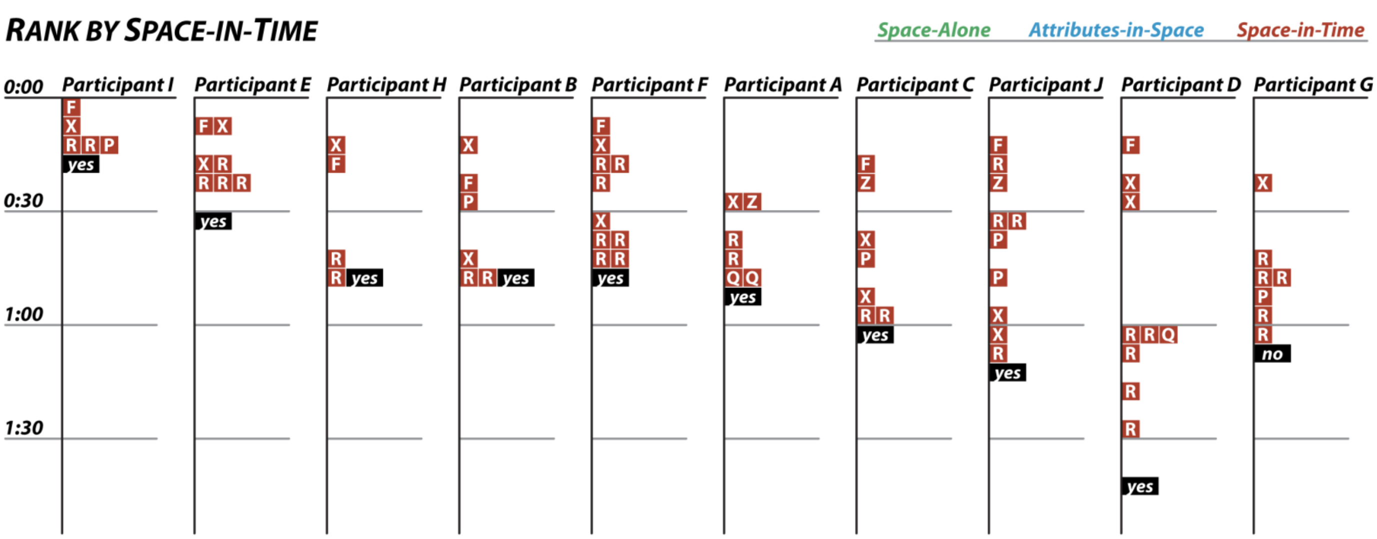


Figure 6.11: Interaction Logs for *Rank* by *Space-in-Time* (#9).

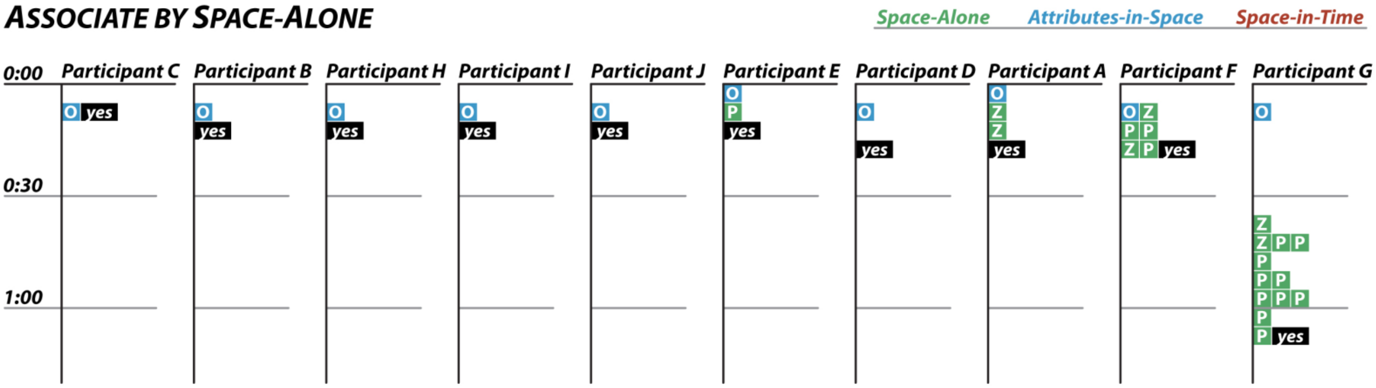


Figure 6.12: Interaction Logs for *Associate* by *Space-Alone* (#10).

#10. *Associate* by *Space-Alone*: Which route should Harrisburg citizens take to get to the west bank of the Susquehanna River during an evacuation related to Three Mile Island?

The *associate* by *space-alone* question (#10: Figure 6.12) proved to be among the easiest included in the protocol (tied for the shortest average response at 0:18; third in frequency and diversity of supporting interactions at 3.0 and 1.6 respectively). The reason for the relative ease in completing the question, despite the relatively sophisticated nature of the *associate* operator generally, is that the answer could be acquired from one of the included contextual layers without any additional cognitive effort. All participants immediately recognized this solution, applying the *overlay* operator within the first 10 seconds of the session, rather than trying to derive the information mentally. Six participants were able to ascertain the correct answer by applying the *overlay* operator alone, as they did not need to view the map road labels provided only at the larger cartographic scales, given their familiarity with the City of Harrisburg; a seventh participant (Participant E) applied the *pan* operator to recenter on the location of the answer, but also did not need to apply the *zoom* operator to read the labels. The other three participants (Participant A, F, and G) used the *zoom* operator to confirm their answer. Perhaps the clearest example of the lost-browser persona occurred when Participant G was applying *zoom* to confirm his or her response; this example of the lost-browser persona is particularly poignant given the overall ease in answering the question exhibited by other participants. The initial application of *zoom* was applied to the opposite side of the Susquehanna River as Harrisburg (near the City of Enola, on the west bank), zooming the map to an area with which the participant was less familiar. Participant G initially applied *pan* to move the map in the opposite direction of the desired location, only correcting himself or herself when centering upon a known landmark. Thus, it is possible to apply the *overlay* operator prior to *zoom*, but still subsequently apply the *zoom* operator in an uninformed manner.

#11. *Associate* by *Attributes-in-Space*: From 2006 through 2010 (i.e., the complete time span), is the geographic pattern of prostitution (16) related to the geographic pattern of sex offenses (17)?

The *associate* by *attributes-in-space* question (#11) was much more challenging than the *associate* by *space-alone* question (#10), although 8 of the 10 participants still responded correctly (Figure 6.13). The *filter* operator was essential for completion of the *associate* by *attributes-in-space* question (#11), with all participants applying the *filter* operator to both the *attributes-in-time* and *space-in-time* operands. Compared to the excessive uses of *filter* to complete the *identify*, *compare*, and even *rank* objectives, the application of *filter* is justified for the *associate* objective, as participants needed to view and evaluate the distributions of different subsets of crime incidents in order to characterize their relationship. *Filter* also is essential for the *associate* by *space-in-time* question (#12), and, especially, the three questions including a *delineate* objective (#13-15). Thus, it is possible that the *search* operator better supports the less sophisticated objectives (e.g., *identify*, *compare*, and possibly *rank*) while the *filter* operator better supports the more sophisticated objectives (e.g., *associate* and *delineate*). The *search* operator was not applied in support of any questions including the *rank*, *associate*, or *delineate* objectives. Successful participants also applied *reexpress* or *zoom* to increase the number of crime incidents included in each temporal bin, and thus displayed on the map at once.

A clear commonality between the two interaction strategies resulting in incorrect answers is the application of the *sequence* operator to animate the cartographic representation over time (Participant A and Participant D). Cartographic animation is particularly useful for understanding broad trends over time—an important component of the *associate* objective—but is less appropriate for communicating specific changes, as humans are known to be 'blind' to many of the changes in a dynamic visual scene (Simons and Levin, 1997, Goldsberry and Battersby, 2009). Application of the *sequence* operator for temporal cartographic animation had mixed results in the cartographic interaction study. Participant F applied it successfully, constructing and viewing two separate animations. However, Participant A and Participant D were unable to make sense of the constructed cartographic animation (i.e., the ***blind-sequencer*** persona), despite an emphasis in the 1-on-1 training on cartographic animation and its utility for spatiotemporal crime analysis. Participant A quickly abandoned the animation and instead began applying the *retrieve* operator to both the map and the histogram, behavior indicative of the unsure-retriever persona. In contrast, Participant D played through several different cartographic animations, spending almost 90 seconds interpreting the animations, and responded confidently, but incorrectly.

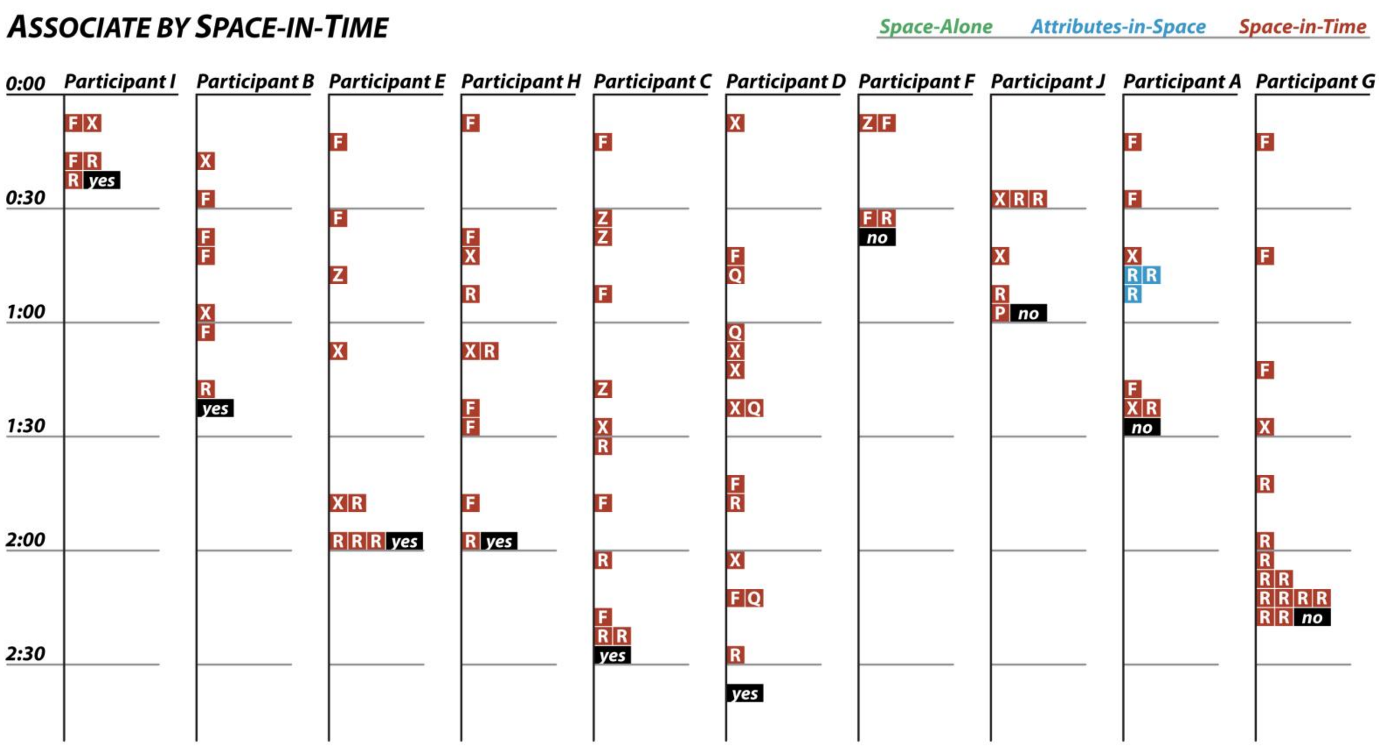


Figure 6.13: Interaction Logs for *Associate* by *Attributes-in-Space* (#11).

#12. *Associate* by *Space-in-Time*: From 2006 through 2010 (i.e., the complete time span), does the trend in crime increase or decrease across Harrisburg from noon (12:00) to midnight (24:00)?

The *associate* by *space-in-time* question (#12; **Figure 6.14**) was among the most challenging in the protocol, exhibiting the second lowest accuracy rate (only 60%; tied with the *compare* by *space-in-time* question, #6) and the second highest average response time (1:36). Like the *compare* by *space-in-time* (#6) and *rank* by *space-in-time* (#9) questions, successful interaction for the *associate* by *space-in-time* question (#12) was contingent upon selection of the appropriate visual isomorph (composite day by hour of the day). For the six participants that correctly answered the question, the sooner that the participant identified the appropriate visual isomorph, the sooner that he or she was able to respond. Three of the four participants that responded incorrectly exhibited behavior of the mistaken-reexpresser persona. Participants J and F incorrectly requested both composite year by month and composite month by day visual isomorphs. Participant G incorrectly requested a composite year by month visual isomorph and proceeded to exhibit unsure-retriever behavior when presented with the unexpected view. Even participants that answered the question correctly exhibited the mistaken-reexpresser persona to some degree, as only Participant I displayed the correct visual isomorph on the first application of the *reexpress* operator. It is important to note that of the six participants that correctly answered the question, only Participant D evoked the *sequence* operator to animate through the hour bins. While Participant D was able to interpret the animations correctly—and thus did not succumb to the pitfalls of the blind-sequencer persona—he or she required the longest amount of time to respond, both for participants that responded correctly and incorrectly.

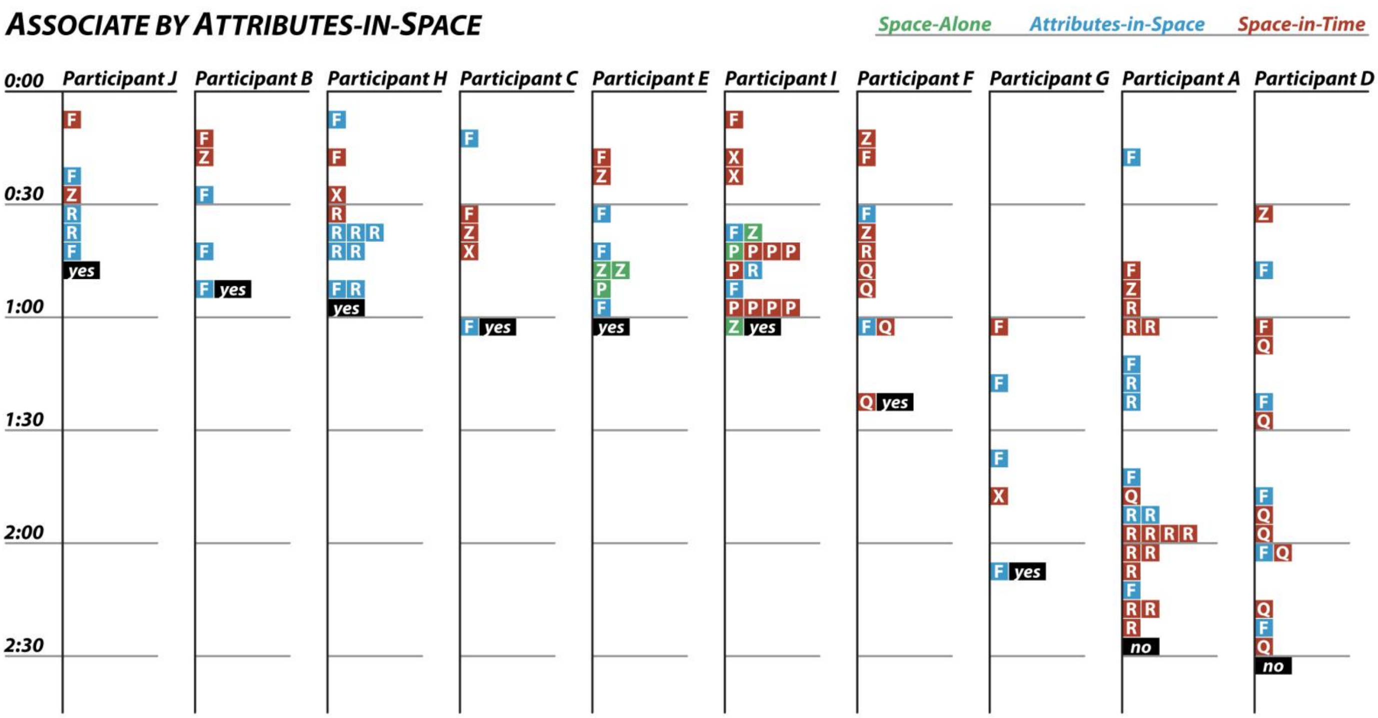


Figure 6.14: Interaction Logs for *Associate* by *Space-in-Time* (#12).

#13. *Delineate* by *Space-Alone*: Which police districts exhibit clusters of increased criminal activity from 2006 through 2010 (i.e., the complete time span)?

Participant performance on the *delineate* by *space-alone* question (#13) overall was good (accuracy of 90%), but the interaction strategies applied to answer the question exhibited a high amount of variation (**Figure 6.15**). As expected, most of the participants applied the *overlay* operator at some point in the session to plot the Police District contextual data layer; however, the most efficient participant (Participant A) did not do this, perhaps because he or she was able to recall the boundaries from experience without offloading this cognitive process onto the cartographic representation. Nine of the ten participants applied the *filter* operator by *space-in-time* at least once, usually early in the interaction strategy; such successful application of *filter* provides additional evidence that the *filter* operator increases in importance as the objective increases in sophistication. Interestingly, the three most efficient participants (Participant A, I, and G) applied the *reexpress* operator to generate a composite year by month; it is unclear why the *reexpress* operator provided such an advantage, as the question was not contingent upon selection of a visual isomorph different from the linear timeline. This finding also is counter to mistaken-reexpresser behavior exhibited in questions pairing the *compare*, *associate*, and *delineate* objectives with the *space-in-time* operand (questions #6, #12, and #15 respectively). It therefore is possible that misuse of the *reexpress* operator (i.e., the mistaken-reexpresser persona) is a larger concern when investigating the *space-time* operand compared to the *space-alone* or *attributes-in-space* operands.

The *sequence* operator appeared to be effective for answering the *delineate* by *space-alone* question (#13), as all four participants (Participants F, D, C, and H) evoking the operator did respond correctly. Interestingly, Participant B exhibited behavior analogous to the lost-browser persona (i.e., rapid application of the *pan* and *zoom* operators) during roughly the final minute of his or her interaction strategy, but applied the browsing operators to the *space-in-time* operand rather than the *space-alone* operand. The lone participant to answer incorrectly misinterpreted his or her application of the *zoom* by

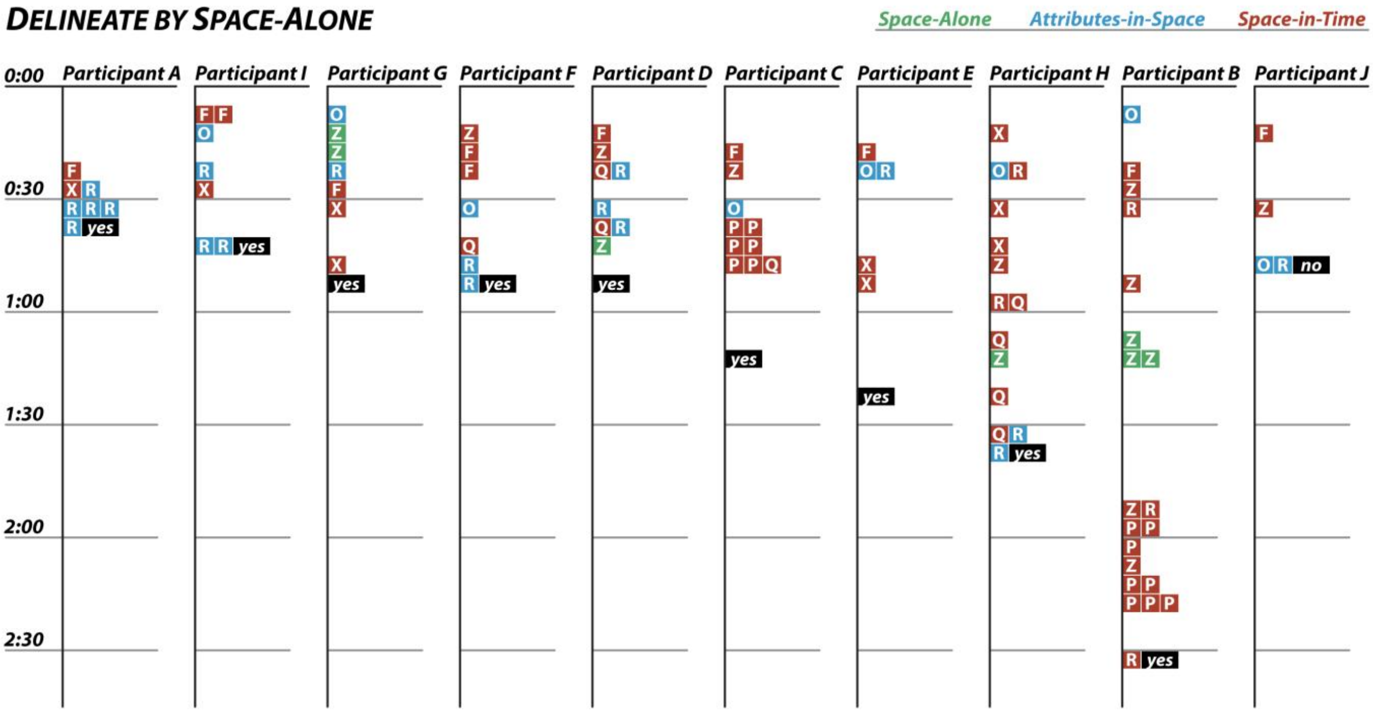


Figure 6.15: Interaction Logs for *Delineate* by *Space-Alone* (#13).

space-in-time, changing the binning unit to a single day and therefore answering the question with regard to one day of criminal activity instead of the complete five years of crime incident data; it is possible that the participant believed he or she requested a composite view (likely composite week by day of the week), rather than changing the binning unit only through the *zoom* by *space-in-time* operator.

#14. *Delineate* by *Attributes-in-Space*: From 2006 through 2010 (i.e., the complete time span), how many different ways (i.e., how many different MOs) was fraud (11) committed across Harrisburg?

The *delineate* by *attributes-in-space* question (#14; Figure 6.16) was by far the most challenging of the 15 questions included in the protocol, with only 3 of 10 participants answering the question correctly (30% accuracy rate, compared to an overall 82% accuracy rate). Participants required 2:13 to respond on average (the next closest question required 37 seconds less on average to answer), with 3 of the 10 participants requiring the complete three minutes (although one of these participants was able to answer correctly when prompted that time had expired); frequency and diversity scores also ranked among the highest in the 15 question set (1st and 3rd respectively). Despite this difficulty, the interaction strategies completed by the three participants that correctly answered the question are remarkably similar. Participants F, J, and B began by applying both the *filter* operator by *space-in-time* to limit the linear extent and the *zoom* operator by *space-in-time* to change the temporal binning unit from day to year. This trio of participants then proceeded to apply the *filter* operator to the *attributes-in-time* operand numerous times, effectively delineating a new category with each application of *filter*. Thus, the interaction strategies of the successful participants exemplify the utility of the *filter* operator for the more sophisticated objectives, especially *delineate*.

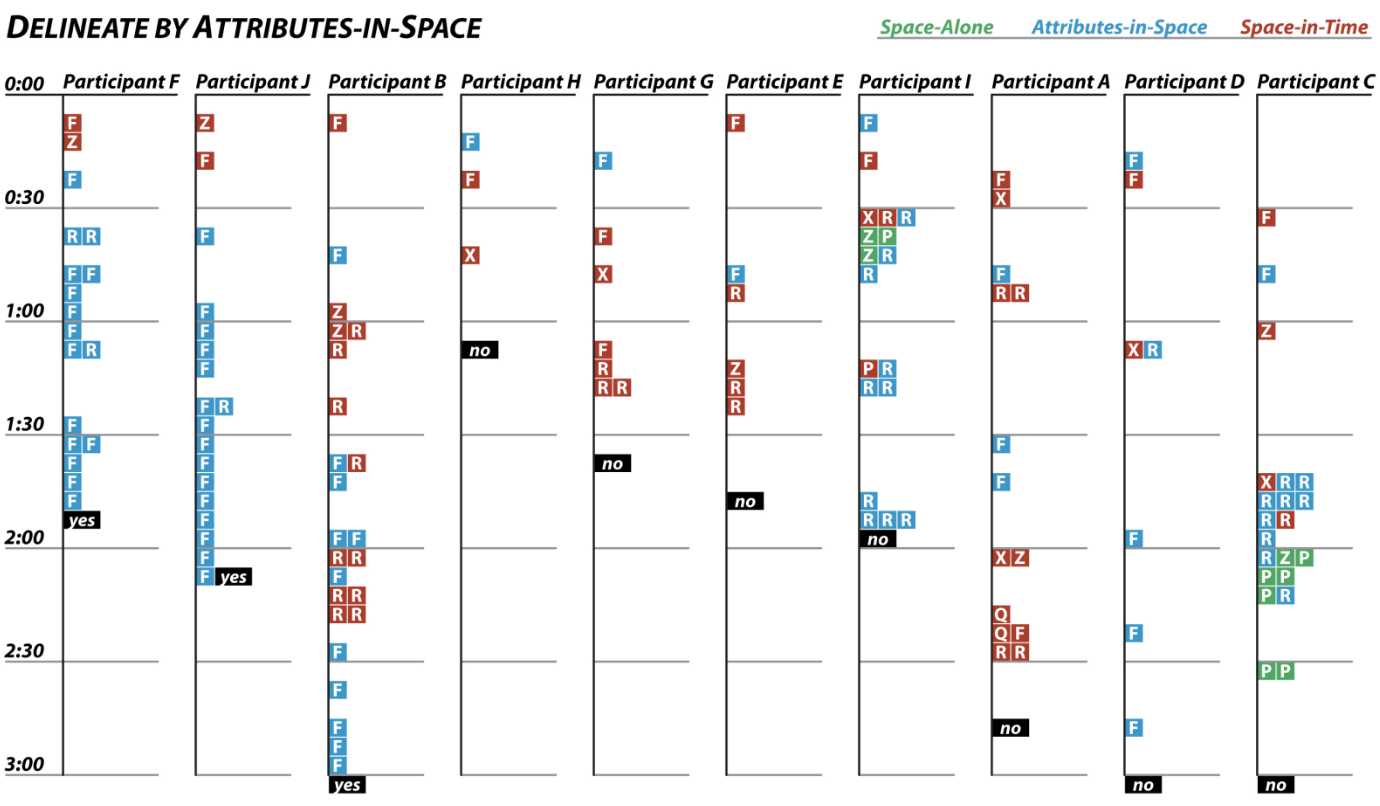


Figure 6.16: Interaction Logs for *Delineate* by *Attributes-in-Space* (#14).

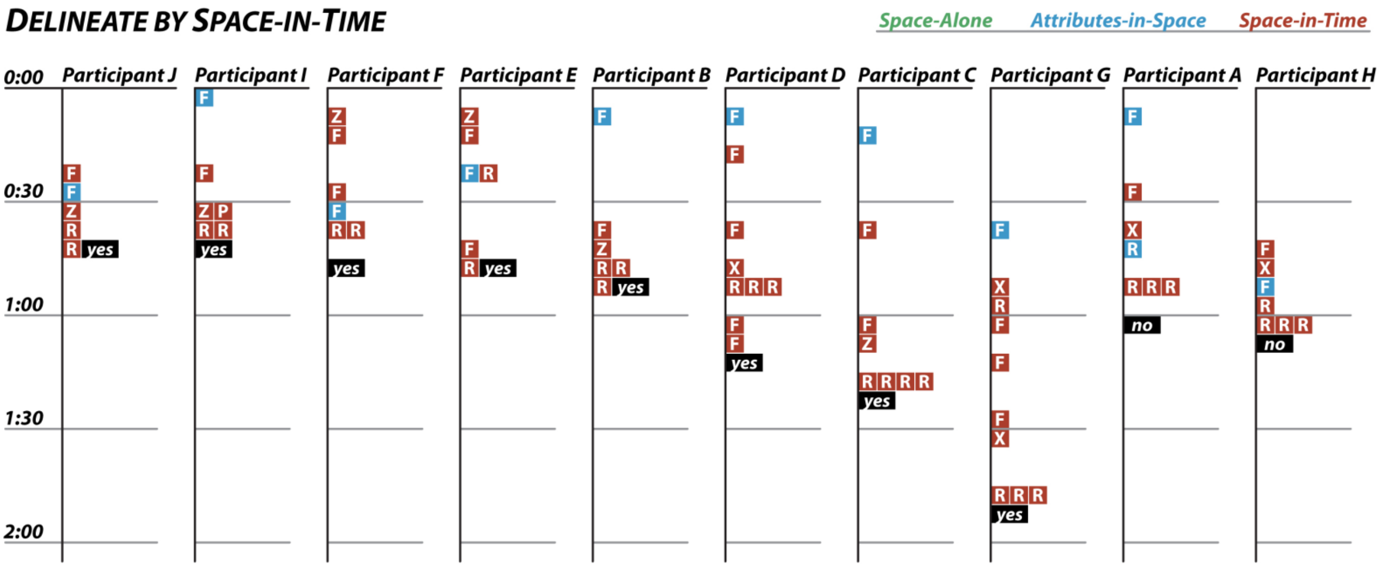


Figure 6.17: Interaction Logs for *Delineate* by *Space-in-Time* (#15).

#15. *Delineate* by *Space-in-Time*: The 2008 spike in robbery (03) incidents in Harrisburg spanned across which months?

Overall, performance was much better on the *delineate* by *space-in-time* question (#15; **Figure 6.17**) as compared to the *delineate* by *attributes-in-space* question (#14), with 8 of 10 participants responding correctly. As with the other questions including the *delineate* objective (#13 and #14) an emphasis was placed on the *filter* operator, applied by all 10 participants early in the interaction strategy to both the *attributes-in-time* and *space-in-time* operands. Interestingly, six of the eight participants that correctly answered the question also applied the *zoom* operator to the *space-in-time* operand at some point in the interaction strategy. All participants also applied a small set of *retrieve* operators to conclude the interaction strategy. Thus, most participants tightly followed Shneiderman's (1996) visual information seeking mantra to solve the *delineate* by *space-in-time* question (#15). The primary commonality between participants that incorrectly responded (Participant D and Participant C) is the application of the *reexpress* operator at some point during the second minute of the interaction strategy; as a result, neither participant was able to finish the question within the three minutes. Such behavior is consistent with the mistaken-reexpresser persona also observed in questions pairing the *compare* and *associate* objectives with the *space-in-time* operand (questions #6 and #12).

6.5 Conclusion: Towards a Syntactics of Cartographic Interaction Primitives

This chapter reported on an interaction study investigating the prototypically successful and unsuccessful cartographic interaction strategies performed when using the *GeoVISTA CrimeViz* cartographic interface, providing insight into the third goal of the dissertation (**Section 1.5.3**). The taxonomy of cartographic interaction primitives developed in **Chapter 5** was sufficiently comprehensive to describe all cartographic interactions possible in *GeoVISTA CrimeViz* and, equally as importantly, proved valuable for structuring the interaction strategies performed with the cartographic interface during the study. Several initial insights into a syntactics of cartographic interaction primitives were uncovered by analyzing logs of participant interactions, including the distinction between the *search* and *filter* operator according to the level of sophistication in the objective, the importance of the *overlay* operator for informed application of the *zoom* operator, and potential issues with applying the *reexpress* operator for tasks regarding the *space-in-time* operand. A set of personas also were developed to distinguishing unsuccessful interaction strategies from successful ones. However, it is unclear the degree to which these insights are specific to the *GeoVISTA CrimeViz* cartographic interface, leaving a broadly applicable syntactics of cartographic interaction primitives an ongoing goal requiring additional scientific research. As the reach of Cartography evolves with the changes to technology and practice, it will become ever more pressing to understand the *how?* question of the science and practice of cartographic interaction, formalizing a syntactics of cartographic interaction primitives and generating an associated list of recommendations for the design and development of cartographic interfaces. Additional details regarding the significance and outlook of the research reported in the dissertation are offered in **Chapter 7**, the concluding chapter of the dissertation.

Chapter Seven: Conclusion
Towards a Science of Cartographic Interaction

Overview:

The final chapter of the dissertation summarizes the insights on cartographic interaction generated by the dissertation and provides a research agenda with which to move forward. Contributions of the dissertation research are first summarized (**Section 7.1**), organized according to the three research goals presented in **Section 1.5**. An outlook for the science of cartographic interaction then is provided, organized around five topics identified through the dissertation research that require additional research (**Section 7.2**). After offering this research agenda, a comprehensive view on Cartography is presented, identifying science as but one way of knowing regarding cartographic representation and cartographic interaction (**Section 7.3**). The chapter concludes with a parting note from the author (**Section 7.4**).

7.1 Summary of Contributions

In the opening chapter, the breadth of Twenty-first Century Cartography is characterized across a pair of dimensions: (1) *mapmaking* versus *map use* and (2) *cartographic representation* versus *cartographic interaction* (**Figure 1.4**). While the former dimension traditionally has been included within the definition of Cartography (**Section 1.1**), the latter dimension reflects the recent impact of the Digital Revolution, and associated Information Age, on the field of Cartography (**Section 1.3**). Cartographic representation has and should continue to be a fundamental topic of scientific inquiry within Cartography; there is still much to learn about how maps should be designed and put to use. However, the pervasiveness and ubiquity of digital computing technologies has elevated the complementary topic of cartographic interaction to an equal level of importance; research is needed on both cartographic representation and cartographic interaction, as well as the synergy between the two. Yet, cartographic interaction is a topic that has received relatively little scientific attention within Cartography (see **Section 3.1** for a listing of several existing theoretical frameworks on cartographic interaction), despite its growing application and popularity in practice. Taking a growth perspective on Cartography (**Figure 1.3**), the dissertation research directly engages with this under-examined portion of Twenty-first Century Cartography, to the end of establishing a science of cartographic interaction. The theoretical developments and empirical findings of the dissertation regarding cartographic interaction are summarized in the following subsections, organized according to the contributions made to each of the three research goals outlined in **Section 1.5**. An outlook on this work then is provided in **Section 7.2**, focused around several key research items regarding cartographic interaction that require additional scientific attention. The dissertation closes with a comprehensive view on Cartography (**Section 7.3**)—in which science is but one epistemology for understanding cartographic representation and cartographic interaction—and a parting note to future scholars and practitioners who find their way to Cartography (**Section 7.4**).

7.1.1 Questions for a Science and Practice of Cartographic Interaction

As stated in **Section 2.1**, science begins with questions. It is the first research goal of the dissertation to identify and explore the questions that need to be addressed by a science of cartographic interaction and then to review the current state of understanding regarding these questions. The first set of contributions towards this research goal are primarily theoretical, leveraging extant research on interaction within Cartography and related disciplines to generate a pair of theoretical frameworks useful for structuring the investigation and understanding of cartographic interaction. The first, overarching framework comprises ***six fundamental questions*** germane to a science of cartographic interaction (**Table 2.1**): (1) ***what?***, (2) ***why?***, (3) ***when?***, (4) ***who?***, (5) ***where?***, and (6) ***how?*** This framework is broad enough to encapsulate the meaning of cartographic interaction (*what?*), its *raison d'être* (*why?*), an interface-based (*when?*), user-based (*who?*), and technology-based (*where?*) perspective on cartographic interaction, and the fundamental ***primitives*** that altogether constitute cartographic interaction strategies (*how?*). Existing research insights are summarized under each question, where possible, producing a snapshot of the current state of science regarding the five *W's* (**Chapter 2**) and the important *how?* question (**Chapter 3**).

The background review on the sixth *how?* question yielded a new way of conceptualizing and organizing existing taxonomies of cartographic interaction primitives. Each of the several dozen interaction primitive taxonomies reviewed in **Chapter 3** aligns with one of three stages included in Norman's (1988) ***stages of (inter)action model*** (**Figure 3.1**): (1) ***objectives*** (**Figure 3.2**), (2) ***operators*** (**Figure 3.3**), and (3) ***operands*** (**Figure 3.4**). The stages of (inter)action model itself is not a new contribution, but its association to the three components of cartographic interaction (i.e., placing the **Figure 2.1** definition of cartographic interaction through the center of the **Figure 3.1** stages of interaction model) provides a new way to organize extant research on interaction taxonomies and to reveal the otherwise unknown connections among these taxonomies. This second, more focused framework allows for direct comparison of taxonomies offered at the same stage of interaction and for identification of taxonomies that are not internally consistent or that span across multiple stages. Organization of interaction primitives according to stages of interaction proved fruitful when approaching the second and third research goals of the dissertation, which specifically address the *how?* question. Discussion regarding the limitations of applying Norman's stages of (inter)action model for conceptualizing cartographic interaction primitives is provided in **Section 7.2.3**.

The second set of contributions towards the first research goal were empirical. The aforementioned theoretical frameworks on cartographic interaction were leveraged in an interview study to compare the current states of cartographic interaction science and practice. Several of the insights generated showed congruency between science and practice, including: (1) the general definition of cartographic interaction, (2) the contemporary appropriateness of focusing solely on digital interactions, (3) the conceptualization of cartographic interaction as a continuum from high to low rather than a binary of interactive versus non-interactive, (4) the broad-based need for additional interactive links between visual and computation methods (i.e., ***visual analytics***), (5) a notion that higher levels of cartographic interaction should be provided as user expertise increases, and (6) the perception that the speed of the interaction is the most important system constraint (although no immediacy threshold must be met for the map to be 'interactive'). However, many of the insights revealed a significant disconnect between science and practice, including: (1) the application of cartographic interaction primarily in support of ***analysis*** and ***presentation*** rather than ***exploration***, (2) an overall desire for a larger number of interactions with increased freedom (in contrast to the ***productivity paradox*** discussed in science), (3) an emphasis on user ***expertise*** over user ***ability*** and user ***motivation***, (4) the relatively uncommon nature of a user-centered approach to design and development of a cartographic interface, and (5) an overall technological concern regarding bandwidth connectivity and security rather than processing power. The cartographic interaction interviews also identified several topics that are not even considered in contemporary scientific work, and therefore cannot draw comparison to practice, including: (1) the importance of live information to the quality of interaction, (2) a request for developers to experiment with their cartographic interface designs instead of relying on convention (i.e., avoiding the ***lorem ipsum map***), and (3) the impact of institutional- and individual-level barriers to acquiring and using cartographic interaction. Finally, the cartographic interaction interview study demonstrated several variations across practice, including (1) the overall disagreement among participants on what constitutes an 'interactive map' and (2) the disagreement over the relative importance of expertise acquired through education versus experience. Individual insights regarding the practice of cartographic interaction are reported in **Chapter 4**.

7.1.2 A Taxonomy of Cartographic Interaction Primitives

As stated in **Section 3.1**, theory is essential to science. The second research goal of the dissertation is to contribute to one of the key gaps in our theoretical understanding of cartographic interaction identified from the reviews of cartographic interaction science and practice. In particular, the second research goal is to address the important *how?* question by developing a taxonomy of cartographic interaction primitives that is empirically derived. Such a taxonomical framework is useful for at least three reasons. First, such a taxonomy provides a common lexicon for describing competing interaction designs and interface strategies that is needed to support classroom and workshop education on cartographic interaction as well as collaboration across teams of designers and developers engineering cartographic interfaces. Second, the taxonomy informs the design and analysis of scientific experiments, allowing for a systematic approach to investigating cartographic interaction both in terms of scoping individual, controlled experiments and aggregating research insights from these experiments into a single corpus. Finally, the taxonomy informs the design and evaluation of interfaces providing cartographic interaction, with the ultimate goal of generating a syntactics of cartographic interaction primitives to prescribe such designs and use strategies (**Section 7.2.2**).

The contribution made towards the second research goal represents a substantial step towards this grand challenge, although, as indicated in **Section 7.2.1**, additional research is needed. A pair of card sorting studies were administered to sort a universe of statements, drawn from the reviews on cartographic science and practice, that represent either the objective or operator stage of interaction (**Chapter 5**). The resulting taxonomy of cartographic interaction primitives includes four dimensions, each aligning with a different stage of interaction (**Figure 5.3**): (1) ***goals***, (2) ***operands***, (3) ***objectives***, and (4) ***operators***. Each dimension is summarized in the following, as the taxonomy of interaction primitives is among the most important contributions of the dissertation research.

Although the first card sorting study was specific to objectives, there were several competing criteria on which many participants subdivided their set of objective categories, leading to a large degree of variability across participant sorts. The first competing criterion aligns with the *goals* stage of interaction, resulting in a three-part taxonomy of user goals that increase in complexity in the following order: (1) ***procure*** (cartographic interactions that are performed in order to retrieve information about the represented geographic phenomena), (2) ***predict*** (cartographic interactions that are performed in order to assist the user in forecasting what may occur in the future based on current conditions of the represented geographic phenomena), and (3) ***prescribe*** (cartographic interactions that are performed in support of deciding what should occur in the future based on current conditions of the represented geographic phenomena); the majority of cards (~150 of 176) included in the operator card sorting study represented the *procure* goal. This set of focused user goals—which emphasize the desired outcome of the cartographic interaction—represents a supplement or potential replacement to the set of broader user goals included in the swoopy diagram—which emphasize the current stage of science (**Section 2.3**).

The second competing criterion applied by many of the participants aligns with the *operand* stage of interaction. Three operand primitives were identified from the first card sorting study, modifying Peuquet's ***TRIAD*** (1994) framework and Andrienko et al.'s (2003) ***search target*** dimension to focus on interactions that are explicitly cartographic: (1) ***space-alone*** (cartographic interactions in which the user interacts only with the geographic component of the cartographic representation), (2) ***attributes-in-space*** (cartographic interactions in which the user interacts with the attribute component of the cartographic representation to understand how one or several characteristics of a geographic phenomenon vary in space), and (3) ***space-in-time*** (cartographic interactions in which the user interacts with the temporal component of the cartographic representation to understand how a dynamic geographic phenomenon acts in time).

Unique primitives at the *objective* stage of interaction were revealed once controlling for the goal and operand dimensions. The objective dimension includes a set of five primitives that increase in sophistication in the following order: (1) ***identify*** (cartographic interactions that are performed to examine and understand a single map feature), (2) ***compare*** (cartographic interactions that are performed to determine the similarities and differences between two or more map features), (3) ***rank*** (cartographic interactions that are performed to determine the order or relative position of two or more map features), (4) ***associate*** (cartographic interactions that are performed to determine the relationship between two map features or among three or more map features), and (5) ***delineate*** (cartographic interactions that are performed to organize map features into a logical structure). Several participants applied a third competing sorting criterion that closely follows the Andrienko et al. (2003) ***search level*** dimension, although this competing criterion only was applied within the *identify* objective.

The second card sorting study successfully generated a taxonomy of primitives at the *operator* stage of interaction, with participant sorting strategies exhibiting a large amount of similarity overall. Operator primitives were discriminated further according to ***enabling interactions*** versus ***work interactions*** (**Section 2.4**). Five primitives were separated as enabling interactions: (1) ***import*** (enabling cartographic interactions that load an existing dataset or previously generated cartographic representation into the cartographic interface), (2) ***export*** (enabling cartographic interactions that extract part or all of a generated cartographic representation, the geographic information underlying the representation, or the status of the system for future use outside of the cartographic interface), (3) ***save*** (enabling cartographic interactions that store the generated cartographic representation, the geographic information underlying the representation, or the status of the system for future use within the cartographic interface), (4) ***edit*** (enabling cartographic interactions that manipulate the geographic information underlying the representation, which then alters all subsequent cartographic representations of that information), and (5) ***annotate*** (enabling cartographic interactions that add graphic markings and textual notes to the cartographic representation to externalize insight generated from work interactions). Approximately 50 of 206 cards included in the operator card sorting study represented enabling interactions.

Finally, twelve core work operator primitives were identified once accounting for enabling interactions: (1) ***reexpress*** (interactions that set or change the visual isomorph used in the cartographic representation or information views linked to the cartographic representation), (2) ***arrange*** (cartographic interactions that manipulate the layout of a visual isomorph when multiple, typically linked visually isomorphic views are provided), (3) ***sequence*** (cartographic interactions that generate an ordered set of related cartographic representations), (4) ***resymbolize*** (cartographic interactions that set or change the design parameters of a cartographic representation form without changing the represented map features or the cartographic representation form itself), (5) ***overlay*** (cartographic interactions that adjust the features types included in the cartographic representation), (6) ***reproject*** (cartographic interactions that set or change the cartographic projection used to transform the three-dimensional geographic information to a two-dimensional screen), (7) ***pan*** (cartographic interactions that change the geographic center of the cartographic representation), (8) ***zoom*** (cartographic interactions that change the scale and/or resolution of the cartographic representation), (9) ***filter*** (cartographic interactions that alter the cartographic representation, and information views linked to the cartographic representation, to indicate map elements that meet one or a set of user-defined conditions), (10) ***search*** (cartographic interactions that alter the cartographic representation, and information views linked to the cartographic representation, to indicate a particular location or map feature of interest), (11) ***retrieve*** (cartographic interactions that request specific details about a map feature or map features of interest), and (12) ***calculate*** (cartographic interactions that derive new information about a map feature or map features of interest). For each primitive included in the final taxonomy (regardless of dimension), connections are made to the existing interaction taxonomies reviewed in **Chapter 3** where possible.

7.1.3 Prototypically Successful and Unsuccessful Cartographic Interaction Strategies

As stated in **Section 6.1**, the ultimate promise of a taxonomy of cartographic interaction primitives, and the associated *how?* question of a science of cartographic interaction, is the generation of design and use guidelines for cartographic interaction, or a ***syntactics*** of interaction primitives. It is the understanding of the primitives' relationship to one another, and to the broader mapping context, that operationalizes the taxonomy for practical application to cartographic interface design. However, because formulation of a syntactics of cartographic interaction primitives is a research goal that is necessarily ongoing (see **Section 7.2.2** for details), the third and final goal of the dissertation is to initialize this research effort by identifying prototypically successful and unsuccessful cartographic interaction strategies with a single cartographic interface. To this end, a cartographic interaction study was administered with the user group of a cartographic interface called *GeoVISTA CrimeViz* (**Chapter 6**). The aforementioned taxonomy of cartographic interaction primitives explicitly informed the experimental design of the cartographic interaction study, illustrating the utility of such theoretical frameworks for both the interview protocol (i.e., the set of questions included in the protocol) and subsequent qualitative data analysis (i.e., the set of codes used to compartmentalize the interaction logs).

The cartographic interaction study yielded several key insights into the taxonomy of cartographic interaction primitives that inform future work into its syntactics. First, a general increase in question difficulty was observed across the objective primitives according to the ordering of *identify-compare-rank-associate-delineate*, confirming that the objectives do increase in their sophistication in the order proposed in **Chapter 5**. Second, participants most easily responded to questions regarding the *space-alone* operand; overall difficulty of questions regarding the *attributes-in-space* and *space-in-time* operands were similar, with participants requiring slightly more time to respond to questions including the *attribute-in-space* operand and slightly more frequent and diverse interactions to respond to questions including the *space-in-time* operand. The *retrieve*, *filter*, and *zoom* operators were the most frequently and extensively applied in support of the tested questions, suggesting participants generally followed Shneiderman's (1996) ***visual information seeking mantra*** without being directed formally to do so. Fourth, the utility of the *search* and *filter* operators was split according to the level of sophistication of the objective, with *search* more useful for the *identify*, *compare*, and *rank* objectives and *filter* more useful for *associate* and *delineate* objectives. Finally, it is important to note that participants overall performed better than expected on the tasks included in the cartographic interaction study, perhaps reflecting the increased levels of user motivation generated by the MILC approach to design and development of *GeoVISTA CrimeViz* (see **Section 7.2.5** for additional discussion).

Several of the insights generated from the cartographic interaction study allowed for development of user ***personas***, or chronic user issues in applying the operator primitives that occurred frequently across participants and across tasks. Personas included: (1) the ***excessive-filterer*** (an interaction behavior in which the *filter* operator is unnecessarily applied as part of a routine, negatively impacting productivity), (2) the ***unsure-retriever*** (an interaction behavior in which the *retrieve* operator is applied unsuccessfully in rapid succession), (3) the ***uninformed-zoomer*** (an interaction behavior in which the *zoom* operator is applied without the proper context provided by the *overlay* operator), (4) the ***lost-browser*** (an interaction behavior in which the *zoom* and *pan* operators are applied unsuccessfully in rapid succession), (5) the ***mistaken-reexpresser*** **(**an interaction behavior in which the *reexpress* operator is applied to generate an inappropriate visual isomorph), and (6) the ***blind-sequencer*** (an interaction behavior in which application of the *sequence* operator results in user confusion). Construction of personas proved a useful approach for describing key bottlenecks according to operator primitives and may be a fruitful way forward for linking science to practice (see **Section 7.2.5** for additional details).

7.2 Outlook: A Research Agenda for the Science of Cartographic Interaction

The contributions of the dissertation research summarized in **Section 7.1** represent a substantial step towards a science of cartographic interaction. However, many more questions were identified through this initial effort that deserve additional attention. Much like Arthur Robinson (1952: vii) before me, I "hope that the half-told story will excite the curiosity of others to investigate further"; there is still much work to be done. The research reported in the dissertation reveals at least five major topics that have only incomplete answers, or perhaps still remain at the initial question stage. Each of these topics is considered in the following subsections, forming a research agenda for a science of cartographic interaction with which to move forward.

7.2.1 An Evolving Taxonomy of Cartographic Interaction Primitives

The first ongoing research goal remains formalization of a taxonomy of cartographic interaction primitives, or an underlying theoretical framework needed to answer the important *how?* question of a science of cartographic interaction. The taxonomy presented in **Chapter 5** represents an important, empirically derived contribution towards this broad research goal, although the taxonomy developed is not without limitations. The objective card sort used to derive the taxonomy exhibited a large amount of variation due to the presence of three competing criteria. Future research should be completed to treat each of these stages of interaction separately, both with the set of cards generated through the dissertation research and with additional sets of cards elicited through other techniques. Further, both the objective and operand sort would benefit from a follow-up closed sorting study, emphasizing the evaluation rather than the generation of the interaction primitive categories (**Figure 5.1**). It also is important to note that the taxonomy, as currently presented, assumes classical or Aristotelian categories of primitives with clean demarcations among primitives. The nature of the interaction primitives instead may be better captured by radial categories, with shades of gray within each primitive and degrees of overlap among the primitives (Lakoff, 1987). Follow-up studies using the paired or triad comparison methods (see **Section 5.2.1**), or even semantic differential (Harrower et al., 1997), may provide insight into the central prototype and peripheral members for each interaction primitive. Each of the described future research avenues would allow for refinement and extension to the four-dimensional taxonomy of cartographic interaction primitives presented in the dissertation.

Even with these research extensions, it arguably is important for the taxonomy to remain malleable to encapsulate both emergent technologies and broad shifts in cartographic interaction use. The best way to support such evaluation is through continual consultation with cartographic interaction practice. Further, this ongoing, critical examination must include additional user groups and application domains; while the cartographic interaction interviews reported in **Chapter 4** did span seven unique application domains, no one domain was represented well enough to capture reliable, domain-specific insights regarding the subsequent taxonomy. Such checkpoints need not be at the scale of research described in the dissertation, but instead may be smaller evaluations included in a user-centered approach to design and development of a single cartographic interface for use in a single application domain. Such smaller, domain-specific sets of insights afford iterative refinement to the taxonomy, allowing for it to remain current in the face of changing technology constraints on and general user demand of cartographic interactions; the opportunity to establish a synergy between science and practice is discussed further in **Section 7.2.5**.

7.2.2 Towards a Syntactics of Cartographic Interaction Primitives

The second topic on cartographic interaction requiring future research attention directly relates to the final goal of the dissertation: establishing a syntactics of cartographic iteration primitives. It is such a syntactics of interaction primitives, not just the taxonomy characterizing interaction primitives, that truly should be considered the "grand challenge of interaction" (Thomas et al., 2005: 76). The cartographic interaction study did generate several key insights into the syntactics of interaction primitives, as summarized in

Section 7.1.3. Yet, the promise of a syntactics of cartographic interaction primitives remains unrealized, and it is likely that such a promise will prove difficult to fulfill, particularly in comparison to the syntactics of visual variables so commonly evoked in support of cartographic representation. The visual variable framework is one constructed primarily for the human perceptual ability of vision; other sets of variables developed for cartographic representation—such as the dynamic variables (DiBiase et al., 1992), the sonic variables (Krygier, 1994), and the tactile variables (Griffin, 2002)—also rely primarily upon human perceptual abilities. Thus, the visual variables and related taxonomies for cartographic interaction lend themselves well to controlled perceptual experimentation, which in turn reduces the difficulty in empirically confirming their syntactics.

In contrast, empirical examination of cartographic interaction and its primitives is more complicated, as the successful application of cartographic interaction primitives requires a mixture of human perception, cognition, and motor skills, as discussed in **Section 2.5**. Variation across each dimension may act to dampen the signal collected from a cartographic interaction study, masking the true nature of each interaction primitive and their relations to one another. Further, the inclusion of cognition also necessitates control for and examination across additional user characteristics, such as user expertise and user motivation. The stages of interaction model once again may serve as a useful framework for structuring research, as the execution sequence (**Figure 3.1: left**) largely is discriminated according to cognition (#2: Forming the Intention), perception (#3: Specifying an Action), and motor skills (#4: Executing the Action). A viable future research agenda therefore may include examination at only one stage of interaction at a time (e.g., investigation of goals, objectives, operators, or operands only), with control across other dimensions such that only one primitive from the other stages are included in the experimental design. For instance, it may be appropriate to examine only the *filter* operator in a cartographic interaction study, but to see how its use varies across the five objectives, or, to examine only the *delineate* objective, but to see how its accomplishment varies according to different sequences of operators; it also is likely that different sets of operators are more or less appropriate for different user goals (e.g., *exploration*, *analysis*, *synthesis*, or *presentation*; *procure*, *predict*, or *prescribe*). These insights—which control for variation across perception, cognition, and motor skills—then can be collated and summarized to meet the broad goal of a syntactics of cartographic interaction primitives.

7.2.3 Syntactics and the Cartographic Interaction Context

The taxonomy of cartographic interaction primitives and their associated syntactics, once realized, present a very neat theoretical framework for conceptualizing cartographic interaction. Throughout the dissertation, the empirical generation of such theoretical frameworks is stressed as a key unmet need for the science of cartographic interaction; in fact, the general absence of such theory regarding cartographic interaction is the underlying motivation for the work reported in the dissertation. Yet, it is important to remember that such theoretical frameworks remain simplifications of the phenomenon that they model; they are abstractions, and, just like maps, by definition miss the nuance exhibited in reality. Of particular concern is the stages of interaction model, on which much of the research in the dissertation regarding the *how?* question is organized. Ostensibly, the stages of interaction model is a closed system of discrete benchmarks that must be accomplished in order to complete a single interaction exchange. Such an abstracted workflow lends itself to the same criticisms of the ***communication model***, which dominated the science of cartographic representation in the 20th century (Board, 1967, Koláčný, 1969). As reviewed in **Section 1.1**, such closed models assume an optimal map use and optimal map user without considering the situated circumstances and kinds of knowledge that ultimately contextualize the cartographic interaction. The definition offered in **Section 2.1** presenting cartographic interaction as a dialogue between user and map mediated by a computing device further reinforces this association between the stages of interaction model and the communication model.

It therefore is important to consider the context of the cartographic interaction in subsequent research, as such context is likely to impact the design and use of cartographic interaction significantly. Examination of user characteristics (i.e., a ***user-based perspective***; **Figure 2.1: left**), such as expertise and motivation, is a first consideration given the influence of cognition on the cartographic interaction. To this end, additional research is needed to understand if and how the syntactics of cartographic interaction primitives varies according to characteristics such as experience, education, familiarity, interest, and need (see **Section 2.5**). However, it is important to avoid privileging the user and to consider variations in the cartographic interface as well (i.e., an ***interface-based perspective***; **Figure 2.1: right**); it is not just that the user manipulates the interactive map in support of his or her goal, but it also is true that the resulting change to the map manipulates the user, in terms of modifying or realigning mental schema held by the user regarding the portrayed geographic phenomenon. Therefore, future research is needed to understand if and how the syntactics of cartographic interaction primitives varies according to broader issues of work productivity, interface complexity, and interface constraint (see **Section 2.4**). Finally, the computing device through which the cartographic interaction is mediated must be considered during experimental design (i.e., a ***technology-based perspective***: **Figure 2.1: middle**); technological constraints such as input capabilities, bandwidth, processing power, and display capabilities all may impact the cartographic interaction strategies performed by participants during scientific research on cartographic interaction (see **Section 2.6**). Thus, any work towards a syntactics of cartographic interaction primitives must also control for or directly consider variation across the five *W's* presented in **Chapter 2**.

7.2.4 Integrating Cartographic Representation and Cartographic Interaction

The dissertation research thus far treats cartographic interaction as an area of inquiry isolated from cartographic representation, essentially placing a hard dividing line between the top and bottom halves of the **Figure 1.4** characterization of Twenty-first Century Cartography. Such a perspective holds the practical advantage of carving out a tractable problem for investigation by the dissertation research, but does not hold true when considering the actual practice of mapmaking and map use. Instead, there is likely to be a large synergy between cartographic representation and cartographic interaction, with the cartographic representations presented influencing the cartographic interactions applied to manipulate those representations, and therefore the syntactics of cartographic interaction primitives. To reiterate a conclusion offered in **Section 2.4** in response to Keehner et al. (2008), while it definitely matters what you see (i.e., the cartographic representation), you may not know what you need to see until you begin to interact (i.e., the cartographic interaction); the ***visual thinking*** experience relies on both the representations and the interactions. Therefore, a fourth topic requiring future scientific research is the integration of research on cartographic interaction with research on cartographic representation.

A particularly promising line of research includes reevaluation of time-tested principles or conventions regarding cartographic representation when cartographic interaction is provided. For instance, issues fundamental to the design of choropleth maps, such as classification and color schemes, may be less important when such maps are interactive, as the map user can impose the solution that best fits his or her problem context through the supported cartographic interactions (i.e., the *resymbolize* operator). It may be less important to class the choropleth map altogether with provision of cartographic interaction, as limitations of an unclassed choropleth map can be overcome with the *filter* and *retrieve* operators. It is important to note that empirical research may reveal that the opposite is true for choropleth classification and color schemes, as it may be that users are unable to apply one or several of these operators successfully for the choropleth representation and therefore consistently generate uninformative or misleading representations. Further, it may be that certain cartographic interaction operators are inappropriate for certain cartographic representation forms. For instance, should a user be allowed to *reproject* a choropleth map, changing the cartographic representation from an equivalent projection to one that distorts areas (and therefore may mislead the user about the mapped pattern)? The same holds true for other types of thematic maps, such as proportional symbol maps (do we let users interactively resize the proportional symbols?), dot density maps (should users be able to apply the *retrieve* operator onto dots representing an aggregate of the represented geographic phenomenon?), isoline maps (should the user be allowed to *overlay* multiple sets of isolines?), flow maps (does the affordance of interaction finally allow such maps to be scaled to hundreds or thousands of map features), and cartograms (should a user always be allowed to *reexpress* a cartogram as a choropleth map?). It is easy to envision a textbook on Cartography some ten years from now that sequences through chapters according to map type, as is traditional, but provides an equal amount of background on both representation and interaction design considerations for the given cartographic interaction form.

7.2.5 Integrating Science and Practice

The final topic on cartographic interaction requiring additional attention is perhaps the most important one: integrating the science of cartographic interaction with its practice. The dynamic nature of the application domains and computing technologies underpinning the design and use of maps presents a challenge to both scholars and practitioners within Cartography. Accordingly, scholars and practitioners together are thrust into the role of the eternal learners, sharing the burden of constant filtering and translation of nascent developments in related (and perhaps unrelated) fields in order to affect positive change within Cartography, all while maintaining a clear and progressive agenda for Cartography itself. Therefore, better connections need to be fostered between science and practice in order to support Cartography as a whole. For practitioners, this partnership starts with the release of open code libraries, and associated documentation or tutorials that solve challenging technical issues that otherwise may overwhelm research resources; this also includes the unabated communication of the most pressing questions requiring research attention. That Cartography has important artistic and ethical components (see **Section 7.3**) is further reason why severing science from practice only results in hindering both.

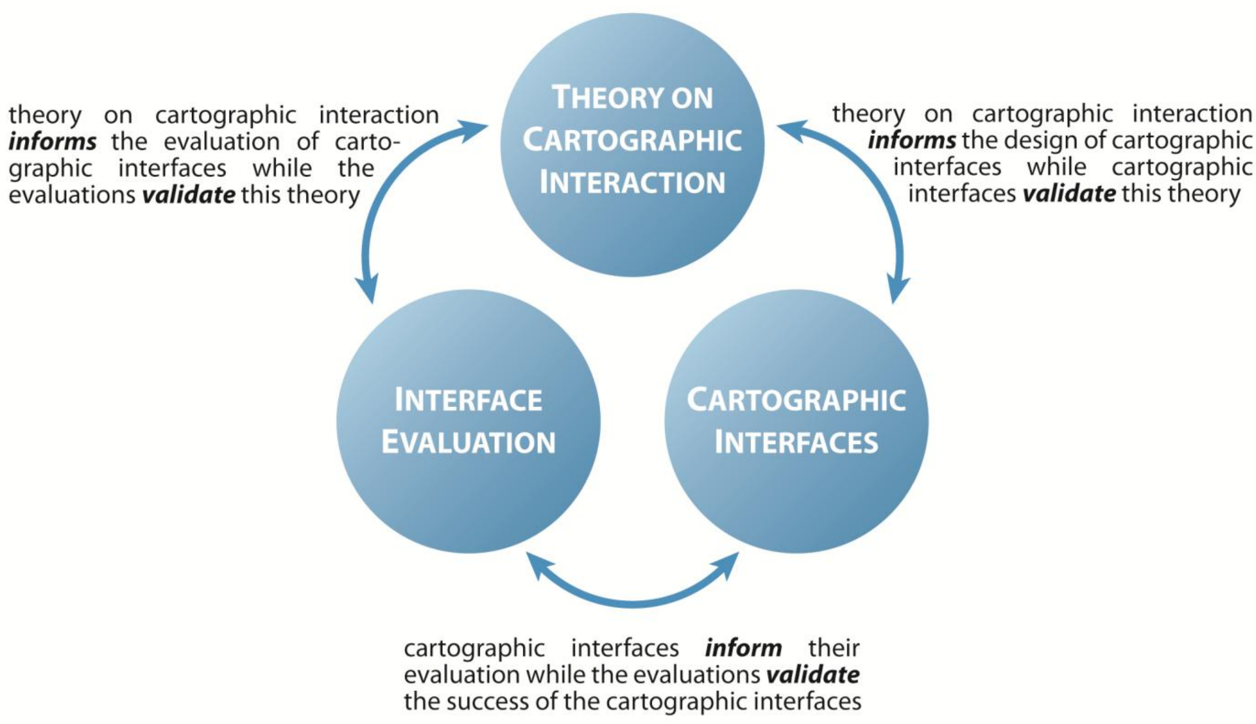


Figure 7.1: The Integration of Basic and Applied Research on Cartographic Interaction. There is a great synergy between basic and applied research for the science of cartographic interaction, as insights generated through the design and evaluation of cartographic interfaces are needed to validate theoretical frameworks and empirical findings on cartographic interaction (redrawn from Roth and Harrower, 2008: 49).

For scientists, this partnership starts with the inclusion of both basic and applied research goals in any scientific project. Integration of basic and applied research is not an unfortunate compromise forced by the unprecedented dynamism of Cartography as a result of the Digital Revolution and associated Information Age. In other words, applied cartographic science is not a Faustian bargain made to keep its academic stature afloat, but rather an opportunity afforded by the artisan roots of the craft. In many ways, basic and applied cartographic research are synergistic, each amplifying and complementing the other, both for cartographic representation and for cartographic interaction. Specific to the science of cartographic interaction, Roth and Harrower (2008: 49) described this synergistic relationship as the "Three-part validation system of theory, applications, and evaluation for Interactive and Web-based Cartography." Theory remains the primary goal of a science of cartographic interaction (**Figure 7.1: top**), with basic science forming the backbone of the cartographic knowledge base. However, theoretical frameworks and empirical findings arguably are worthless unless validated (or refuted) by case study cartographic interfaces designed according to this theory (**Figure 7.1: bottom-right**), as the ultimate purpose of theory on cartographic interaction is to inform the design of individual cartographic interfaces. Further, insights gleaned through the evaluations of these cartographic interfaces can and should be triangulated with the logical arguments and empirical evidence constituting the scientific body of knowledge on cartographic interaction, appending, revising, or completely rethinking existing theory where appropriate (**Figure 7.1: bottom-left**). For scientists, this partnership also includes the identification of original and open methods for disseminating the knowledge constructed from the project to the professional cartographers that can make use of it

7.3 A Comprehensive View of Twenty-First Century Cartography

In the broadest sense, it is the goal of this dissertation to establish a science of cartographic interaction, both in identifying its fundamental questions and contributing to initial frameworks and insights towards these questions. Therefore, science and the associated application of discursion and empiricism are emphasized throughout. However, science is but one of several possible approaches for generating insight for Cartography, both for cartographic representation and cartographic interaction. **Figure 7.2** presents a comprehensive view of Twenty-First Century Cartography that extends beyond this scientific way of knowing (**Figure 7.2**), focusing upon the integration across the diverse topics of study and methods of inquiry that constitute Cartography. The **Figure 7.2** framework draws a parallel to Sack's (1997) ***relational framework***—or comprehensive model showing how all of the parts are connected to form the whole—that is used to characterize the field of Geography as one that is intrinsically integrative. Sack's relational framework leverages the concept of place, central to the study of Geography, as the central 'loom' by which three bodies of knowledge (meaning, nature, and social relations) and three approaches for knowing (the scientific, the aesthetic, and the moral) are woven into a single fabric. The relational framework therefore provides a philosophical foundation for Geography, characterizing its ontology (the concept of place), its ontics (the topics of meaning, nature, and social relations), and its epistemologies (the scientific, the aesthetic, and the moral).

Similarly, the **Figure 7.2** framework provides a philosophical foundation for Cartography, integrating its ontologies, ontics, and epistemologies. The **Figure 7.2** description of Cartography pivots upon the map, much as Sack's conceptualization of Geography pivots upon place. Cartography's ***ontology***, or pursuit of the nature of being, is and always will be a question of the map itself. The cartographic ontology is one characterized by existentialism; considering the radial categories illustrated in **Figure 1.3**, the properties that define existence may include degree of abstraction and map scale (for the original case of 'map') or instead may include web dissemination and cartographic interaction (for the case of the 'digital map'). The question "Is this a map?" defines how Cartography is researched and practiced, as well as how maps are made and used. Therefore, it is upon the map that the cartographic ontics meet the cartographic epistemologies, that the bodies of cartographic knowledge meet the ways of knowing this knowledge.

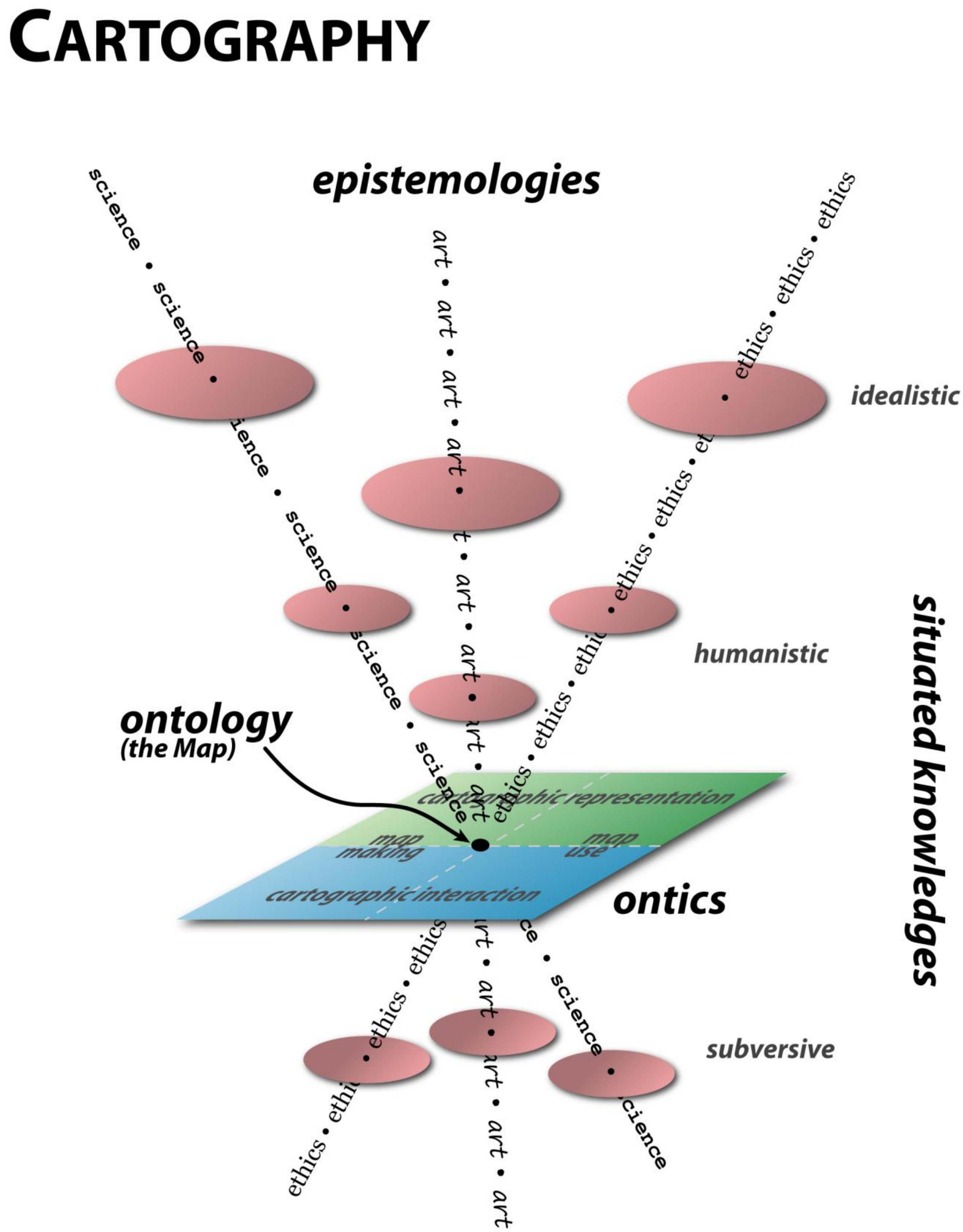


Figure 7.2: A Comprehensive View on Twenty-First Century Cartography. The ontology of Twenty-First Century Cartography is the map. Its ontics include two important dichotomies: (1) mapmaking versus map use (a traditional dichotomy) and (2) cartographic representation versus cartographic interaction (an emergent dichotomy). This body of knowledge can be expanded through at least three epistemologies: (1) science, (2) art, and (3) ethics; the focus of the dissertation is on the former, but all three are viable ways of knowing about Cartography. Within these epistemologies, situated knowledges can be applied at three levels: (1) idealistic, (2) humanistic, and (3) subversive.

Cartography's ***ontics*** describe the bodies of knowledge to which cartographers actively contribute and from which cartographers draw. The cartographic ontics align directly with the **Figure 1.4** scope of Twenty-First Century Cartography under a growth perspective. They include two important dichotomies, the first being the traditional distinction between mapmaking and map use and the second being an emergent distinction between cartographic representation and cartographic interaction. As discussed in **Section 7.2.3**, it is the emergent nature, or contemporary significance, of the second distinction that motivated the research on cartographic interaction reported in the dissertation. The cartographic ontics clearly overlap, both within the dichotomies and across them; the overlap occurs at the map itself, as the map must draw from each of these bodies of knowledge to come into existence.

This pair of ontical dichotomies are complemented with several ***epistemologies***, or ways of knowing about mapmaking and map use as well as cartographic representation and cartographic interaction. The cartographic epistemologies intersect the cartographic ontics at the map, as it is through the generation and examination of maps that the epistemologies contribute to the ontics. Two of the three cartographic epistemologies are included in the definition of Cartography offered in **Section 1.1**: Cartography is the *art* and *science* of mapmaking and map use (with the map then comprising both representations and interactions). The ***scientific*** epistemology, or way of knowing through discursion and empiricism, is emphasized in the dissertation research on cartographic interaction, as well as Robinson's (1952) initial call for functional map design, which ultimately merged with Bertin's (1967|1983) work on semiotics to form the science of cartographic representation. However, the ***artistic*** epistemology, or a way of knowing through aesthetics and emotion, remains critical to the discipline and arguably has a longer tradition within Cartography. Following Sack's (1997) relational framework, it is necessary to add the third ***ethical*** epistemology, or way of knowing through equity and probity. Understanding what is appropriate (i.e., ethical), and why, is equally as important as understanding what is functional (i.e., science) and beautiful (i.e., art). Monmonier's (1991) argument for breaking from the one-map paradigm—among the first arguments in support of cartographic interaction—is one that is explicitly based on ethics. Further, ethics perhaps are the dominant cartographic epistemology employed for Critical Cartography (Harley, 1989, Wood, 1992). Thus, while the dissertation focuses upon the scientific epistemology, all three epistemologies have a place in cartographic scholarship; it therefore is appropriate to redefine Cartography as the art, science, and *ethics*, or mapmaking and map use.

Finally, it is important to remain cognizant of the cartographer himself or herself and the ***situated knowledges***, or unique sets of cartographic and non-cartographic experiences, they leverage when generating or applying cartographic knowledge. The impact of situatedness is important both in the generation of new knowledge (primarily the role of the academic cartographer, although this may no longer be the case, as described in **Section 7.2.5**) and the application of existing knowledge (i.e., the practice of mapmaking and map use). These situated knowledges position the cartographer differently with regard to their epistemology, adjusting the orientation of the cartographer in relation to the ontologies and ontics with which they are engaging. The ***idealist*** viewpoint is one that searches for generalized truths; the scientific work on defining the optimal user, and thus producing the optimal map, is one example of such an endeavor. In contrast, the ***humanistic*** viewpoint is one that considers the unique conditions that contextualize mapmaking and map use (Tuan, 2011), and therefore is conceptually nearer to the map itself (as illustrated in **Figure 7.2**). The application of user-centered design perhaps is one example of a humanistic viewpoint regarding the scientific epistemology, as the emphasis is on design and development of a single cartographic interface to meet a single map use scenario and user group, rather than generating insights that are generalizable across all map uses and map users. Finally, the ***subversive*** viewpoint is one that is intentionally radical, using approaches and techniques counter to the status quo (Pinder, 1996, Crampton and Krygier, 2006), and therefore is conceptually beneath the surface of the cartographic ontics (as illustrated in **Figure 7.2**). Such a viewpoint may be dubious in motive, as with Cartography's history of propaganda maps in support of political persuasion (Muehlenhaus, 2010). However, the subversion can (and thinking ethically, should) be positive, jarring map users from their preconceptions and allowing for generation of new insights regarding the represented phenomenon (Denil, 2011).

In close, Twenty-First Century Cartography is all of these things. It is a discipline ontologically aligned with the map. It is a discipline whose ontics comprise at least two dichotomous bodies of knowledge. It is a discipline constructed by artistic, scientific, and ethical epistemologies. Finally, it is a discipline in which situated knowledges, or individual viewpoints, are influential on the generation and application of these cartographic ontologies, ontics, and epistemologies. While the dissertation research emphasizes cartographic interaction, and the scientific way of generating insight about cartographic interaction, it is essential to remain sensitive to all Cartography is and can be.

7.4 Conclusion: A Parting Note

It is an exciting time to be a cartographer, whether you consider yourself an academic, a professional, both, or neither. The fast pace change of computing technologies means that new opportunities are opened for Cartography every day; the bevy of cutting edge cartographic interfaces surely will continue to impress. Cartography has never been more relevant to contemporary society, nor has it had the potential to do as much good for our world. While it is difficult to predict how the discipline will look in 5, 10, or especially 50 years, I hope that my argument for a growth perspective (**Figure 1.3**), for embracing both cartographic representation and cartographic interaction, is a strong one. My argument for growth primarily relates to a scientific approach to Cartography given my own personal interests manifested in the dissertation work, but should resonate equally for the artistic and ethical components of the discipline as well. There is simply too much too gain—too much good that could be done—by opening new avenues of research and practice. Similarly, there is simply too much to lose—too much work that could be undone or lost completely—if the existing principles of cartographic representation are not maintained and promulgated. I am thankful for the collective knowledge generated by the many brilliant people working in Cartography that came before me and am excited to meet and learn from the intelligent and motivated people that find Cartography in the years to come.

Appendix A: Interview Protocol
Protocol for Background Interviews on Cartographic Interaction

A.1 Introduction

You have agreed to participate in a qualitative study aimed at understanding how digital maps and map-based software currently are applied to support the daily work of expert users. Participants have been recruited from a variety of domains in order to generate a comprehensive portrayal of contemporary interactive map use. Your input will inform my dissertation research specifically and the next generation of map-based tools developed at the GeoVISTA Center broadly.

The term 'interactive map' can be used to describe a wide variety of digital tools, ranging from simple, one-off applications or prototypes, often available online (e.g., a Google Maps mashup) to robust, fully-featured desktop software that have some sort of central map view (e.g., ESRI's ArcGIS). During our conversation, I will ask you how such tools support (or could support) your work or the work of others in your field/domain; any type of 'interactive map' along the aforementioned continuum that you wish to discuss is fair game.

The interview will last approximately 60-minutes and will be audio recorded for subsequent transcription and qualitative data analysis. Any research staff at the Penn State GeoVISTA Center assisting me with the analysis will have been trained by Penn State University in handling confidential information. In the event of publication, all identifiers will be removed so that your employers and peers will be unable to link you to your responses. Do I have your permission to start audio recording the session?

<turn on recorder>

Do you have any questions before we begin?

A.2 Biographical/Background Survey

To begin, I will ask you a set of short, structured biographical questions. The purpose of the biographical portion is to establish the context of your responses to the main interview questions. For these questions, please make your response brief. Finally, I may already know the answer to several of the following biographical questions through our prior communication; please still answer these questions so that we have an audio record to link with the remainder of your responses.

1. Please state your name, the agency, department, or organization with which you are currently affiliated, and your current job title?

2. Please provide 5-7 keywords that you feel best characterize your field/domain. Please list both general and specific keywords. How many years have you been working in this field/domain?

3. If you have had any post-secondary training, please list the degree and/or certificate. If you were trained in a different field/domain than your current work, please list several keywords that describe the field/domain in which you were trained.

4. Have you held any previous positions that required you to use geographic information and interactive maps? If yes, please list the organizations with which you were affiliated and your past job title(s).

5. How frequently do work with geographic information in your own daily work (e.g., *daily, weekly, monthly, yearly, never*)?

6. How frequently do you use static/print maps (either made by you or by others) in your own daily work (e.g., *daily, weekly, monthly, yearly, never*)?

7. How frequently do you use interactive maps or map-based software in your own daily work (e.g., *daily, weekly, monthly, yearly, never*)?

A.3 Work Tasks & Geographic Information

I will now ask you a set of semi-structured questions about your work responsibilities at your current and past positions. Specifically, I am interested in the work tasks that you need to complete and the individual sub-steps or string of steps you follow to complete these tasks. I am also interested in the nature of the geographic information (i.e., your datasets) that you use while completing these tasks. Please be as detailed as possible in your description of your work responsibilities; it may also help to describe these in an active voice.

1. Please describe the geospatial datasets that you use in your daily work *(ask follow-ups only if unclear from responses)*:

    a. is the geographic phenomena conceptually discrete or continuous in space?

    b. does the geographic phenomena change smoothly or abruptly across space?

    c. is the dataset composed of individual incidents or aggregates?

    d. is the dataset primarily homogenous numerical data or a mixture or numerical and non-numerical data (e.g., categorical attributes, long text fields).

2. What work tasks do you carry out that require you to use these geospatial datasets. Please describe these tasks as narrowly and specifically as possible.

    a. What is the purpose of performing this task? What is the overall goal or objective that you hope to accomplish? What is the result or output of performing this task?

    b. What percentage of the tasks you complete use geospatial data?

    c. What percentage of the tasks you complete use static maps? Which of the tasks listed above require you to use static maps?

    d. What percentage of the tasks you complete use interactive maps? Which of the tasks listed above require you to use interactive maps?

3. Do you complete these tasks in a typical order or workflow?

    a. Is it possible to compartmentalize or decompose each task into a prototypical workflow of discrete sub-steps? If yes, try to be as narrow as possible when describing these sub-steps. If not, why not?

b. Is the work process iterative in any way?

c. Were you taught this workflow or is it something that you figured out on your own?

d. Are there other possible ways of achieving the goals of the workflow? For example, do you have co-workers who use a different approach.

4. Are there any tasks / sub-steps that you complete using a series of static maps that would be improved if you had an interactive version of the map?

    a. What would the interactive version let you do that you cannot do now?

A.4 User Demonstration

OK, now let's take a look at your examples. Recall that I asked you to provide me with three types of examples:

(1) map-based systems that are currently integrated into your daily workflows or, if appropriate, digital maps that you have helped develop,
(2) map-based systems that you would like to use, but currently do not, or particularly good examples of one-off digital maps that you have come across, and
(3) map-based systems that you have used in the past, but abandoned, or particularly bad examples of one-off digital maps (especially those that are popular in your field).

Given your input on these examples, I've chosen one from each category to discuss; we will look at more if there is time. For each example:

1. Spend a minute or two to demonstrate the basic functionality of the interactive map, as you understand it. Please verbalize what you are doing and why as you interact with the tool.

2. Which of your current work tasks does this tool support? Quickly demonstrate how the tool supports each of these tasks, explaining why you are using the tool the way you are.

    a. How do or might you use these tools to transform or manipulate your datasets?

    b. How do or might you use these tools to represent or symbolize your datasets?

    c. How do or might you use these tools to support problem solving or decision making?

3. Which tasks / sub-steps does the interactive map support that are not part of your current work responsibilities, but are of potential use to your own work and to your field/domain? Why?

4. Which tasks doesn't the interactive map support? How could this tool be improved to support these tasks?

5. Can you recall any times that these tools were especially or surprisingly useful for accomplishing a given task? Similarly, can you recall any times that these tools failed to support your work? When listing these special situations, please also describe what you were trying to accomplish and how you went about accomplishing it.

6. What are your favorite two or three aspects/features of this tool? What are your least favorites? Why?

A.5 Debriefing: Reflections on Interactive Map Use

I wish to close by asking you to reflect on the current use of interactive maps in your field/domain. Some of these questions may seem unusual or use unfamiliar wording, but please try to offer any insights that you may have.

1. What makes a map 'interactive' (*what to let participant explain before prompting*)?
    a. Are systems that take a long time to respond to user input interactive maps?
    b. Are map-based systems like ArcMap interactive maps?
    c. Are mashups interactive maps?
    d. Are animations interactive maps?
    e. Are paper maps interactive maps?
2. Is adding interactivity to the map always good or always bad? In what situations is it good and in what situations is it bad? Why?
3. What are the basic 'objectives' or user tasks that an interactive map should and could support? What typically mapping objectives would be more easily completed with non-map interfaces?
4. How widespread is the current use of digital maps and map-based systems by professionals in your field? Why do you think this is the case?
    a. How common are desktop interactive maps?
    b. How common are web-based interactive maps?
    c. How common are web map mashups?
5. Do you think the training on both *making* and *using* interactive maps is sufficient in your field? How would you go about training individuals to use interactive maps in your domain?
6. Is there anything else you would like to share about interactive maps that we have not already discussed?

Appendix B: Objective & Operator Card Sets
Set of Primitive Instances for the Objective & Operator Card Sorts

B.1 Objective Cards

ID	Objective Card
1	read off the attribute value of a map item
2	determine which of two map features has a larger attribute value
3	establish the characteristics that make a map feature distinctly recognizable
4	determine the specific position of a map feature
5	recognize two map features as different or distinct
6	place map features into specifically defined devisions in a classification
7	join map features into groups of the same, similar, or related type
8	order map features according to an attribute value
9	notice similiarities and differences among map features
10	link or join multiple map features in a relationship
11	establish a direct connection between two map features
12	find instances of identifiable features in a spatial dataset
13	consider multiple map features or patterns
14	bring domain knowledge to bear on the identified map features and their relationships
15	identify the attribute of a map feature
16	identify relationships between several patterns
17	examine a single map feature
18	relate two or more map features
19	look at or inspect a map feature
20	simultaneously inspect two or more map features rather than one
21	allocate map features into bins according to a threshold value
22	identify a subset of map features and highlight or delete them

ID	Objective Card
23	analyze the strength and nature of relationships among map features
24	find the attributes of a set of map features
25	find map features that satisfy concrete conditions on attribute values
26	compute an aggregate numeric representation of a set of map features
27	find map features possessing an extreme value of an attribute over the dataset's range
28	rank a set of map features according to an ordinal attribute value
29	find the span of attribute values within a set of map features
30	characterize the distribution of an attribute across a set of map features
31	identify anomalies within a set of map features with respect to an expected relationship
32	find clusters of similar attribute values within a set of map features
33	determine useful relationships between two attributes of a set of map features
34	mark a map feature of interest
35	show me something else about the dataset
36	show me a different arrangement of the dataset
37	show me a different representation of the dataset
38	show me more or less detail about a map feature
39	show me map features that meet a condition
40	show me related map features
41	where are the nearest sewers to a hazardous chemical release?
42	where can I stage my emergency response operations?
43	get an idea of the growth and movement of a toxic plume
44	who should I move first after a sustained chemical release?

ID	Objective Card
45	how close is the exposure to a vulnerable building?
46	is the risk of exposure to a chemical release a lot less here than there?
47	where are the nearest schools to the toxic chemical release?
48	what explosives materials are known to be inside a building that is on fire?
49	how fast is the fire truck going?
50	how big is the building that is on fire?
51	are there buildings nearby that are at risk of catching fire?
52	locate the building that is on fire on a map
53	find a different route to a building that is on fire if one way is closed
54	detect the location of a crime series within the city
55	look for clusters of robberies within a section of the city
56	find other cases that match a particular commercial burglary case
57	look into a spike of disorderly conduct cases in an area
58	look into a set of serious crime offenses to see if they are related
59	has this area been hit by crime in the last month?
60	how did the West Nile Virus spread across the Mississippi River Valley?
61	get the area of impact of a natural disaster
62	where is our location in relation to another reponse team?
63	what will happen at the same location in five years from now when there is another hurricane?
64	where were the crowd disturbances during the Nuclear Security Summit in Washington DC?
65	where did the 7.0 magnitude or greater earthquakes occur?
66	look for routes that still are open after the earthquake
67	what is the drive time between an event and the closest emergency response center?
68	monitor the location of emergency responders
69	quantify the amount of damage caused by a natural disaster
70	examine the relative concentrations of different ground water contaminants
71	see if the remediation procedure resulted in reducing the geographic extent of the chemical

ID	Objective Card
72	identify your house based on an aerial image in Google Earth
73	determine the soil contamination region from a chemical leak
74	prioritize potential sites to build a natural gas plant
75	find potential sites to put up a wind turbine, which must be a minimum distance away from properly lines
76	which areas of Florida potentially will be impacted by the hurricane?
77	give me all insurance policies within one kilometer of the hurricane track
78	which area has the highest frequency of available insurance adjustors?
79	where does the wind speed have a probability of being 64 knots or higher?
80	discern between two types of polices on the map
81	how far was the property from the storm track?
82	how many acres is the assessment site?
83	how close does the plaintiff in the court case live to the contamination site?
84	which county has the highest mesothelioma mortality rate?
85	compare this case to the case in New Orleans
86	where are the largest clusters of asbestos exposure?
87	what is unique about this location on the map?
88	which chemicals found in the area may cause brain cancer?
89	what proportion of autism cases could be related to sewer farm sites?
90	compare the region with the highest rate of child neurodevelopmental disorders to the area with the lowest
91	look for the source of the mercury contamination
92	compare the disease rate in this county to the national average
93	was there a change in the rate of prostate cancer here between the two years?
94	predict the spatial outbreak pattern of a disease
95	show trends in STD rates in Atlanta over time
96	identify community level risk factors associated with STD rates
97	how many obesity-related disease cases were received from that area with no public recreation activities?
98	is socioeconomic status correlated spatially to gonorrhea rates?

ID	Objective Card
99	identify communities that are in poverty and have high disease rates
100	where are the high risk clusters of disease morbidity?
101	identify health care centers that are close to the communities with high disease rates
102	what is the relationship between air pollution level and meteorological variables?
103	what is the percent of urbanness within one kilometer of the sample site?
104	what is the nearness of the sample site to an interstate?
105	compare the estimated air pollution levels from two models that include a different set of predictive variables
106	what is the elevation at the sample point?
107	get directions to go on a trip
108	how many patients were treated at this hospital last year?
109	how many cases are our competitors treating compared to our hospital?
110	is there a spatial association between age and rural status?
111	calculate the potential cost of cancer treatment in the region
112	find spatial predictors of rural/urban status
113	compare the distribution of patients over 65 years old to the distribution of patients that were not treated with radiation
114	where are the hospital patients coming from?
115	compare aerial photos of the region from two different years
116	find a boat ramp on the lake
117	where was this salesman before and after his stay in the town?
118	what are the differences in routes between peddlers that are based locally and salesman selling national brand name products?
119	what is the proportion of town visitors to town population?
120	how many hotels were in the town in the late 1800s?
121	this small town community is connected to which major urban systems?
122	what local businesses would cause this salesman to travel to this town?
123	which salesman travels to the town the most?
124	what is the geographic extent of visitors to this hotel?

ID	Objective Card
125	are there other salesmen that exhibit the same travel pattern as this person?
126	show the spatial extent of the flood
127	where will the airplane be able to complete a radio link with the base?
128	what areas would flood if the water was 11 feet above the gauge?
129	what is the best route for the tank to take?
130	have any apprehensions occurred in the last seven days in this area?
131	are the cases included in the recent assault spike associated in anyway?
132	where did the drug seizure take place?
133	did the added policing resources cause the criminal activity to shift away from that area?
134	where has fencing increased over time?
135	is the criminal activity more significant here compared to there?
136	where is the best place to put a new sensor?
137	look at what is in an area before going out to the field
138	correlate bits of intelligence information with information from sensors
139	where is the radio tower?
140	find the path the vehicle should take to cross the river
141	find an appropriate landing location for the airplane
142	are there differences in energy consumption when aggregated to the state level versus the county level?
143	derive specific values about the overall pattern of US imports
144	which states are the most populated?
145	compare the energy use habits of two localities
146	how does corn move across the landscape from farms to homes?
147	where should I go on my walk?
148	compare the historic vegetation to the current vegetation
149	how geographically diverse is the readership of my blog?
150	how many people from Boston read this article?

ID	Objective Card
153	where am I on this map?
154	how does the overall voting pattern relate to where I live?
155	compare the results of the election to the overall poverty rate
156	estimate the taxi fair to get to the restaurant
157	assess the value of land along the coast
158	how far back should you develop from the coastal bluff?
159	count the number of buildings along the shoreline
160	what are the demographic characteristics of neighborhoods with high infant mortality rates?
161	identify where all vacant homes are within the city
162	find a harbor to anchor your ship
163	when will the bluff erosion reach my house?
164	generate a travel itinerary
165	locate yourself along the coast

ID	Objective Card
166	how many drilling sites are within 100 miles of deep water quartz?
167	how much money was spent in our ward compared to other wards?
168	what is the distance to the nearest university?
169	what kind of zoning is this property?
170	are robberies more prevalent on weekends or weekdays?
171	where has your candidate been spending the most time campaigning?
172	is there a correlation between the amount of money the candidate is raising in each state and the number of appearances she is making in those states?
173	determine the location where the endangered fish was caught
174	figure out the surface area of the Hudson River harbor estuary
175	where are there concentrations of fish?
176	calculate the distance the fish traveled from its release point to its capture point
177	what is the range of the endangered species?
178	do indigenious peoples live in the same areas as the endangered species?

B.2 Operator Cards

ID	Operator Card
1	mouse over the collection of map features on which an operator should be applied
2	highlight the brushed map features, as well as items in other panels that correspond to these features
3	remove map features from the display that were not brushed
4	delete the selected map features
5	brush the map to cause the names of map features to appear
6	change the magnification of the map
7	show information about the highlighted subset of map features in other non-map views
8	arrange a large number of maps for simultaneous comparison
9	gain an overview of the entire collection of map features
10	zoom in on map features of interest
11	filter out map features not of interest

ID	Operator Card
12	select a map feature or group of features and get details
13	view relationships among map features
14	keep a history of actions to support undo, replay, and professive refinement
15	extract a sub-collection of map features along with the query parameters
16	change the viewpoint of the map
17	select map features through direct manipulation
18	alternate between more than one graphic version of a spatial data set
19	display more than one spatial data set in the same coordinate space
20	highlight a particular subset of map features for visual discrimination
21	reveal extra information about a map feature on demand
22	see an overview of the map

ID	Operator Card
23	change a parameter of the map representation
24	switch among multiple map displays of the same spatial data
25	link multiple representations of the same spatial data together
26	change the variable that is mapped
27	highlight a set of map features that appear to be outliers
28	focus on map features that fall within a particular range of values
29	replace one color scheme with an alternative color scheme
30	adjust the position of the viewer
31	display one time slice after another on the map
32	dynamically change the projection
33	focus on an interesting subsets of map features
34	display the map feature in more detail
35	drill down into a map feature while preserving an overview of all features
36	generate multiple different representations of the same spatial data
37	control the camera position and range of view of the map
38	indicate a feature or region of interest to be the subject of some operation
39	increase screen space for a focus area to see details, while showing other areas in a smaller space to preserve context
40	adjust the display scale to restrict the extent of the view
41	view map features hidden off-screen
42	alter the map projection
43	access the exact information related to a map symbol
44	differentiate a subset of the map features
45	switch among multiple map representation strategies
46	alter map symbolization choices such as classification scheme, color scheme, interpolation type, or contour interval
47	select map features by drawing a box on the map
48	manipulate the attribute values of a map feature
49	select a theme for display on the map
50	select a map feature
51	display only those map features that meet certain criteria
52	import the model results from NOAA into a GIS system
53	hit a button to bring up an isopleth map of chemical concentration
54	type in a street name and address number
55	zoom out the map to see what else is in the area
56	click on the building symbol to get sprinkler information, the alarm type, and floor plans
57	take a picture of the map and start marking it up
58	run an animated fly through in Google Earth
59	take a snapshot of the map and type in text instructions on top of it
60	choose one of several different symbolization templates
61	click on the layer panel to show layers of different types of crimes
62	load the latest crime cases into ArcMap
63	zoom into an area of the city where there is a peak in crime
64	look at a location from different angles
65	define a query to filter or narrow the crime incident dataset
66	string together a series of maps into a slideshow
67	log onto an internet mapping website
68	pan along the route to the emergency response site in order to see what it looks like
69	edit attribute fields in the Map Server application so that the map shows the latest information
70	make a hard copy of the map to give to a coodinating officer
71	zoom into a location on the map to look at the weather warning
72	overlay a recent aerial image of Haiti to see the current ground conditions
73	drop a symbol on the map that indicates the estimated location of the explosion
74	mark up the map to indicate where to send resources
75	use a utility to export the data to Google Earth
76	show a perspective view of the topography and hydrology

ID	Operator Card
77	set an appropriate projection and coordinate system for the map
78	redraw a line feature in ArcMap that needs to be edited
79	draw a polygon and retrieve an average for the area selected
80	zoom to the extent of the project area
81	turn the names of the building owners on and off
82	brush the map features to see their attributes
83	perform a query that specifies the range of contaminant concentration levels to be shown on the map
84	search for a specific wind turbine using an ID
85	download shapefiles of the storm event
86	import a hurricane track into the GIS
87	zoom to a county when clicked
88	use a dropdown box to add other storm tracks to the map
89	export the data on the map to a .csv file
90	using the identify tool, click on the points to get specifics
91	change the symbols so that feature type is represented using shapes instead of colors
92	highlight the map features that match the filtering parameters
93	click play to begin the map animation
94	orbit around the digital globe
95	type in the address where a toxic chemical was released
96	change the map to show the distribution of colorectal cancer for a different race
97	mouse over the map to get an info window to pop up
98	change the color scheme used for the choropleth map
99	zoom in to see what is around the point source
100	import a real-time data feed on hospital patients to generate a map
101	classify the counties into categories based on the STD rate distribution
102	toggle different map layers on and off
103	define the layout of the map title, legend, and so on

ID	Operator Card
104	save the map so that you can come back later to make a modification
105	enter search words into Google Maps to find target communities in Pittsburgh
106	click a feature on the map for more information
107	manipulate the smoothing parameters of an air pollution map so that the surface is more or less smooth
108	use the identify tool to evaluate the geographic predictors of exposure at a particular site
109	download elevation data from the National Map
110	project the map using the Albers equal area conic projection
111	change which layers are displayed on the map
112	measure the distance between a point source and a disease case
113	search for a specific geographic place
114	write a query to show all points with undefined values
115	click and drag the route to change the directions
116	zoom into the map to see features in a higher resolution
117	export the map into an image file format
118	select a point to change the attribute data
119	color code patient locations based on age
120	use the annotation editor to add notes about each hospital to the map
121	digitize a boundary to define the extent of the site
122	overlay a historical aerial photo onto Google Earth
123	use a transparency slider to change the opacity of an image overlay
124	create a .kml file in ArcMap to view in Google Earth
125	click on a placemark for a bubble pop up with text, photos, and a link to the website
126	change the temporal extent from seven to fourteen days
127	turn on the layer showing the count of guests per hotel
128	get a screenshot of the map
129	click on a roadblock to view a log of the activity
130	change the speed of the aircraft in the animation

ID	Operator Card
131	mouse wheel into the map to view a different level of granularity
132	toggle layers on and off in ArcGIS
133	drag the map by clicking on it
134	use the annotation tools to draw arrows on the map indicating important locations
135	click on the area of the flood to get a profile of the river basin
136	select a different background image for the map
137	change the transparency of the top map layer
138	view the map from a different angle
139	create a new .mxd map document in ArcMap
140	export the map as a .pdf
141	zoom in to get a sense of the criminal activity in the area
142	query all incidents from the last fourteen days
143	turn on the tactical infrastructure layer
144	animate the map over time
145	select all apprehensions that fall within a mile of the address
146	drill down into the map to see the trail on high resolution imagery
147	pan the map to a different location
148	overlay the image from yesterday onto today's image for comparison
149	click on the icon indicating where the picture was taken and see the metadata
150	search for GeoRSS feeds that can be plotted onto the map
151	query for a specific location
152	zoom into your address and see if your house is under water after evacuating
153	select two cities and calculate the distance between them
154	adjust the way that energy production is standardized
155	bring it down to the county level to get a larger cartographic scale
156	enter in a type of food and generate a map to see how it is distributed
157	toggle back and forth between a proportional symbol and dot density map

ID	Operator Card
158	change the orientation of the map from north as up
159	lay thematic data on top of the map
160	play the movie to see how energy use builds up on the map
161	click on the orchard symbol to get photos of it
162	load a predefined dataset onto the map
163	filter the blog hits to see the distribution of first time visitors only
164	roll over a state to see how many visits came from it
165	start with a map of the world and zoom into an area of interest
166	apply a different style to the look of the basemap
167	download a map made by someone else and begin editing it
168	log in and browse the maps you have made
169	control the layer visibility
170	get started by loading a stock map design of the world
171	save a map as a project file to allow other people to collaborate on it
172	roll back to an earlier version of the map
173	change the projection of the map without changing the data loaded onto it
174	brush over the first district of California to see how people voted
175	click on points along the sample route and drag them to another location to modify the route
176	enter your address
177	filter the mapped data according to a thematic attribute
178	change the visual presentation of the map by modifying the color palette used
179	place a point to indicate the position of a new marina
180	make the top layer transparent to see if there is something underneath it or not
181	navigate from one place to another on the map
182	select a subset of the dataset that is relevant to the management problem
183	zoom into the map with a slider bar
184	download the lighthouse dataset as a .kml file

ID	Operator Card
185	click on a shipwreck to get metadata and other rich information about the shipwreck
186	draw a red line to mark something of interest on the map
187	resymbolize map features using a different attribute
188	switch the basemap
189	use the lasso to zoom into a country
190	turn on a building reference layer
191	refine your search using a set of buttons
192	lighten up the top layer on the map
193	print out a hard copy of the map
194	change the category of crime that is shown on the map
195	use the widget to narrow down the number of crimes that are shown on the map

ID	Operator Card
196	change the relative sizing of circular proportional symbols
197	hover over the location of the campaign speech to see more information about it
198	share a map that you have made
199	pan the mashup just like a Google Map
200	play a cumulative map animation
201	place a marker on the approximate location of where the fish was caught
202	find Hoboken
203	save the data on the map as a table
204	move across the map to find another position where a fish was caught
205	toggle among four different types of symbologies
206	select an animal and show on the map the extent of its habitat

Appendix C: Card Sorting Protocol
Protocol for Interaction Objective and Operator Card Sorts

C.1 Introduction

Thank you for agreeing to participate in the set of card sorting studies; we greatly value your input and appreciate the time you have set aside to participate in this research! In the following, we provide critical background information about the project and instructions for completing the pair of card sorting studies; it is essential that you review these instructions before completing the card sorting studies. Please feel free to ask any questions before completing the studies themselves.

C.2 Background:

The pair of card sorting studies investigates two important issues related to the design and development of interactive mapping and geovisualization applications, described as interaction *objectives* and interaction *operators*:

> **Objectives:** An objective is the *task* that the user wishes to complete or the *question* that the user is attempting to answer with the mapping system. In interactive mapping and geovisualization, these objectives are accomplished through generation of an appropriate visual (i.e., a map) that provides the necessary information to complete the task or answer the question. Objectives are the key component of the initial task analysis or work domain analysis completed before design/development of an interactive map begins, during which the key needs of the users are identified and articulated. Examples of objectives include the statements "Compare the results of the election to the overall poverty rate" and "Which areas of Florida potentially will be impacted by the hurricane?"
>
> **Operators:** In contrast, an operator is the *digital tool* through which accomplishment of an objective is made possible; operators are the *interfaces* provided to users to transform the map in a way that supports their task or answers their question. Operators are the key component of the conceptual design and prototyping stages of design/development, when the designers explore alternative interface solutions to support the previously identified user needs. Examples of operators include the statements "Brush over the first district of California" and "Zoom in to see the point source."

A prior study was completed with professional interactive map *users* from a variety of application domains to elicit statements about both objectives and operators; these statements include both generic descriptions and specific examples of objectives and operators. In the pair of card sorting studies, you will be asked to apply your experience and training as a interactive map *designer* to group these statements into logical categories based on similarity; the first card sorting study is specific to objectives, while the second is specific to operators. In your categorization, <u>do not</u> sort the cards based on the domain from which the statements were offered (e.g., do not put all statements about hurricanes into one category), but instead make connections across domains, with each category potentially containing examples from a variety of domains. In other words, **the goal of the two card sorting studies is to identify cross-cutting categories of objectives and operators that are general to any interactive mapping context**.

C.3 Instructions:

The set of card sorting studies are implemented using the WebSort.net (http://www.websort.net) tool. Upon entrance to a card sorting study, you will be asked to insert your email address for identification; your email address is collected to allow you to be compensated for participating in the research and will be replaced with an anonymous identifier for all subsequent analysis and reporting. You then will be prompted with a set of instructions similar to those provided here, but specific to either objectives or operators, depending on which of the two studies you currently are completing. These instructions can be accessed at any time during the study using the "Instructions" button. Also included in this instructions panel is language regarding informed consent to the research study. Please review the informed consent statement so that you are aware of your rights as a participant. It should be noted that your participation is entirely voluntary and you may discontinue the study at any time; you will not need to sign a document explicitly consenting to participation, as participating in the study implies your consent.

The WebSort tool uses a tabletop metaphor that is conceptually similar to sorting a stack of index cards on a flat table. On the left, you'll see the list of statements (cards) that you will need to sort. To begin sorting, drag a statement from the left column and drop it on the empty workspace in the middle of the screen. When you drop the card, a container will appear that represents a new category, and the statement will be placed inside it. Once created, you can drop additional cards into the container to form the category. These categories can be moved around the workspace, although they cannot be resized; clicking on the header of the category allows you to key in a name for the category. There is no correct number of categories, or number of cards per category, but make sure that you think about how the items relate to each other in order to ensure that the categories are as internally homogenous and externally distinctive as possible.

Several additional notes about the card sorting studies:

- The Websort tool does not allow you to save a session and return to it later, meaning you will need to complete each sort in a single work session. **Closing the browser during the sort will lose any progress you have made in sorting the cards.** You are allowed to complete the two card sorting studies in separate work sessions.
- Because Websort uses a tabletop or workspace metaphor, use of a large screen or dual screens will improve efficiency in completing the card sorting studies and is therefore recommended (although not required for participation).
- Please refine each categorization after an initial sort of the set of cards by taking an additional pass through the structure; you can revise the contents of categories using the same drag and drop functionality used to move cards from the left panel to the workspace.
- In order to submit your categorization, all cards must be placed into a category and all categories must be given a name. It is recommended that you create both a "Discard" category and an "Other" category for cards that do not appear to be descriptions/examples of an objective or operator (Discard) and for cards that are clearly objectives or operators, but do not fit cleanly into your classification (Other); do your best to keep the contents of these categories to a minimum.
- After completing each sort, please provide notes explaining your approach to categorizing the set of cards using the "Leave a comment" tab. This may include a description of competing approaches you considered, definitions of categories, identification of problematic cards or categories, an explanation for cards included in the Other and Discard categories, or any other notes you feel should be communicated to the researchers.

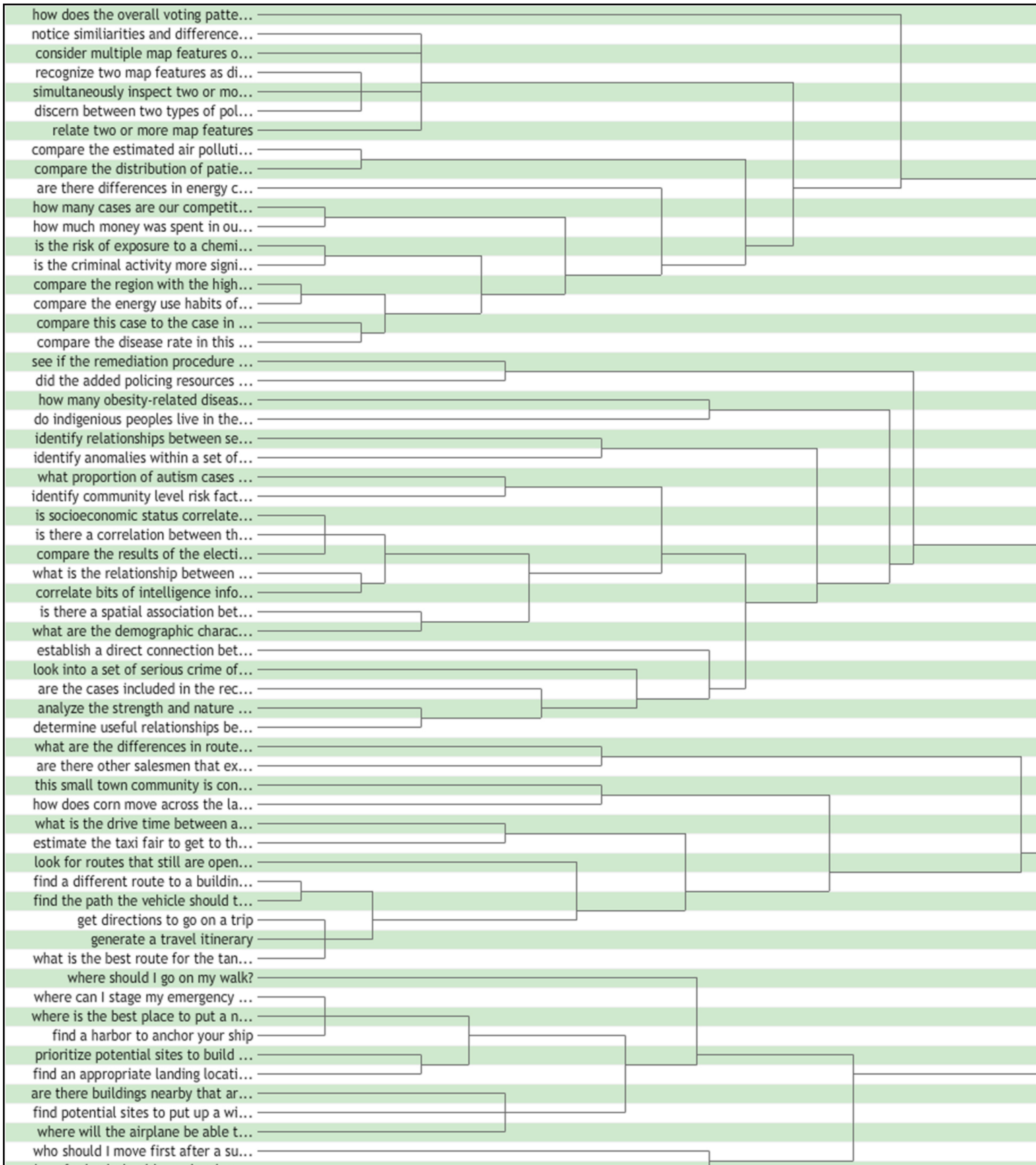
Again, the card sorting study will be open until **<*close date*>**; biweekly email reminders will be send until the close date. Upon completion of the study, we will contact you to acquire the mailing address to which we should send your monetary compensation.

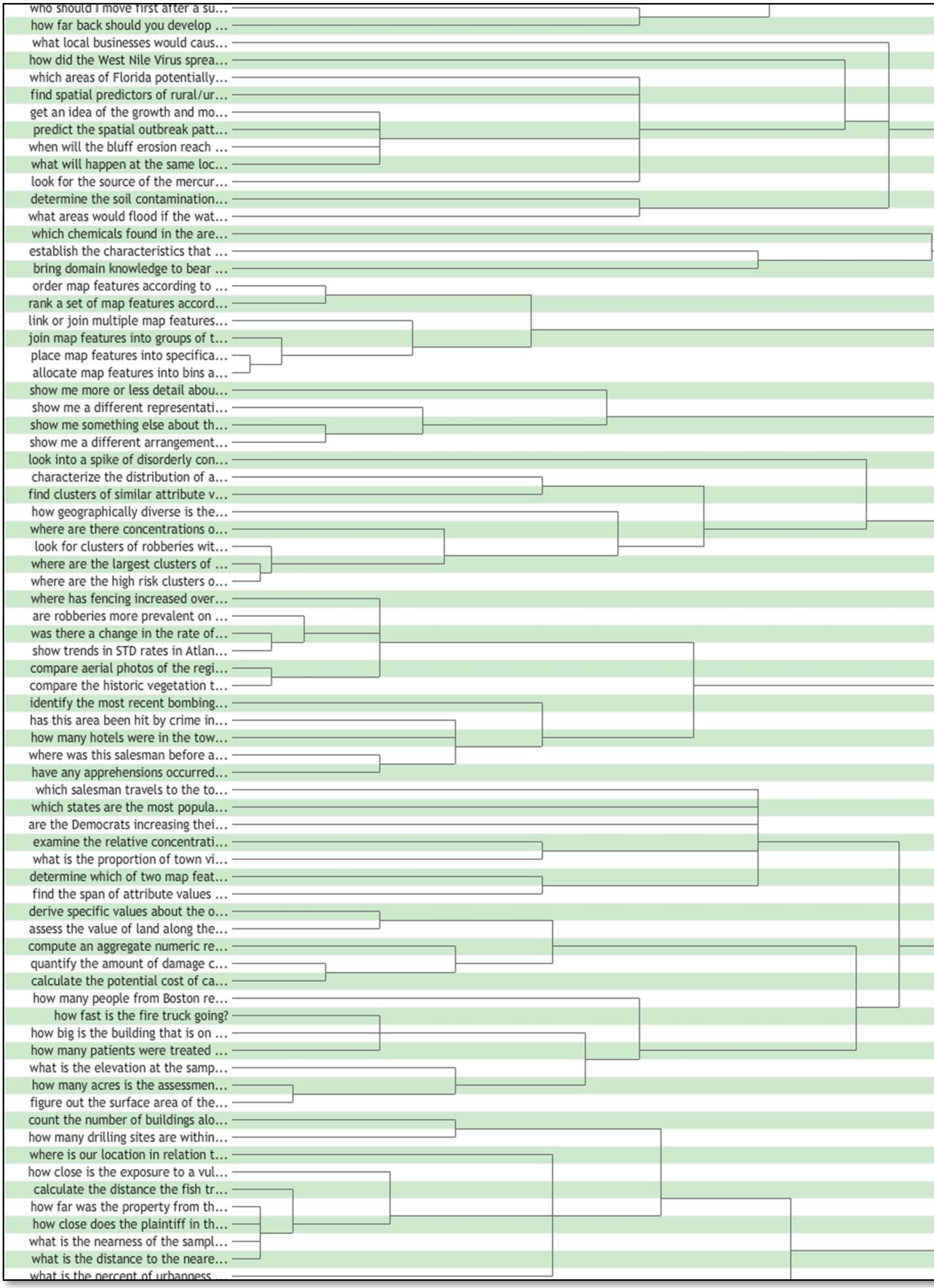
After reading these instructions, please proceed to the following links to complete the card sorting studies; please complete the objective sorting study first and the operator sorting study second:

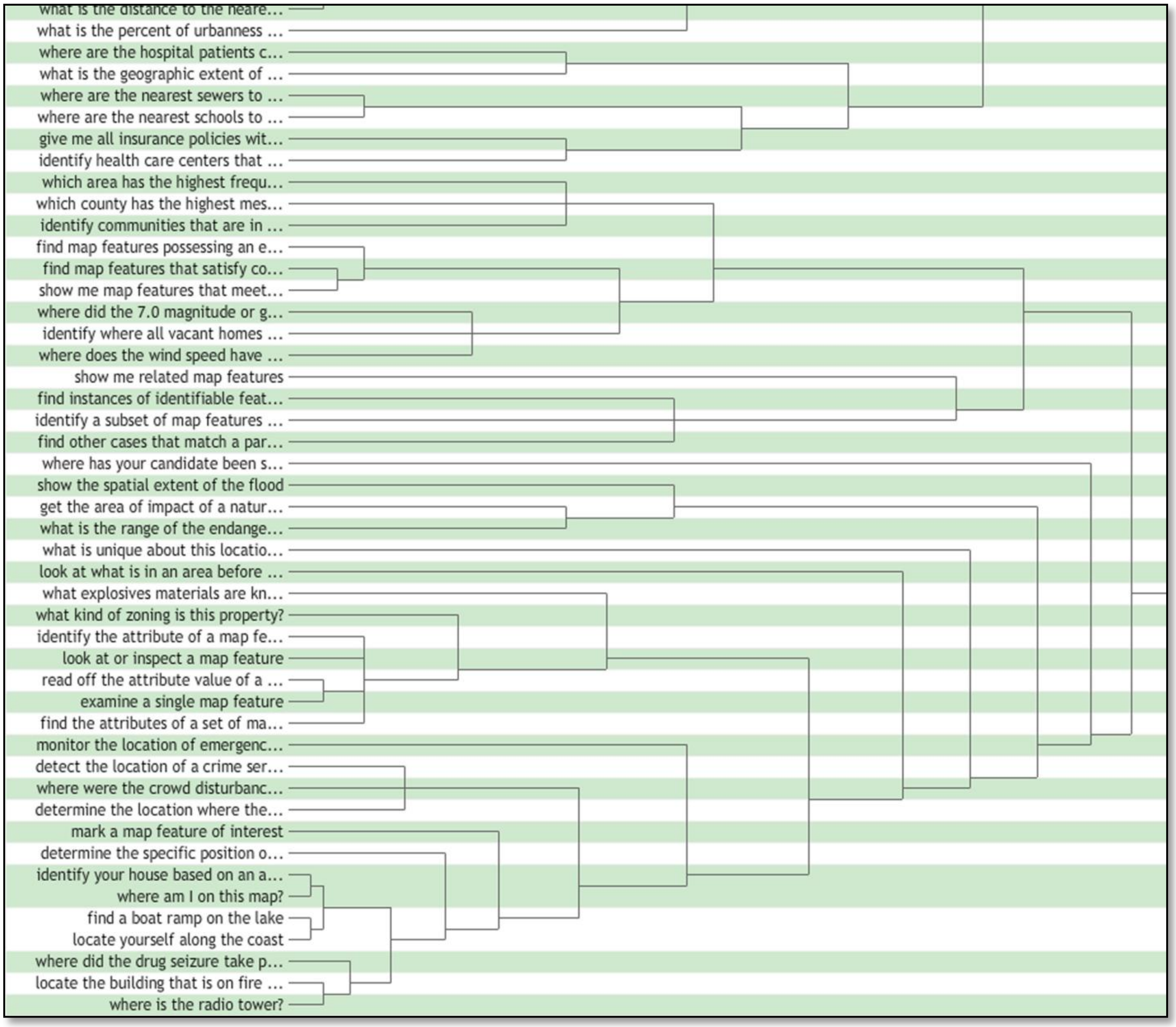
1. Objective Sorting Study: **<*link*>**
2. Operator Sorting Study: **<*link*>**

Appendix D: Card Sorting Dendograms
Visual Interpretation of Hierarchical Clustering Results

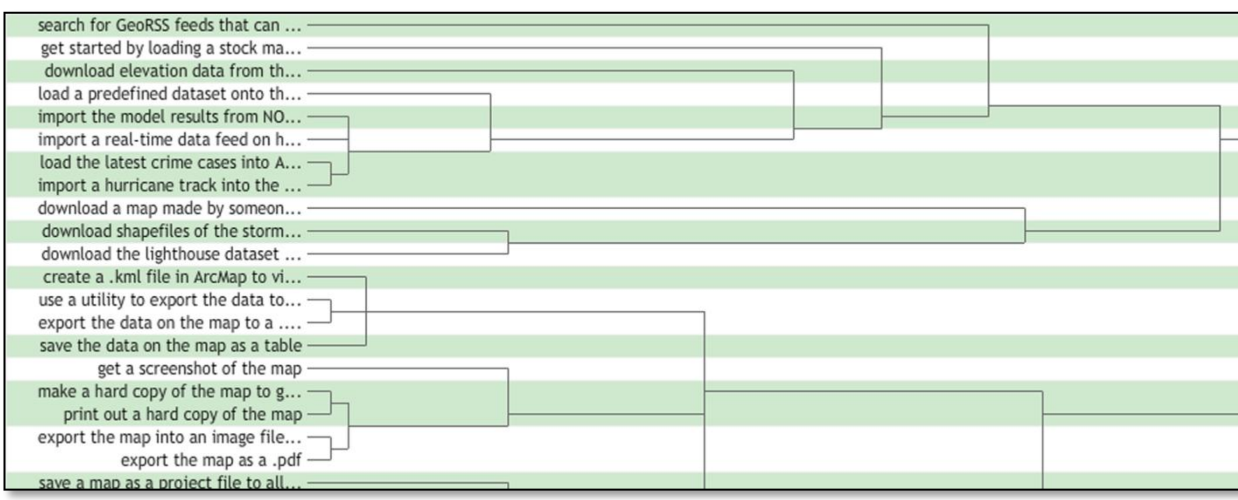
D.1 Objective Dendogram

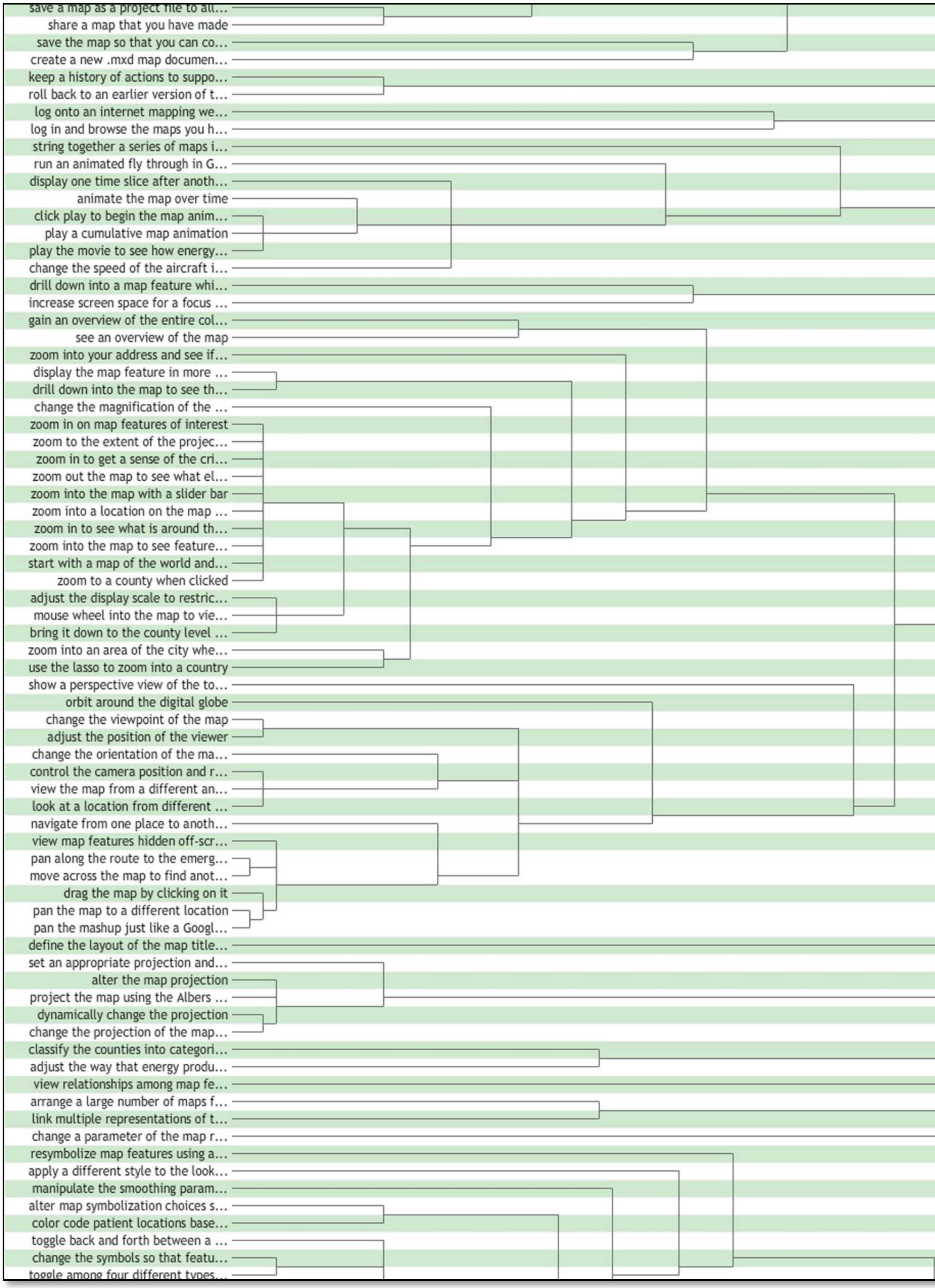


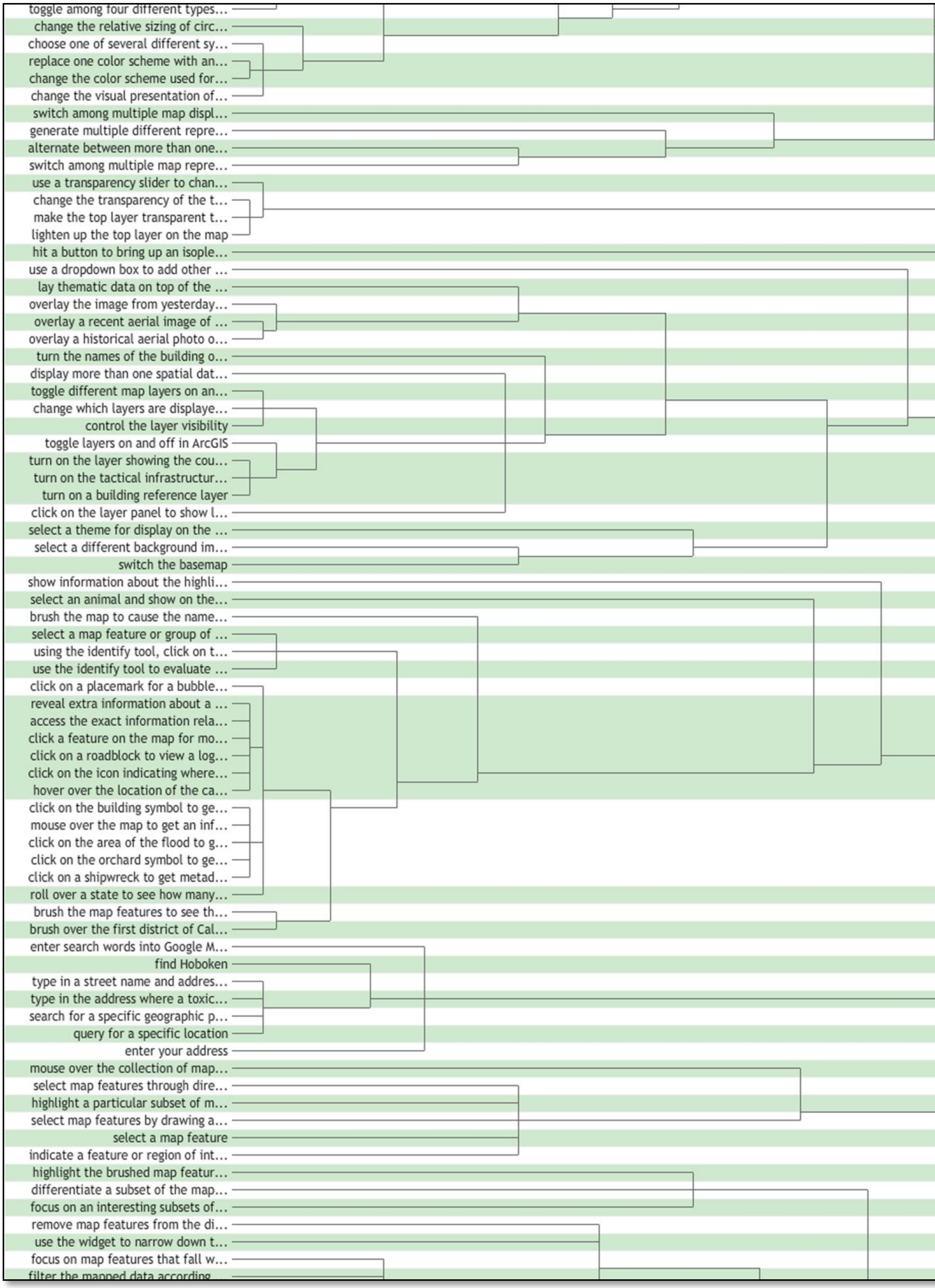

who should I move first after a su…
how far back should you develop …
what local businesses would caus…
how did the West Nile Virus sprea…
which areas of Florida potentially…
find spatial predictors of rural/ur…
get an idea of the growth and mo…
predict the spatial outbreak patt…
when will the bluff erosion reach …
what will happen at the same loc…
look for the source of the mercur…
determine the soil contamination…
what areas would flood if the wat…
which chemicals found in the are…
establish the characteristics that …
bring domain knowledge to bear …
order map features according to …
rank a set of map features accord…
link or join multiple map features…
join map features into groups of t…
place map features into specifica…
allocate map features into bins a…
show me more or less detail abou…
show me a different representati…
show me something else about th…
show me a different arrangement…
look into a spike of disorderly con…
characterize the distribution of a…
find clusters of similar attribute v…
how geographically diverse is the…
where are there concentrations o…
look for clusters of robberies wit…
where are the largest clusters of …
where are the high risk clusters o…
where has fencing increased over…
are robberies more prevalent on …
was there a change in the rate of…
show trends in STD rates in Atlan…
compare aerial photos of the regi…
compare the historic vegetation t…
identify the most recent bombing…
has this area been hit by crime in…
how many hotels were in the tow…
where was this salesman before a…
have any apprehensions occurred…
which salesman travels to the to…
which states are the most popula…
are the Democrats increasing thei…
examine the relative concentrati…
what is the proportion of town vi…
determine which of two map feat…
find the span of attribute values …
derive specific values about the o…
assess the value of land along the…
compute an aggregate numeric re…
quantify the amount of damage c…
calculate the potential cost of ca…
how many people from Boston re…
how fast is the fire truck going?
how big is the building that is on …
how many patients were treated …
what is the elevation at the samp…
how many acres is the assessmen…
figure out the surface area of the…
count the number of buildings alo…
how many drilling sites are within…
where is our location in relation t…
how close is the exposure to a vul…
calculate the distance the fish tr…
how far was the property from th…
how close does the plaintiff in th…
what is the nearness of the sampl…
what is the distance to the neare…
what is the percent of urbanness …

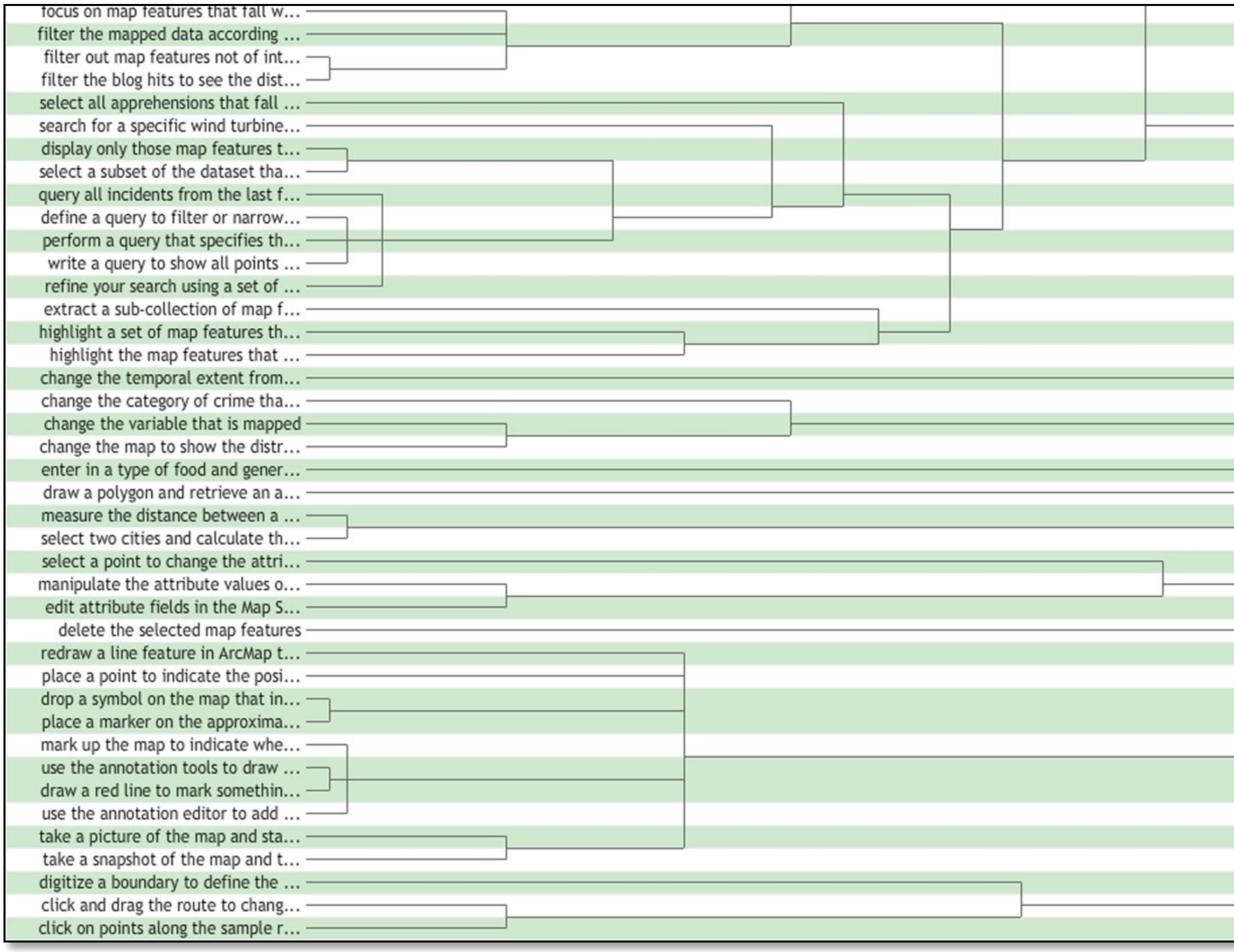


D.2 Operator Dendogram




save a map as a project file to all…
share a map that you have made
save the map so that you can co…
create a new .mxd map documen…
keep a history of actions to suppo…
roll back to an earlier version of t…
log onto an internet mapping we…
log in and browse the maps you h…
string together a series of maps i…
run an animated fly through in G…
display one time slice after anoth…
animate the map over time
click play to begin the map anim…
play a cumulative map animation
play the movie to see how energy…
change the speed of the aircraft i…
drill down into a map feature whi…
increase screen space for a focus …
gain an overview of the entire col…
see an overview of the map
zoom into your address and see if…
display the map feature in more …
drill down into the map to see th…
change the magnification of the …
zoom in on map features of interest
zoom to the extent of the projec…
zoom in to get a sense of the cri…
zoom out the map to see what el…
zoom into the map with a slider bar
zoom into a location on the map …
zoom in to see what is around th…
zoom into the map to see feature…
start with a map of the world and…
zoom to a county when clicked
adjust the display scale to restric…
mouse wheel into the map to vie…
bring it down to the county level …
zoom into an area of the city whe…
use the lasso to zoom into a country
show a perspective view of the to…
orbit around the digital globe
change the viewpoint of the map
adjust the position of the viewer
change the orientation of the ma…
control the camera position and r…
view the map from a different an…
look at a location from different …
navigate from one place to anoth…
view map features hidden off-scr…
pan along the route to the emerg…
move across the map to find anot…
drag the map by clicking on it
pan the map to a different location
pan the mashup just like a Googl…
define the layout of the map title…
set an appropriate projection and…
alter the map projection
project the map using the Albers …
dynamically change the projection
change the projection of the map…
classify the counties into categori…
adjust the way that energy produ…
view relationships among map fe…
arrange a large number of maps f…
link multiple representations of t…
change a parameter of the map r…
resymbolize map features using a…
apply a different style to the look…
manipulate the smoothing param…
alter map symbolization choices s…
color code patient locations base…
toggle back and forth between a …
change the symbols so that featu…
toggle among four different types…


toggle among four different types…
change the relative sizing of circ…
choose one of several different sy…
replace one color scheme with an…
change the color scheme used for…
change the visual presentation of…
switch among multiple map displ…
generate multiple different repre…
alternate between more than one…
switch among multiple map repre…
use a transparency slider to chan…
change the transparency of the t…
make the top layer transparent t…
lighten up the top layer on the map
hit a button to bring up an isople…
use a dropdown box to add other …
lay thematic data on top of the …
overlay the image from yesterday…
overlay a recent aerial image of …
overlay a historical aerial photo o…
turn the names of the building o…
display more than one spatial dat…
toggle different map layers on an…
change which layers are displaye…
control the layer visibility
toggle layers on and off in ArcGIS
turn on the layer showing the cou…
turn on the tactical infrastructur…
turn on a building reference layer
click on the layer panel to show l…
select a theme for display on the …
select a different background im…
switch the basemap
show information about the highli…
select an animal and show on the…
brush the map to cause the name…
select a map feature or group of …
using the identify tool, click on t…
use the identify tool to evaluate …
click on a placemark for a bubble…
reveal extra information about a …
access the exact information rela…
click a feature on the map for mo…
click on a roadblock to view a log…
click on the icon indicating where…
hover over the location of the ca…
click on the building symbol to ge…
mouse over the map to get an inf…
click on the area of the flood to g…
click on the orchard symbol to ge…
click on a shipwreck to get metad…
roll over a state to see how many…
brush the map features to see th…
brush over the first district of Cal…
enter search words into Google M…
find Hoboken
type in a street name and addres…
type in the address where a toxic…
search for a specific geographic p…
query for a specific location
enter your address
mouse over the collection of map…
select map features through dire…
highlight a particular subset of m…
select map features by drawing a…
select a map feature
indicate a feature or region of int…
highlight the brushed map featur…
differentiate a subset of the map…
focus on an interesting subsets of…
remove map features from the di…
use the widget to narrow down t…
focus on map features that fall w…
filter the mapped data according…


focus on map features that fall w…
filter the mapped data according …
filter out map features not of int…
filter the blog hits to see the dist…
select all apprehensions that fall …
search for a specific wind turbine…
display only those map features t…
select a subset of the dataset tha…
query all incidents from the last f…
define a query to filter or narrow…
perform a query that specifies th…
write a query to show all points …
refine your search using a set of …
extract a sub-collection of map f…
highlight a set of map features th…
highlight the map features that …
change the temporal extent from…
change the category of crime tha…
change the variable that is mapped
change the map to show the distr…
enter in a type of food and gener…
draw a polygon and retrieve an a…
measure the distance between a …
select two cities and calculate th…
select a point to change the attri…
manipulate the attribute values o…
edit attribute fields in the Map S…
delete the selected map features
redraw a line feature in ArcMap t…
place a point to indicate the posi…
drop a symbol on the map that in…
place a marker on the approxima…
mark up the map to indicate whe…
use the annotation tools to draw …
draw a red line to mark somethin…
use the annotation editor to add …
take a picture of the map and sta…
take a snapshot of the map and t…
digitize a boundary to define the …
click and drag the route to chang…
click on points along the sample r…

Appendix E: *GeoVISTA CrimeViz* User Guide
Description of Features and Instructions for Use

E.1 Overview of *GeoVISTA CrimeViz*

GeoVISTA CrimeViz is a web-based mapping application supporting exploration, analysis, and sensemaking of criminal activity in space and time. A user-centered approach was taken to transition the *GeoVISTA CrimeViz* concept for use by the Harrisburg Bureau of Police (HBP). Utilizing a suite of geovisual analytics tools, analysts and officers at the HBP can identify complex spatiotemporal patterns of crime, allowing them to unlock important insights about the nature of criminal activity within the city. This guide provides an overview of the current features and functionality of the *GeoVISTA CrimeViz* application as tailored to support the needs of HBP.

GeoVISTA CrimeViz includes three primary panels (**Figure E.1**): (1) a central, interactive map with basic Google Maps web service controls for spatial exploration, analysis, and sensemaking; (2) a set of filtering controls on UCR code and MO along with a series of togglable contextual map layers for attribute exploration, analysis, and sensemaking; and (3) an interactive temporal histogram combined with a suite of temporal animation, filtering, and reexpression controls for temporal exploration, analysis and sensemaking. Discussion is organized according to these three panels.

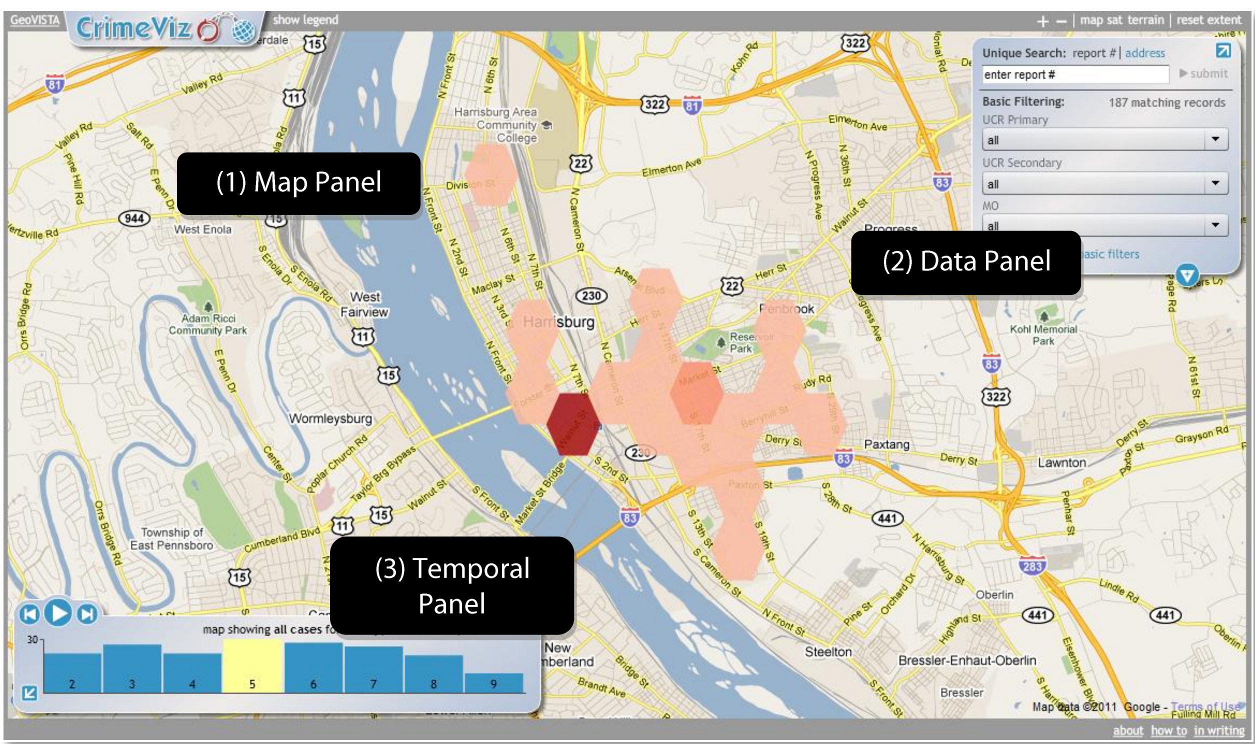


Figure E.1: The *GeoVISTA CrimeViz* application (http://www.geovista.psu.edu/CrimeViz/)

E.2 The Map Panel

The Google Maps web mapping service capabilities are integrated into the central Map Panel using the Google Maps API. The other control panels sit on top of the map and can be minimized to provide maximum area for visual analysis of patterns in the map.

E.2.1 Map Navigation and Basemap Style

GeoVISTA CrimeViz provides controls in the top-right frame to manipulate the portion of the map that is shown as well as the basemap depiction (**Figure E.2**). The analyst can zoom the map (i.e., change the scale) to show more or less detail in the basemap using the 'plus' and 'minus' controls. Three base map depictions are provided: (1) a traditional vector map that shows primarily municipal infrastructure (e.g., roads, government buildings, businesses, recreational areas), (2) a satellite image, and (3) a terrain representation (i.e., a topographic map). The 'reset extent' button resets the map to the initial zoom level and re-centers it over Harrisburg.

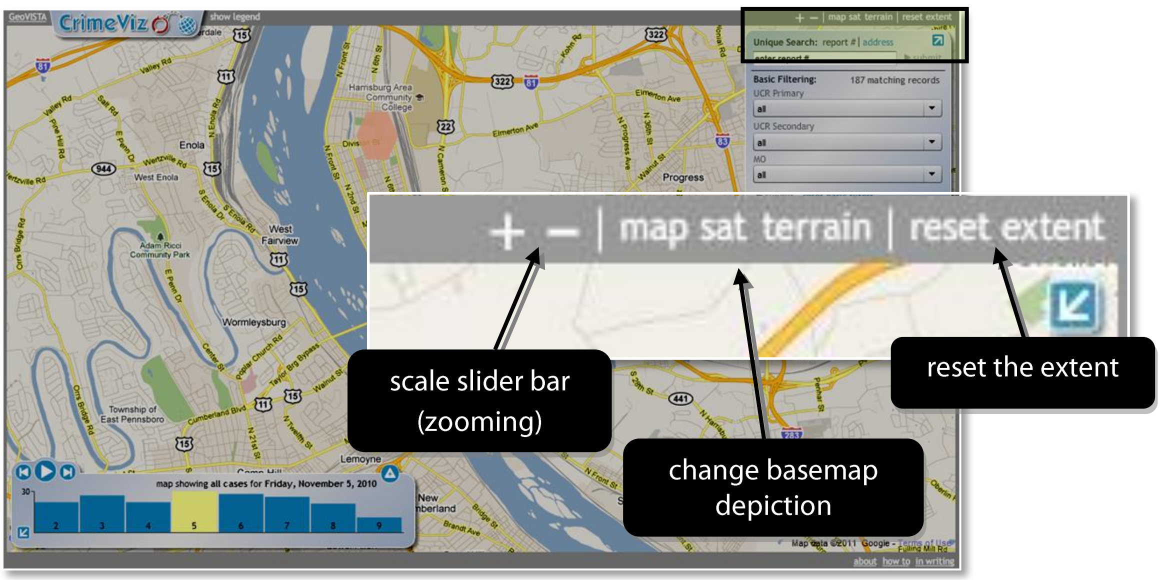


Figure E.2: Interface controls for manipulating the map scale and map depiction.

The analyst can pan the map (i.e., change the map centering) by directly grabbing and dragging the map itself (press and hold the left mouse button to grab the map and drag to reposition). Double-clicking the left-mouse button both pans and zooms to the clicked location.

E.2.2 Hexagon Overview

Upon entering the application, *GeoVISTA CrimeViz* provides a 'hot spot' overview of the crime incidents aggregated to a hexagonal grid. Hexagons are colored based on the frequency of crime incidents occurring within the hexagonal bounds, with the darker red indicating more crimes. A hexagon is not shown if the region does not contain any crimes, allowing the analyst to discriminate spatial clusters of crime easily. Moving the cursor over a hexagon reveals how many crimes have been reported in that region (**Figure E.3**).

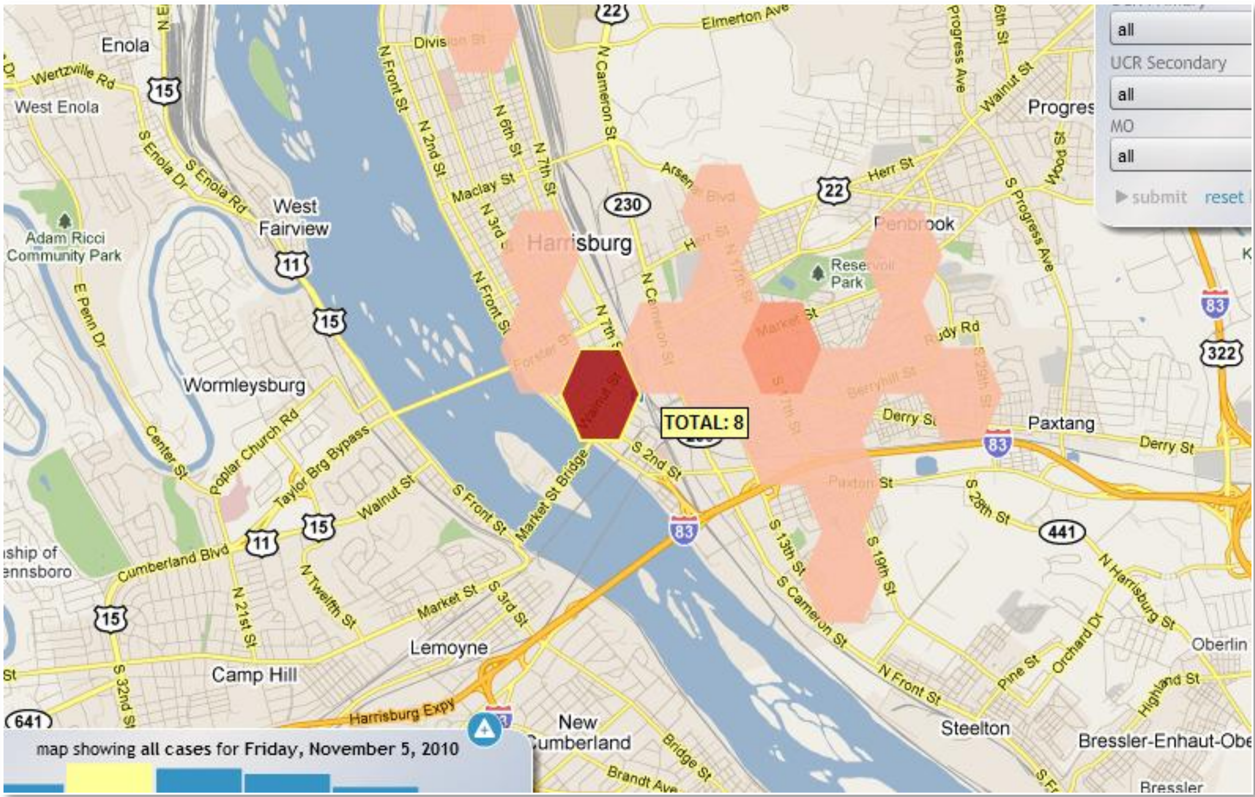


Figure E.3: Mousing over a hexagon retrieves the frequency of crime incidents within its bounds. Clicking on the hexagon zooms to its extent, showing a detailed point view.

E.2.3 Point Details View

Clicking on a hexagon zooms in to its extent to show a details view of each individual crime location. The analyst can return to the overview by zooming out to a larger extent using the 'minus' or 'reset extent' tools described above. In the details viewing mode, individual crimes are shown as points. Each point is labeled with the two-digit primary UCR (universal crime report) code associated with that incident type and colored to differentiate among broader categories of criminal activity; violent crimes are shown in red, property crimes are shown in green, vice crimes are shown in blue, accidents are shown in purple, and other crimes (e.g., ordinance violations) are shown in grey.

Clicking on a crime incident point opens an information window containing details about the case record, including the case number, date, district, description, and address (**Figure E.4a**). The analyst can then open Google Street View to investigate the location near the crime (**Figure E.4b**—available in Firefox and Google Chrome only). To exit the Street View, click the "x" in the lower-right corner.

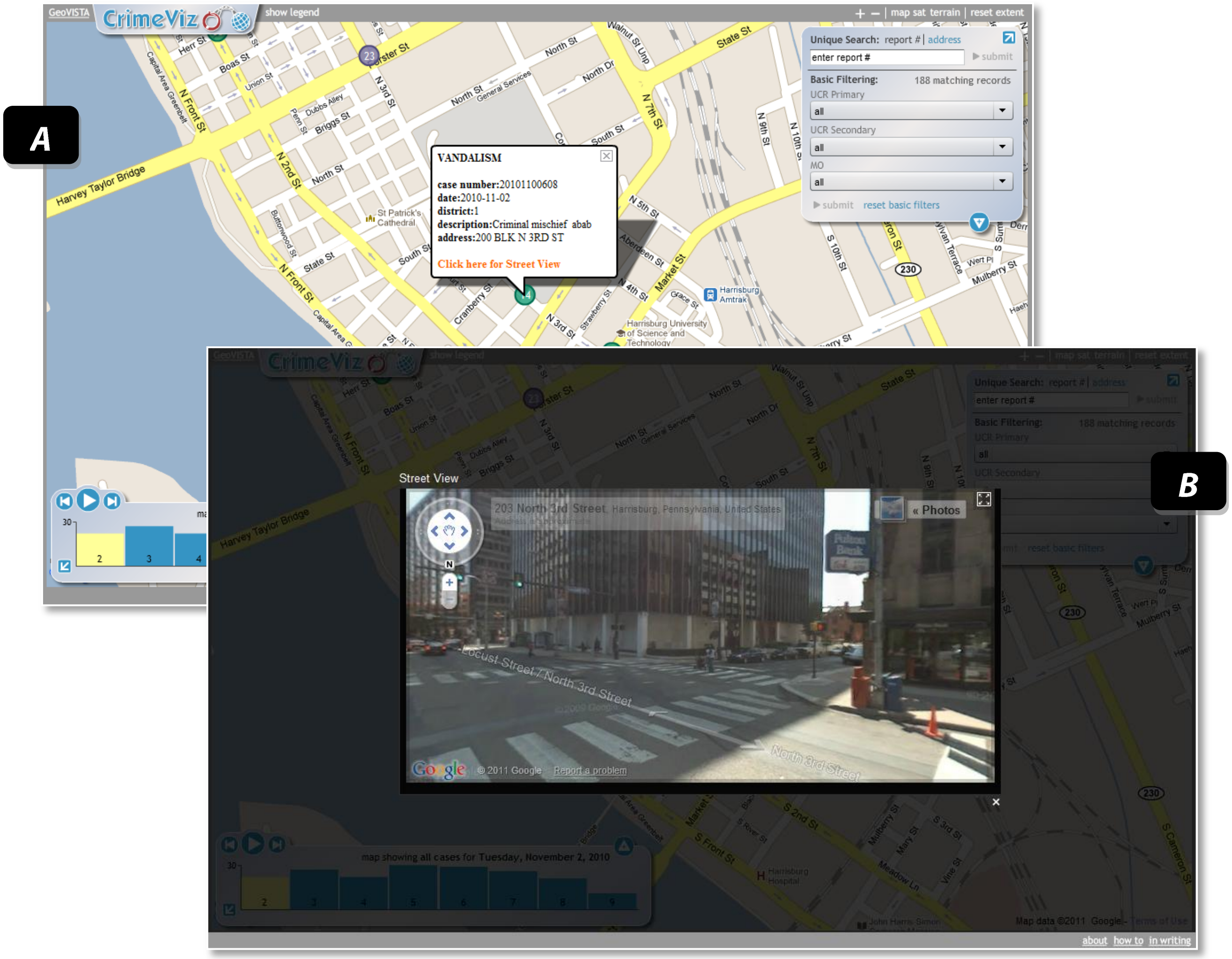


Figure E.4: (a) Select a point to retrieve details about the crime incident. **(b)** Activate and interact with the Google Street View image showing the location of the crime.

E.2.4 Map Legend

Clicking on the 'show legend' button in the upper-left corner expands the legend to aid interpretation of the map symbols (**Figure E.5**). The top of the legend shows the value for the color of the hexagons in the overview, while the bottom of the legend shows the meaning of the color coding in the detailed points view. The legend can be collapsed by clicking either the "show legend" button or by clicking the arrow in the upper-right corner

Figure E.5: The map legend.

E.3 The Data Panel

The Data Panel (**Figure E.6**) is located in the upper-right corner of the application. This panel is used to search the database for specific entries or locations, to filter the data shown in the display, and to toggle on contextual map layers. To collapse this panel and view more of the map, click the arrow in the upper-right corner.

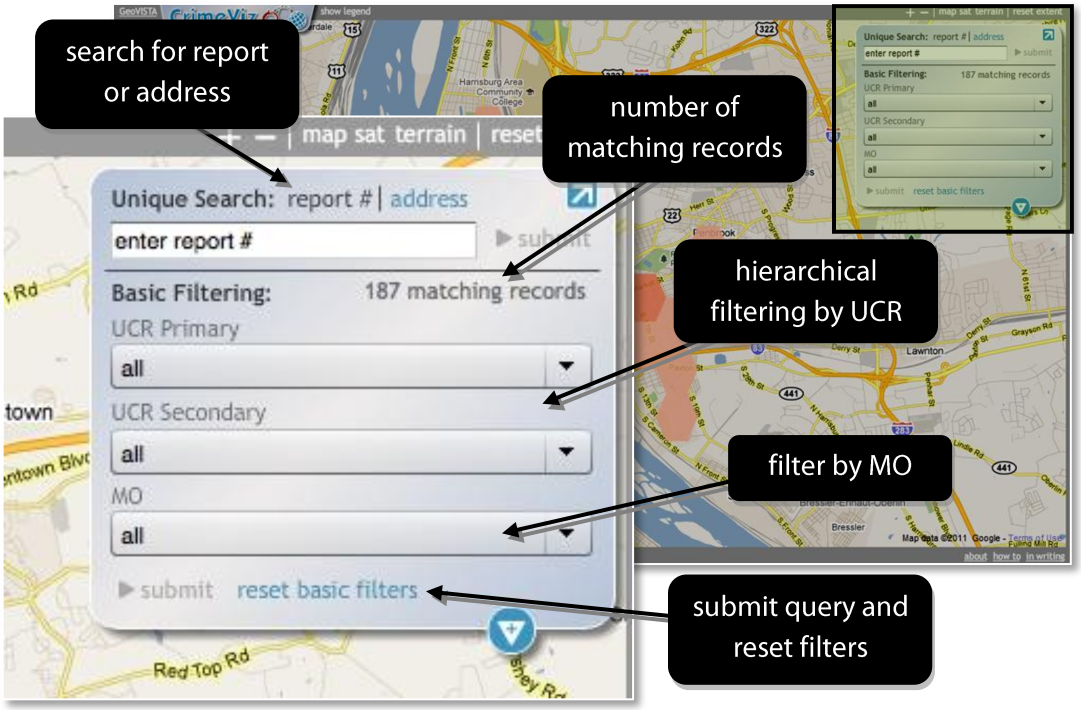


Figure E.6: The Data Panel includes controls to search for specific cases or locations and to filter the overall set of records by UCR code or MO.

E.3.1 Address and ID Unique Search

The 'Unique Search' box is located at the top of the Data Panel. Using the pair of toggle buttons, the analyst can specify a unique search either by an eleven-digit report number or by an address within the city. If a matching record or address is found, the map is zoomed and panned to that location; in the case of a matching report number, the information window also is activated. Once the analyst has entered in a report number or address into the text box, the 'submit' button activates to allow initiation of the search query.

E.3.2 UCR Filtering Menus

Below the 'Unique Search' controls are the 'Basic Filtering' controls. These controls allow filtering by UCR code and *modus operandi* (MO) using a series of drop-down menus. Individual crime incidents are organized according to a four-digit UCR code, the first two digits indicating the crime type and the second two digits indicating a discriminating condition within that crime type; these two components are split into two menus for hierarchical searching ('UCR Primary' and 'UCR Secondary' respectively). Selection of a crime type in the 'UCR Primary' menu updates the options in the 'UCR Secondary' and also updates the third 'MO' menu, or a listing of the possible methods for committing the selected crime type.

If there is no primary UCR code selected, then all possible options can be selected from the 'UCR Secondary' and 'MO' menus; such selections then update the 'UCR Primary' to indicate the crime type associated with the analyst's selection. Once the analyst has changed a filtering parameter, the 'submit' button activates to allow initiation of the filtering query. The 'matching records' text indicates the number of incidents that match the filtering parameters. The analyst can reset the basic filtering parameters using the 'reset basic filters' button (i.e., "show all").

E.3.3 Advanced Filtering

Clicking on the 'expand' tab (i.e., the circular button with the expansion triangle) at the bottom of the Data Panel expands or collapses the Advanced Data Panel (**Figure E.7**). The 'Advanced Filtering' controls are located at the top of the panel. These tools allow filtering by police district, by police grid, or by a keyword or phrase (i.e., the 'any field contains' button). Once the analyst has changed an advanced filtering parameter, the 'submit' button activates to allow initiation of the advanced filtering query. When enabled, the 'Maintain Basic' option restricts the query to the parameters used in the Basic Filtering section. The analyst can reset the advanced filtering parameters using the 'reset basic filters' button (i.e., "show all").

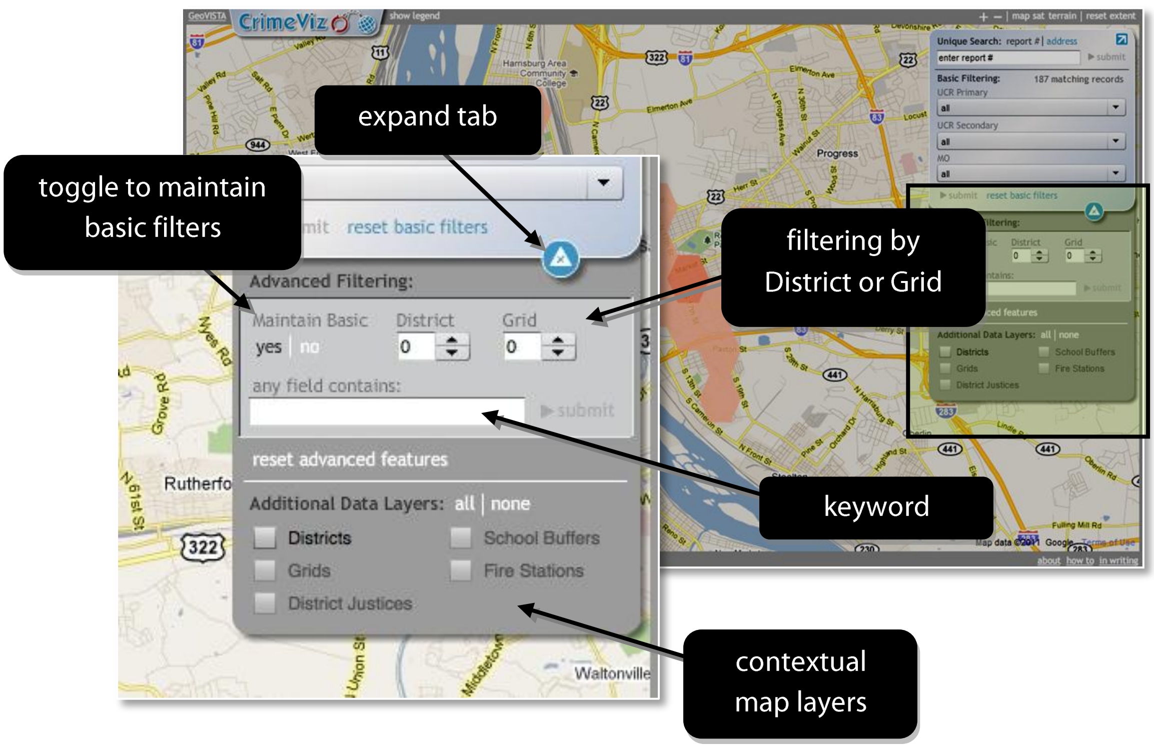


Figure E.7: The Advanced Data Panel includes additional filtering controls as well as contextual map layers to aid map interpretation.

E.3.4 Context Layer Toggles

Below the 'Advanced Filtering' tools are options to show 'Additional Data Layers', or contextual information to support interpretation of map patterns. These check boxes toggle on or off layers that give contextual information about Harrisburg (e.g., police district, police grid, or justice jurisdiction boundaries as well as school and fire locations).

E.4 The Temporal Panel

The Temporal Panel is found in the lower-left corner of the application (**Figure E.8**). This panel houses a robust set of tools for examining temporal patterns of criminal activity. Like the Data Panel, the Temporal Panel can be minimized using the arrow in the lower-left corner.

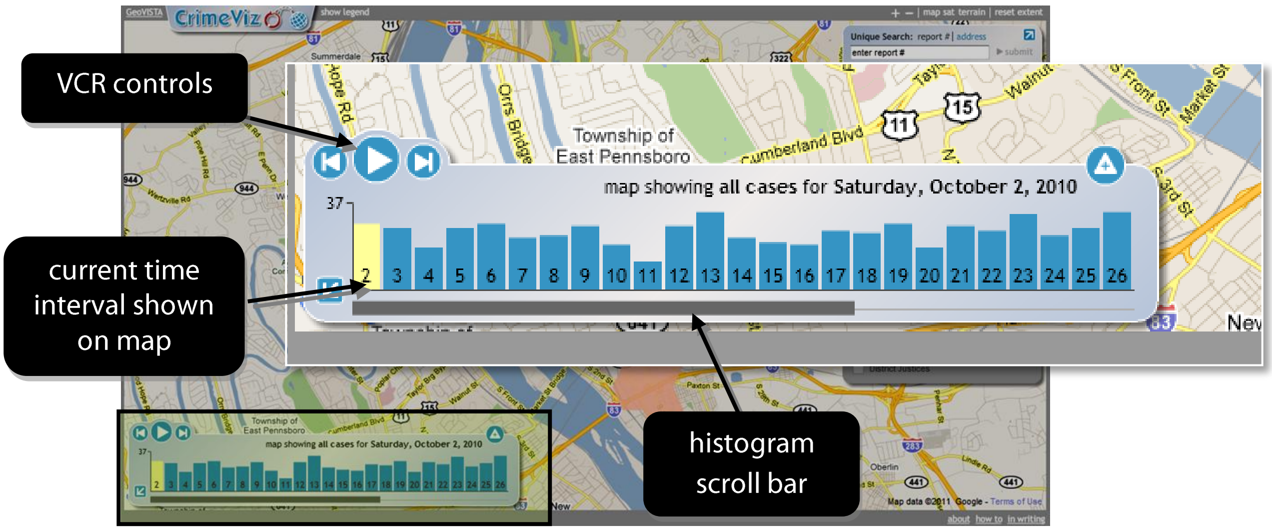


Figure E.8: The Temporal Panel includes an interactive histogram that doubles as a temporal legend as well as VCR animation controls.

E.4.1 Histogram

The primary temporal exploration tool is the interactive histogram. Crime incidents are aggregated according to regular time intervals, or bins, with the height of the bin indicating the frequency of crimes within that time period. The default view shows the frequency of crime incidents per day for the past seven days. The map view shows the spatial distribution of the crime incidents within the currently selected bin (in yellow); analysts can advance the map to a different time interval by clicking on a different bin. An information window indicating the frequency of crime incidents is provided when mousing over an individual bin. When the filtering and reexpression parameters produce a large number of bins, a scroll bar is added to the bottom of the histogram to allow viewing across all bins; the scroll bar is sized to indicate the portion of the histogram that is currently showing.

E.4.2 Animation Controls

Change in crime patterns over time can be explored further by using the map animation features of *GeoVISTA CrimeViz*. Above the histogram is a set of VCR-like animation controls. Pressing the play button begins a looped map animation, showing each bin or time interval in sequence. Pressing the forward or backward button stops any looped playback and move the next bin in the direction indicated by the button.

E.4.3 Sequencing Method and Binning Unit

Clicking on the 'expand' tab in the upper-right corner of the Temporal Panel expands or collapses the Advanced Temporal Panel (**Figure E.9**). At the top of the Advanced Temporal Panel are two menus for reexpressing the temporal histogram (i.e., changing the way in which the crime incidents are organized into temporal bins): the 'Sequencing Method' and the 'Binning Unit'.

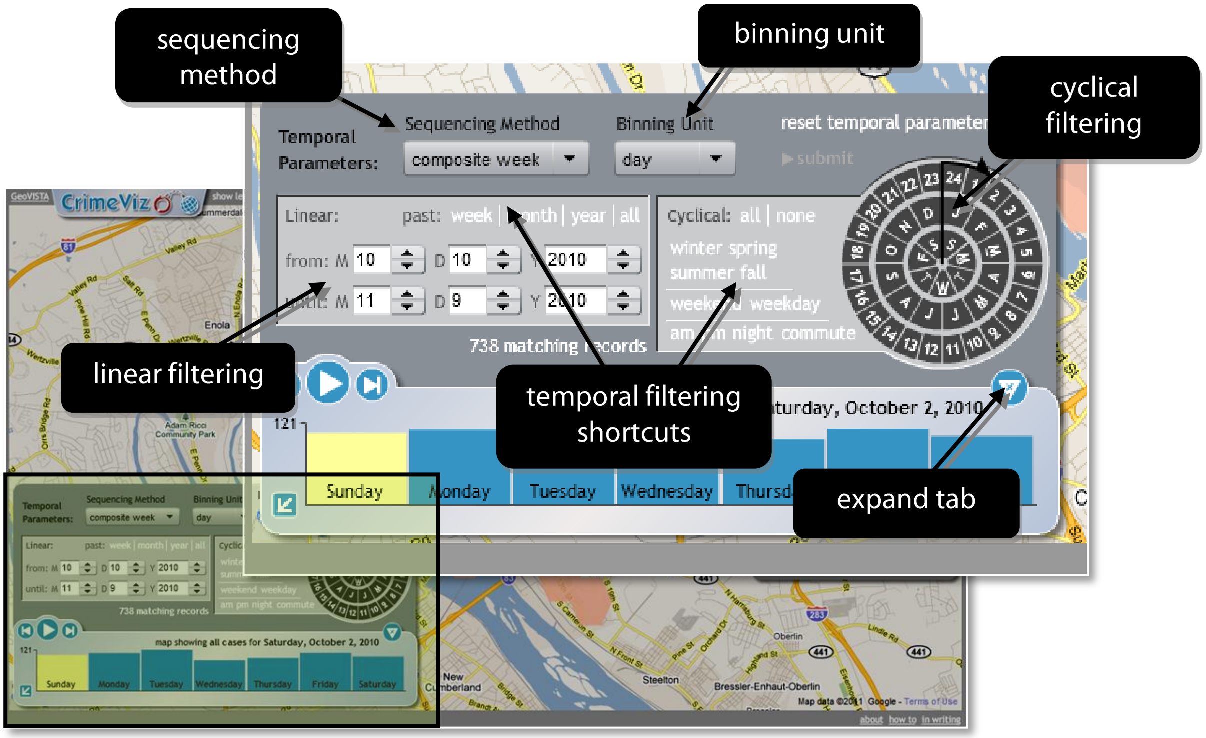


Figure E.9: The Advanced Temporal Panel includes an interactive histogram that double as a temporal legend and VCR animation controls.

The 'Sequencing Method' defines the manner in which the histogram is constructed. The default is a 'linear timeline', or a view of the first time interval bin to the last in succession. For example, a linear timeline binned by day across 14 days of criminal activity would result in 14 histogram bins.

In contrast, the composite options create an average year, month, week, or day to facilitate interpretation of cyclical or recurring patterns. For example, a composite week binned by day across 14 days would result in only seven bins, the first showing the total for both Sundays, the second showing the total for both Mondays, and so on.

The 'Binning Unit' option defines the granularity level of the temporal unit for the bins in the histogram. Depending on the 'Sequencing Method' type, the binning unit can range from an hour to year.

E.4.4 Linear Temporal Filtering

Below the reexpression controls are the 'Linear' temporal filtering controls, which allow the analysts to set the start and end date of the histogram (i.e., the temporal extent or the range of time under examination) using a set of numerical stepping widgets. Shortcuts are provided that update the linear filtering parameters to include the past week, month, year, and all records.

E.4.5 Cyclical Temporal Filtering

To the right of the 'Linear' temporal filtering controls are the 'Cyclical' filtering controls, which allow the analyst to isolate subsets of records within yearly, monthly, weekly, or daily cycles. Cyclical filtering is provided through a 'time wheel' widget, which includes three concentric rings providing filtering by day of the week, month of the year, and hour of the day (from inner-most to outer-most). Shortcuts for season, weekday or weekend, and time of day are supplied for convenience.

Once the analyst has changed a temporal reexpression or filtering parameter, the 'submit' button activates to allow initiation of the query. The 'matching records' text indicates the number of incidents that match the filtering parameters (this is the same value as in the Data Panel). The analyst can reset the basic filtering parameters using the 'reset basic temporal filters' button (i.e., "show all").

E.5 About *GeoVISTA CrimeViz*

For more information about the *GeoVISTA CrimeViz* application, please visit: http://www.geovista.psu.edu/CrimeViz/

GeoVISTA CrimeViz is a product of the Penn State GeoVISTA Center. This material is based upon work supported by the U.S. Department of Homeland Security's VACCINE Center under Award number 2009-ST-061-CI001.

Project Contacts

Alan M. MacEachren | maceachren@psu.edu
Robert E. Roth | reroth@wisc.edu

Project Contributors

Benjamin G. Finch
Wei Luo
Craig A. McCabe
Ryan S. Mullins
Kevin R. Ross
Camilla Robinson

Appendix F: Cartographic Interaction Study Protocol
Protocol for Interaction Study with *GeoVISTA CrimeViz*

F.1 Introduction

You have agreed to participate in an interaction study evaluating a spatiotemporal (i.e., space+time) crime mapping application called *GeoVISTA CrimeViz* developed at the Penn State GeoVISTA Center as part of the Visual Analytics for Command, Control, and Interoperability Environments project (i.e., VACCINE). For the past 18 months, researchers at the Penn State GeoVISTA Center have been working closely with personnel at the Harrisburg Bureau of Police to transition the interface for use by HBP. Today, you will participate in an evaluation of *CrimeViz*, which has the dual goals of improving the usability and utility of the interface for use at HBP as well as generating insights into how such spatiotemporal mapping tools are used in support of crime analysis.

The cartographic interaction study will proceed in three sections. The first section includes a demonstration and opening exploration period with *CrimeViz* to clarify what it can do and how it works. The demonstration provides an overview of the spatiotemporal crime mapping features included in *CrimeViz*, particularly those added since the last Penn State visit to the Harrisburg Bureau of Police. Following the demonstration, you will be allowed to explore *CrimeViz* on your own. During the demonstration and opening exploration, please feel free to ask any questions about the features included in *CrimeViz* and their application in support of crime analysis. This initial introduction to the tools is scheduled to last approximately 15 minutes, although please feel free to ask questions until you are comfortable using the interface.

Following the initial training, you will asked to answer 15 questions (i.e., accomplish 15 objectives) using *CrimeViz*. Your interactions with the interface will be recorded using screen recording software and your verbalizations will be recorded using the computer microphone and backup voice recorders; this information will remain anonymous and your performance will not be communicated to your supervisors; the objective of the study is to evaluate the software, not to measure your performance. Additional instructions for answering the questions will be provided directly before questioning; the questioning section is scheduled to last no more than 45 minutes. Finally, following the formal portion of the study, you will be asked to complete a short survey to collect your opinions of and reactions to *CrimeViz*; the survey will take approximately five minutes to complete.

Do you have any questions before we begin?

F.2 Demonstration and Opening Exploration

To begin, you will be provided a demonstration of *GeoVISTA CrimeViz*. As previously introduced, the demonstration provides an overview of the spatiotemporal crime mapping features included in *CrimeViz*, particularly those added since the last Penn State visit to the Harrisburg Bureau of Police. Please feel free to interrupt the demonstration to ask questions about the features included in *CrimeViz* and their application in support of crime analysis.

<demonstration>

Now that the demonstration is complete, please take several minutes to explore the application on your own. In particular, explore the new features that have been added—or that only now are fully functional—since the last time you used *CrimeViz*. Again, please feel free to ask any questions about the features included in *CrimeViz* and how to apply these features in support of crime analysis.

Do you have any final questions about *CrimeViz* before we begin the formal interaction evaluation?

F.3 Objectives

In the following, you will be asked a set of fifteen questions that are representative of the kinds of spatiotemporal objectives law enforcement personnel may attempt to accomplish with *CrimeViz*. So that I could determine correct answers for the questions, this version of the system only includes incident records through November 9th. In the following, I first will read the question aloud and then hand you a print of the question for your reference. You will be allowed a limit of three minutes to complete each task to ensure that you complete the set of 15 tasks in 45 minutes or less.

Both of our screens display the same browser and we both have control over *CrimeViz*. After I read a question, you will be given control of *CrimeViz*. Please feel free to take whatever strategy to interacting with the map to answer the question that you deem appropriate. After you answer a question, or after the three minute time limit has expired, I will take control over *CrimeViz* and refresh the browser to 'reset' the map to the entry state; in the event you reach the three minute limit, I will provide you an opportunity to take a best guess before refreshing the browser. I also will take control of *CrimeViz* in the event that you run into a fatal bug while using it, at which point I again will reset the map and we will proceed to a new question.

As you are interacting with *CrimeViz*, please try to limit your verbalizations in order to concentrate on the task. I will not be able to answer any questions about *CrimeViz* during this portion of the evaluation. Once you believe you have found your answer, please state it out loud. Your interactions with the interface will be recorded using screen recording software and your verbalized answers will be recorded using the computer microphone and backup voice recorders. This information will remain anonymous and your performance will not be communicated to your supervisors. Please do your best to answer the questions, as there is a 'correct' answer for each question. Again, the purpose of this study is to evaluate the *CrimeViz* interface and not your ability to use crime mapping software; we may glean as many insights from incorrect answers as correct ones.

Are you ready for the first question?

F.3.1 *Identify*

1. On what street did incident #20101100945 occur? (*space-alone*) (A: Market Street)
2. What type of crime (by UCR code) is incident #20101100894, which occurred at 200 Herr Street? (*attributes-in-space*) (A: 06-Theft)
3. How many total crime incidents occurred in District #5 on September 1st, 2010? (*space-in-time*) (A: 7)

F.3.2 *Compare*

4. Are Fire Station #2 and Fire Station #8 in the same police district? (*space-alone*) (A: yes)

5. Is incident #20101100945, which occurred on Market Street, the same type of crime (by UCR) as incident #20101100608, which occurred on 3rd Street? (*attributes-in-space*) (A: no)

6. In October 2010, how many more crime incidents occurred within Harrisburg on Sundays compared to Mondays? (*space-in-time*) (A: 26)

F.3.3 *Rank*

7. What school in Harrisburg is closest to Interstate-83? (*space-alone*) (A: Sylvan Heights Science Charter School)

8. Which crime type (by UCR code) was the most common in District #1 on November 5th, 2010? (*attributes-in-space*) (A: 23-Drunkenness)

9. From 2006 through 2010 (i.e., the complete time span), which month exhibited the highest frequency of crime incidents across Harrisburg? (A: March)

F.3.4 *Associate*

10. Which route should Harrisburg citizens take to get to the west bank of the Susquehanna River during an evacuation related to Three Mile Island? (*space-alone*) (A: I-81 bridge)

11. From 2006 through 2010 (i.e., the complete time span), is the geographic pattern of prostitution (16) related to the geographic pattern of sex offenses (17)? (*attributes-in-space*) (A: no)

12. From 2006 through 2010 (i.e., the complete time span), does the trend in crime increase or decrease across Harrisburg from noon (12:00) to midnight (24:00)? (*space-in-time*) (A: decrease)

F.3.5 *Delineate*

13. Which police districts exhibit clusters of increased criminal activity from 2006 through 2010 (i.e., the complete time span)? (*space-alone*) (A: District #1 & District #5)

14. From 2006 through 2010 (i.e., the complete time span), how many different ways (i.e., how many different MOs) was fraud (11) committed across Harrisburg? (*attributes-in-space*) (A: 7)

15. The 2008 spike in robbery (03) incidents in Harrisburg spanned across which months? (*space-in-time*) (A: September and October)

Glossary

3 O's**:** see *three O's*

3 P's**:** see *three P's*

5 W's**:** see *five W's*

6 fundamental questions**:** see *six fundamental questions*

ability**:** the mental or physical limitations of the user

action list**:** a list of usability and utility issues of a cartographic interface that need to be revised before deployment

action research**:** describes a form of field study in which the researcher plays an active role in improving practice, rather than simply observing and recording it

adaptive cartography**:** the provision of cartographic representations and cartographic interfaces that are customized according to the use and user context

affinity diagramming**:** a method for building consensus about cognitive structures that requires a group of participants to categorize a universe of instances according to similarity

affordances**:** signals within the cartographic interface provided to the user about how to interact with the interface

agreement**:** see *card-by-card agreement*

analog cartography**:** the complement to digital cartography that includes any non-digital paper/printed map or any non-digital georeferenced photograph

analysis**:** see *swoopy diagram*

analytic primacy**:** focus during interface design and development on how the interface will support user needs (i.e., the objectives)

annotate**:** see *enabling operator*

arrange**:** see *operator*

art**:** a way of knowing through aesthetics and emotion

associate**:** see *objective*

attributes-in-space**:** see *operand*

average user**:** the mean perceptual and cognitive abilities of humans, used as a benchmark to prescribe optimal cartographic representations

blind-sequencer**:** a persona indicating interaction behavior in which application of the *sequence* operator results in user confusion

brushing**:** a two-step process in which the direct manipulation interface style is used to select one or more map features of interest, with an cartographic interaction operator then applied to this selected map feature or set of map features

calculate**:** see *operator*

cards**:** a single instance (comprising physical objects, textual explanations, and/or graphics/images) from a larger universe included in a card sorting study

card-by-card agreement**:** the percentage of participants that rated a given pair of instances as members of the same group

card-by-card agreement matrix**:** a representation of card-by-card agreement that uses the card order produced from hierarchical clustering for both axes in a two-dimensional table and indicates the card-by-card agreement score for each cell in the matrix, with the cells often colored according to the score

card sorting**:** a method for eliciting cognitive structures that requires participants to organize a set of instances (i.e., cards) into internally-homogenous groupings (i.e., categories) based on similarity along an identified sorting principle (i.e., the sorting criterion)

> **1.** ***generative sorting*****:** the use of the card sorting method to reveal the most appropriate sorting criterion, a logical set of categories, and additional cards to add to the universe
>
> **2.** ***evaluative sorting*****:** the use of the card sorting method to provide feedback about an *a priori* sorting criterion, set of categories, or universe of cards
>
> **3.** ***open sorting*****:** the least constrained variant of card sorting in which participants identify both the sorting criterion and the set of categories during the sort
>
> **4.** ***closed sorting*****:** the most constrained variant of card sorting in which participants are given a predetermined sorting criterion and set of categories to use during the sort
>
> **5.** ***guided sorting*****:** a variant of card sorting in which participants are given a predetermined sorting criterion to use during the sort, but are allowed to create their own categories

Cartography**:** the art, science, and ethics of mapmaking and map use

Cartography^3**:** a framework built atop the *swoopy diagram* that summarizes all possible map uses according to three axes: (1) revealing unknown insights versus presenting, (2) private map use versus public map use, and (3) high versus low human-map interaction

cartographic animation**:** display of individual maps in rapid succession

cartographic interaction**:** the dialogue between a human and a map through a computing device

cartographic interaction study**:** see *interaction study*

cartographic interface**:** the digital tool through which the cartographic interaction occurs

cartographic perspectives**:** views on the future of Cartography as an area of scientific inquiry

> **1.** ***death*****:** a perspective on Cartography that foresees its undisciplining, with the ability to make maps returned to all spatially-minded individuals

2. ***rebirth*****:** a perspective on Cartography that foresees its reinvention, with academic cartographers resolving or discarding old research topics to make room for new ones

3. ***division*****:** a perspective on Cartography that foresees its apportionment, with Cartography continuing with its traditional research topics and leaving emerging topics to other, related disciplines

4. ***growth*****:** a perspective on Cartography that foresees the integration of emerging research topics on digital cartography with the traditional cartographic research topics

cartographic problematic**:** when abstracting reality (and one's knowledge of reality) to make a cartographic representation understandable and useful, uncertainty is introduced into the cartographic representation

cartographic representation**:** the graphics, sounds, haptics, etc., constituting a map that are employed to encode geographic information

Cartographic Revolution**:** the period of transition from primarily analog mapping and research on cartographic representation to primarily digital mapping and research on both cartographic representation and cartographic interaction

cascading information-to-interface ratio**:** an interface that has multiple levels of interface complexity, with each level increasing the amount and freedom of provided cartographic interactions, without increasing the amount of underlying information in the cartographic representation (e.g., 'regular' versus 'export' mode)

category**:** an internally-homogenous group of instances that is conceptually different from other categories

closed sorting**:** see *card sorting*

cognitive operation**:** see *operational task taxonomy*

command language**:** see *interface style*

communication model**:** a dominant perspective in Twentieth Century Cartography that views the map as a conduit through which a message can be passed from the mapmaker to the map user

compare**:** see *objective*

competitive analysis**:** the critical comparison of existing interfaces that provide similar functionality to the proposed interface

concept mapping**:** a method for eliciting cognitive structures that requires participants to arrange a universe of instances into a comprehensive relational structure, often grouping instances according to more abstract ideas or themes

confirmation**:** see *swoopy diagram*

constraint: a reduction to the number of cartographic interactions and/or the degree of freedom available for performing each cartographic interaction

coordinated, multi-view visualization(CMV)**:** a class of interactive systems that allow the user to create multiple representations of the same dataset, with the operators performed upon one representation permutated to all others

crime analysis**:** the systematic collection, preparation, interpretation, and dissemination of information about criminal activity in support of the mission of law enforcement

crime mapping**:** the mapping and analysis of the spatial component of crime, which includes application of the full suite of GIScience techniques and technologies to criminology

Criminology**:** the scientific study of the causes and control of crime and delinquent behavior, with the goal of understanding criminal activity, rehabilitating convicted criminals, and improving the quality of life within a community

criterion**:** a principle for sorting the cards in a card sorting study that either is identified by the participant (in the case of an open sort) or imposed upon the participant (either guided or closed sorts)

critical incidents**:** cartographic interactions that led to either positive results (i.e., the expected result, or an unexpectedly good result) or negative results (i.e., an unexpected result, or an expectedly bad result)

cyclical temporal filtering**:** application of the *filter* operator to adjust which cyclical temporal units are included in the temporal aggregation

data provenance**:** the tracking of how the original, input dataset is manipulated across interactions

DC CrimeViz**:** a 'one-off' cartographic interface prototype developed to demonstrate the functionality included in the code library, which acted as a precursor to the fully-featured *GeoVISTA CrimeViz*

death perspective**:** see *cartographic perspectives*

delineate**:** see *objective*

dendogram**:** a representation of the results of hierarchical cluster analysis that sorts the cards one-dimensionally according to their agreement and indicates the degree of similarity between individual cards or card clusters by the length of a line extending from the card or cluster to the broader, unifying cluster

digital cartography**:** the complement to analog cartography that includes any map made and disseminated using digital computing technologies

Digital Revolution**:** the period of fast-paced innovation of computing technologies in the latter portion of the twentieth century and the associated impact of personal computing on society

direct manipulation**:** see *interface style*

discount interface evaluation**:** an approach to cartographic interface evaluation that recruits a small set of study participants to the end of quickly and cheaply improving a single cartographic interface

distributed cognition**:** a framework that supposes that externalizations can act as an extension of cognition, allowing individuals to offload cognitive processing onto such externalizations

diversity**:** range of operators in an interaction strategy

division perspective**:** see *cartographic perspectives*

dynamic cartography**:** the combination of system-based (e.g., cartographic animation, real-time information updates) and user-based (i.e., cartographic interaction) changes to a cartographic representation

edit**:** see *enabling operator*

elementary search level**:** reading and interaction with only one map feature

enabling operator**:** an operator primitive that primarily supports enabling interactions

> **1.** ***import*****:** enabling interactions that load an existing dataset or previously generated cartographic representation into the cartographic interface
>
> **2.** ***export*****:** enabling cartographic interactions that extract part or all of a generated cartographic representation, the geographic information underlying the representation, or the status of the system for future use outside of the cartographic interface
>
> **3.** ***save*****:** enabling cartographic interactions that store the generated cartographic representation, the geographic information underlying the representation, or the status of the system for future use within the cartographic interface
>
> **4.** ***edit*****:** enabling interactions that manipulate the geographic information underlying the representation, which then alters all subsequent cartographic representations of that information
>
> **5.** ***annotate*****:** enabling cartographic interactions that add graphic markings and textual notes to the cartographic representation to externalize insight generated from work interactions

enabling (inter)action: an interaction that is required to prepare for, or clean up from, work interactions

epistemology**:** the philosophy of ways of knowing

error frequency**:** the correctness of user responses to benchmark tasks

ethics**:** a way of knowing through equity and probity

ethnographic research**:** the empirical investigation of the qualities, practices, and beliefs of a community of interest

ethnography**:** a written or graphic narrative of a community's qualities, practices, and beliefs

evaluative sorting**:** see *card sorting*

excessive-filterer**:** a persona indicating interaction behavior in which the *filter* operator is unnecessarily applied as part of a routine, negatively impacting productivity

execution**:** the physical human input required to manipulate the provided cartographic interface

expertise**:** the knowledge and skills learned by the user to enhance and append one's innate abilities

exploration**:** see *swoopy diagram*

export**:** see *enabling operator*

extensiveness**:** a metric used in qualitative data analysis indicating the number of sessions in which a specific code was applied or a usability or utility issue occurred

feedback**:** signals in the cartographic interface provided to the user about what happened as a result of the interaction

filter**:** see *operator*

Fitt's law**:** a predictive model based on human motor skills of the time it takes the average user to point to a screen objective

five W's**:** the *what?*, *why?*, *when?*, *who?*, and *where?* questions that altogether determine the application context of cartographic interaction

flexibility**:** designing a cartographic interface to allow users to achieve the same objective using different cartographic interaction strategies (see *usability* for an alternative definition)

focus group**:** a user-based interface evaluation method comprising a purposeful discussion among multiple participants facilitated by a single moderator

form fill-in**:** see *interface style*

freedom**:** the number of ways in which a single cartographic interaction can be performed

frequency**:** the number of operators included in an interaction strategy

functional map design**:** the scientific generation of cartographic design guidelines based upon the perceptual and cognitive limits of the intended map user

gatekeepers**:** individuals external to the research team that aid in recruitment

general search level**:** reading and interaction with several to all map features

generative sorting**:** see *card sorting*

Geocollaboration**:** a subfield of Cartography that focuses upon the design and use of cartographic interfaces that support cooperative and collaborative activities

geographic insight**:** new understanding about the true nature of the studied geographic phenomenon or process

> **1.** ***knowledge-based insight*****:** small bits of knowledge that build upon existing knowledge
>
> **2.** ***spontaneous insight*****:** newly revealed structures that explain patterns in new and existing bits of knowledge

GeoVISTA CrimeViz**:** a web-based map application built using Adobe Flash and PostGreSQL that supports spatiotemporal exploration, analysis, and sensemaking of criminal activity

Geovisual Analytics**:** the science of analytical reasoning about geographic phenomena and processes facilitated by geovisual interfaces to geocomputational methods

Geovisualization: the private, exploratory use of highly interactive maps for the purpose of revealing unknowns

goal**:** what the user is trying to achieve, which motivates the use of geographic information and cartographic interfaces

growth perspective**:** see *cartographic perspectives*

guided sorting**:** see *card sorting*

gulf**:** a failure in communication between users and an interface during an interaction exchange

> **1. *gulf of execution*:** the disconnect between the user's objectives and the provided cartographic interaction operators
>
> **2. *gulf of evaluation*:** the disconnect between what the user expected to accomplish through the cartographic interaction and the interface's representation of the result of the cartographic interaction

hierarchical clustering**:** a technique that builds a nested hierarchy of clusters in which smaller, more homogenous clusters are incrementally combined to form larger, less heterogeneous clusters based on similarity

how?**:** see *six fundamental questions*

humanistic viewpoint**:** a viewpoint that considers the unique conditions that contextualize truths

idealist viewpoint**:** a viewpoint that searches for generalized truths

identify**:** see *objective*

import**:** see *enabling operator*

inefficiency**:** a situation in which the user is presented with flexibility in the way in which a task can be completed, but chooses a suboptimal approach

Information Age**:** the current period directly following the Digital Revolution in which emerging digital technologies are leveraged to make unprecedented volumes of information available and usable

information visualization pipeline**:** the linear sequence of computational transformations from raw data through onscreen rendering

insight**:** see *geographic insight*

intelligent visualization**:** an expert system that leverages the cartographic and domain knowledge that otherwise may be available only as training and help materials to present only context-appropriate representation and interaction solutions

interacting-with**:** see *pattern-matching model*

interaction**:** see *cartographic interaction*

interaction exchange**:** a unique question and answer sequence completed during the cartographic interaction conversation

interaction log**:** a document listing every interaction operator employed during an experiment or real-world interaction session, along with a timestamp

interaction primitives**:** the fundamental kinds or types of cartographic interactions that altogether constitute an interaction session

interaction strategy**:** the sequence of cartographic interaction operators performed to achieve a cartographic interaction objective

interaction study**:** a user-based interface evaluation method that requires participants to complete a set of benchmark tasks with the interface in a controlled setting while their interactions are captured in an interaction log

Interactive Cartography: provision of cartographic interaction primarily for the purpose of communication or presentation of geographic information (e.g., digital atlases, interactive news maps, web-based campus maps, and many map mashups)

interface**:** see *cartographic interface*

interface-centered perspective**:** an emphasis on the cartographic interface component of the cartographic interaction conversation, particularly focusing on upon constraining the available interactions to prevent suboptimal cartographic interaction strategies

interface complexity**:** the combination of the number of cartographic interactions implemented in a cartographic interface and the freedom in performing each provided interaction

interface design**:** the graphics, sounds, haptics, etc., that constitute the interface widget and its feedback mechanism, producing its 'look and feel'

interface evaluation**:** the collection of input and feedback about the requisite level of utility and potential issues with usability of a cartographic interface, ideally, although not necessarily, from a representative set of targeted end users

interface style**:** the way in which user input is submitted to the software to perform the cartographic interaction operator

> **1.** ***direct manipulation*****:** an interface style that relies on the use of pointing devices to probe, drag, and adjust the graphics constituting an interface design
>
> **2.** ***menu selection*****:** an interface style that presents a list of items from which the user may select one or several
>
> **3.** ***form fill-in*****:** an interface style that allows the user to key in a set of characters that indicates the desired parameters for a single interaction
>
> **4.** ***command language*****:** an interface style that allows the user to specify a series of interactions using a powerful syntax of variables and functions
>
> **5.** ***natural language*****:** an interface style that mimics verbal communication between two humans, using complex ontologies and syntax rules to disambiguate user input in order to determine the desired interaction

interview**:** a user-based interface evaluation method comprising a purposeful discussion between a single participant and a single moderator

> **1.** ***structured interview*****:** an interview questioning protocol that comprises a series of focused questions that prompt short and equally focused responses

2. *unstructured interview*: an interview questioning protocol that comprises a set of broad discussion topics or general themes that prompt longer, open-ended responses that vary greatly from person to person

3. *semi-structured interview*: an interview questioning protocol that starts with a set of focused questions, but allows the interviewer to ask probe questions

***knowledge-based insight*:** see *geographic insight*

***linear temporal filtering*:** application of the *filter* operator to adjust the temporal extent or range of the temporal histogram and associated cartographic animation

***linking*:** application of the same cartographic interaction operator applied to a map feature or set of map features in one view to the associated data item or data items in other isomorphic views

***location-based services*:** services, and the interfaces implementing these services, that leverage GPS technology to update the cartographic representation with information that is tailored to the user's current location

***lorem ipsum map*:** the use of a generic interface design and default cartographic styling that improperly relates to the mapped geographic phenomena

***lost-browser*:** a persona indicating interaction behavior in which the *zoom* and *pan* operators are applied in rapid succession

***magic square*:** the optimal visual isomorph to the Number Scramble card game, which represents the nine possible cards (ace through nine) in a three-by-three spatial arrangement in which all rows add to the desired score of 15

mapmaker: the individual designing and developing the cartographic representation and cartographic interaction

***map brewer*:** a cartographic design support system that recommends a subset of appropriate cartographic representation or interaction design solutions based upon expert knowledge, allowing the user then to select their preferred choice from the subset

***map browsing*:** the combination of the *pan* and *zoom* operators

***map mashup*:** the synergistic combination of geographic information feeds and web mapping services provided through application programming interfaces (APIs) to produce a new cartographic interface

***map user*:** the individual employing the cartographic representation and cartographic interaction in support of his or her goals and objectives

***margin coding*:** the marking of a unitized transcript using an established coding scheme

***matrix*:** see *card-by-card agreement matrix*

***memorability*:** see *usability*

***menu selection*:** see *interface style*

***mistaken-reexpresser*:** a persona indicating interaction behavior in which the *reexpress* operator is applied to generate an inappropriate visual isomorph

***modus operandi (MO)*:** the method of committing a crime

***motivation*:** the desire one has to use the cartographic interface either out of necessity (i.e., to complete a work task) or out of interest (e.g., curiosity, entertainment, popularity, recommendation)

***multi-dimensional, in-depth, long-term case study (MILC)*:** an approach to user-based interface evaluation that requires evaluators to work closely with users over a period of years to evaluate and refine an interface iteratively

***multi-layered interface*:** an interface design strategy for bridging the expert-novice divide that recommends provision of a cascading information-to-interface ratio

***natural language*:** see *interface style*

***objective*:** the user's intention in using the interface, or the task that user wishes to complete during the given cartographic interaction exchange

> **1. *identify*:** cartographic interactions that are performed to examine and understand a single map feature
>
> **2. *compare*:** cartographic interactions that are performed to determine the similarities and differences between two or more map features
>
> **3. *rank*:** cartographic interactions that are performed to determine the order or relative position of two or more map features
>
> **4. *associate*:** cartographic interactions that are performed to determine the relationship between two or more map features
>
> **5. *delineate*:** cartographic interactions that are performed to organize map features into a logical structure

***objective-based approach*:** see *three O's*

***ontics*:** the philosophy of bodies of knowledge

***ontology*:** the philosophy of the nature of being

***open sorting*:** see *card sorting*

***operand*:** the recipient of the interaction operator, or the digital/virtual object with which the user is interacting

> **1. *space-alone*:** cartographic interactions in which the user interacts only with the geographic component of the cartographic representation
>
> **2. *space-in-time*:** cartographic interactions in which the user interacts with the temporal component of the cartographic representation to understand how a dynamic geographic or spatial phenomenon acts over time

3. ***attribute-in-space*****:** cartographic interactions in which the user interacts with the attribute component of the cartographic representation to understand how one or several characteristics of a geographic phenomenon varies across space

operand-based approach**:** see *three O's*

operational task taxonomy**:** a three-dimensional characterization of tasks that a user may need to complete with a spatiotemporal visualization tool

1. ***cognitive operation*****:** the visual analytic process applied to the representation (i.e., the objective)

2. ***search level*****:** the percentage of all map features under consideration

3. ***search target*****:** the component of the spatiotemporal information under investigation (i.e., the operand)

operator**:** the functions provided by the cartographic interface to support the user's objective

1. ***reexpress*****:** cartographic interactions that set or change the visual isomorph used in the cartographic representation or information views linked to the cartographic representation

2. ***arrange*****:** cartographic interactions that manipulate the layout of a visual isomorph when multiple, typically linked visually isomorphic views are provided

3. ***sequence*****:** cartographic interactions that generate an ordered set of related cartographic representations

4. ***resymbolize*****:** cartographic interactions that set or change the design parameters of a cartographic representation form without changing the represented map features or the cartographic representation form itself

5. ***overlay*****:** cartographic interactions that adjust the features types included in the cartographic representation

6. ***reproject*****:** cartographic interactions that set or change the cartographic projection used to transform the three-dimensional geographic information to a two-dimensional screen

7. ***pan*****:** cartographic interactions that change the geographic center of the cartographic representation

8. ***zoom*****:** cartographic interactions that change the scale and/or resolution of the cartographic representation

9. ***filter*****:** cartographic interactions that alter the cartographic representation, and information views linked to the cartographic representation, to indicate map elements that meet one or a set of user-defined conditions

10. ***search*****:** cartographic interactions that alter the cartographic representation, and information views linked to the cartographic representation, to indicate a particular location or map feature of interest

11. ***retrieve*****:** cartographic interactions that request specific details about a map feature or map features of interest

12. ***calculate*****:** cartographic interactions that derive new information about a map feature or map features of interest

operators-based approach**:** see *three O's*

overlay**:** see *operator*

owner**:** the project team member responsible for a ticket

paired comparison**:** a method for eliciting cognitive structures that requires participants to rate the similarity between two instances for all possible pairs in a universe of instances

pan**:** see *operator*

participant observation**:** a user-based interface evaluation method in which the researchers watch the participants in their natural environment as they complete their daily work tasks

pattern-matching model**:** a model of visual thinking that acknowledges the influence of human ability on map use, particularly perception (*seeing-that*), cognition (*reasoning-why*), and motor skills (*interacting-with*)

1. ***seeing-that*****:** recognizing previously known patterns and noticing unexpected ones

2. ***interacting-with*****:** mediation between perception and cognition, which can be cognitively offloaded to the cartographic representation through interaction

3. ***reasoning-why*****:** evaluating the viewed patterns and integrating them into existing knowledge schema

persona**:** a description of the expected end users of an interface for use in scenario-based design

predict**:** see *three P's*

prescribe**:** see *three P's*

presentation**:** see *swoopy diagram*

procure**:** see *three P's*

productivity paradox**:** a critique on the immense investment in computing technology in the workplace during the early stages of the Digital Revolution, because, at the time, the investment had led to only marginal increases in workers' productivity

purposive sampling**:** the selection of participants based on their fitness to a small set of predefined criteria associated with the research topic

qualitative data analysis (QDA)**:** the systematic interpretation of qualitative information, such as text reports, websites, photos, maps, and field observations

radial categories**:** categories that have a central prototype, with non-prototypical examples bearing family resemblance to the central prototype according to non-arbitrary, motivating characteristics

***rank*:** see *objective*

***reasoning-why*:** see *pattern-matching model*

***rebirth perspective*:** see *cartographic perspectives*

***reexpress*:** see *operator*

***relational framework*:** a comprehensive model showing how all of the parts are connected to form the whole

***representation primacy*:** focus during interface design and development on the representations and interfaces for manipulating the representations (i.e., operands and objectives respectively)

***reproject*:** see *operator*

***resymbolize*:** see *operator*

***retrieve*:** see *operator*

***revisualization*:** the capture and visualization of an interaction session

***role-based interaction*:** customization of the cartographic interface based on the user's role on the geocollaborative team

***sapient interfaces*:** cartographic interfaces designed based on principles of visual perception from psychology, qualitative formalisms of geographic concepts from spatial cognition, and limitations of human motor skills from ergonomics

***save*:** see *enabling operator*

***schema*:** a cognitive structure against which new insight is compared and into which new insight is integrated

***science*:** a way of knowing through discursion and empiricism

***search*:** see *operator*

***search level*:** see *operational task taxonomy*

***search target*:** see *operational task taxonomy*

***seeing-that*:** see *pattern-matching model*

***semantic zoom*:** a change in the abstraction of the cartographic representation when changing map scales

Semiotics: the study of sign systems

***sensemaking*:** the collection, exploration, evaluation, and presentation of evidence that supports or refutes a set of competing hypotheses about the nature of and solution to a problem, often to the end of making an informed decision about the proper course of action

***semi-structured interview*:** see *interview*

***sequence*:** see *operator*

simplicity principle**:** design parsimony or an economy of design, which applies to both cartographic representation design and cartographic interface design

situated knowledges**:** the sets of cartographic and non-cartographic experiences unique to the cartographer

six fundamental questions**:** six categories of open questions concerning the science and practice of cartographic interaction that requires further investigation

> **1. *what?*:** the definition of cartographic interaction in the context of cartographic research
>
> **2. *why?*:** the purpose of cartographic interaction and the value it provides
>
> **3. *when?*:** the times that cartographic interaction positively supports work, and should therefore be provided
>
> **4. *who?*:** the types of users provided cartographic interaction and the way in which differences across users impacts cartographic interface designs and cartographic interaction strategies
>
> **5. *where?*:** the computing device through which cartographic interaction is provided and the limitations or constraints on cartographic interaction imposed by the device
>
> **6. *how?*:** the fundamental cartographic interaction primitives and the design of cartographic interfaces that implement them

slippy map**:** a tile-based multiscale web-mapping service that provides panning and zooming

sophistication**:** the amount and complexity of the operators required to complete the objective, indicating a continuum from basic objective primitives to sophisticated ones

sorting criterion**:** see *criterion*

space-alone**:** see *operand*

space-in-time**:** see *operand*

spatial ability**:** the practical skills needed to think geographically

spontaneous insight**:** see *geographic insight*

stages of (inter)action model**:** a framework conceptualizing interaction into a two-way exchange between user and operand, with seven observable steps at which a taxonomy of interaction primitives can be established

state-centric**:** an operand-based taxonomy that discriminates interaction primitives according to the information visualization pipeline

structured interview**:** see *interview*

subversive viewpoint**:** a radical viewpoint that considers approaches and techniques that run counter to the status quo

survey**:** a user-based interface evaluation method that requires participants to fill out a document containing predetermined, typically structured questions

swoopy diagram**:** a framework that relates the four stages of science to the number of unique cartographic representations needed by the scientist

> **1.** ***exploration*****:** the earliest stage of science during which the data is examined from multiple perspectives to identify research questions and to generate research hypotheses
>
> **2.** ***confirmation/analysis:*** the second stage of science during which hypotheses are tested formally in order to answer research questions
>
> **3.** ***synthesis*****:** the third stage of science during which insights from multiple iterations of exploration and confirmation are summarized and integrated to triangulate a final solution to the research questions
>
> **4.** ***presentation*****:** the final stage of science during which the uncovered solution is communicated to a wider audience

syntactics**:** formal guidelines for varying representation or interaction primitives according to the mapping content

synthesis**:** see *swoopy diagram*

task-by-type taxonomy**:** a two-dimensional taxonomy of interaction primitives that pairs user objectives with the operand with which they are interacting in order to prescribe the appropriate type of representation

Taylorism**:** an interface design strategy that forces all users to perform interactions using the same, optimal interaction strategy

technology-centered perspective**:** an emphasis on the vehicle through which the cartographic interaction is provided, encompassing issues related to the device's input capabilities, bandwidth size/processing power, and display capabilities

temporal bins**:** equivalent intervals of time used for aggregating events into an overview representation or when applying the *sequence* operator

temporal composite**:** a sequencing approach in which the frequencies for each individual instance of a finite set of cyclical temporal units are averaged or summed to calculate a single, representative value for each of the cyclical temporal units

three O's**:** three recommended approaches to parsing individual interaction exchanges into interaction primitives

> **1.** ***objective-based approach*****:** an approach to compartmentalizing cartographic interaction into primitives according to the user's objective, emphasizing the kinds of tasks the user may wish to complete with the cartographic interface
>
> **2.** ***operator-based approach*****:** an approach to compartmentalizing cartographic interaction into primitives according to the operator implemented in the cartographic interface, emphasizing the cartographic interfaces that make manipulation of the representation possible
>
> **3.** ***operand-based approach*****:** an approach to compartmentalizing cartographic interaction into primitives according to the operand manipulated by the user through the operator, emphasizing characteristics of the digital object with which the user is interacting

***three P's*:** three user goals that motivate use of cartographic interfaces according to the outcome that the user is attempting to attain

> **1.** ***procure*:** cartographic interactions that are performed in order to retrieve information about the represented geographic phenomena
>
> **2.** ***predict*:** cartographic interactions that are performed in order to assist the user in forecasting what may occur in the future based on current conditions of the represented geographic phenomena
>
> **3.** ***prescribe*:** cartographic interactions that are performed in support of deciding what should occur in the future based on current conditions of the represented geographic phenomena

***ticket*:** an individual usability or utility issue logged in an action list

***time wheel*:** a direct manipulation interface widget comprising concentric circles, each of which used for cyclical temporal filtering according to a different temporal cycle

***timeline graphic*:** a representation of an interaction log, showing the operators constituting the interaction strategy across time

***toolkit*:** a component-based approach to design and development of cartographic interfaces that allows the user to access a variety of cartographic representations and cartographic interactions and to combine them in any way he or she sees fit

***TRIAD*:** a framework for conceptualizing spatiotemporal information that includes three components: (1) location ('where'), (2) time ('when'), and (3) objects ('what' and 'who?')

***triad comparison*:** a method for eliciting cognitive structures that requires participants to identify the instance out of a set of three that is most unlike the others for all possible triplets in a universe of instances

***type-centric*:** an operand-based taxonomy that discriminates interaction primitives according to characteristics of the represented information

***uniform crime reporting (UCR) code*:** a set of numerical codes used to identify and index crime incidents by type

> **1.** ***UCR primary*:** the first two digits of the UCR code indicating the crime type
>
> **2.** ***UCR secondary*:** the second two digits of the UCR code discriminating a condition within the primary crime type

***uninformed-zoomer*:** a persona indicating interaction behavior in which the *zoom* operator is applied without the proper context provided by the *overlay* operator

***universal usability*:** an interface that works for a diverse range of users

***unsure-retriever*:** a persona indicating interaction behavior in which the *retrieve* operator is applied in rapid succession

***unstructured interview*:** see *interview*

***usability*:** the ease of using an interface to complete the user's desired set of objectives

user-centered perspective**:** an emphasis on the user component of the cartographic interaction conversation, particularly focusing on user differences across ability, expertise, and motivation

user guide**:** a help document describing the functionality of a cartogrpahic interface

utility**:** the usefulness of an interface for completing the user's desired set of objectives

Visual Analytics**:** see *Geovisual Analytics*

visual accomplishment**:** the change to the operand, provided to the user through feedback, as a result of completing an objective

visual implication**:** the new objectives that can be achieved after first completing a given objective

visual information seeking mantra**:** overview first, zoom and filter, then details-on-demand

visual isomorph**:** a representation of equivalent information in a different visual structure

visual variables**:** the set of graphic dimensions that can be manipulated in order to encode information, resulting in the fundamental representation primitives of information graphics

what?**:** see *six fundamental questions*

when?**:** see *six fundamental questions*

where?**:** see *six fundamental questions*

who?**:** see *six fundamental questions*

why?**:** see *six fundamental questions*

work (inter)action**:** an interaction that accomplishes the desired goal

zoom**:** see *operator*

References

AALST, W. M. P. V. D. (1998) The application of Petri nets to workflow management. *Journal of Circuit Systems and Computers,* 8**,** 21-66.

ABLER, R., ADAMS, J. S. & GOULD, P. (1971) *Spatial organization: The geographer's view of the world,* Englewood Cliffs, NJ, Prentice-Hall.

ADAMS, A. & COX, A. L. (2008) Questionnaires, in-depth interviews, and focus groups. IN CAIRNS, P. & COX, A. L. (Eds.) *Research methods for human-computer interaction.* Cambridge University Press, Cambridge, UK.

AERTS, J. C., CLARKE, K. C. & KEUPER, A. D. (2003) Testing popular visualization techniques for representing model uncertainty. *Cartography and Geographic Information Science,* 30**,** 249-261.

ALBRECHT, J. (1997) Universal analytical GIS operations: A task-oriented systematization of data structure-independent GIS functionality. IN CRAGLIA, M. & ONSRUD, H. (Eds.) *Geographic information research: Transatlantic perspectives.* London, UK, Taylor & Francis.

ALBRECHT, J. & DAVIES, C. (2010) Application Planning. IN HAKLAY, M. (Ed.) *Interacting with geospatial technologies.* West Sussex, UK, Wiley-Blackwell.

AMAR, R., EAGAN, J. & STASKO, J. (2005) Low-level components of analytic activity in information visualization. *Information Visualization.* Minneapolis, MN, IEEE.

ANDRIENKO, G., ANDRIENKO, N., JANKOWSKI, P., KEIM, D., KRAAK, M.-J., MACEACHREN, A. & WROBEL, S. (2007) Geovisual analytics for spatial decision support: Setting the research agenda. *International Journal of Geographical Information Science,* 21**,** 839-857.

ANDRIENKO, G. L. & ANDRIENKO, N. V. (1999a) Interactive maps for visual data exploration. *International Journal of Geographical Information Science,* 13**,** 355-374.

ANDRIENKO, G. L. & ANDRIENKO, N. V. (1999b) Making a GIS intelligent: CommonGIS Project View. *Association of Geographic Information Laboratories for Europe (AGILE) Conference.* Rome, Italy.

ANDRIENKO, N. & ANDRIENKO, G. (2001) Intelligent support for geographic data analysis and decision making in the web. *Journal of Geographic Information and Decision Analysis,* 5**,** 115-128.

ANDRIENKO, N., ANDRIENKO, G. & GATALSKY, P. (2003) Exploratory spatio-temporal visualization: An analytical review. *Journal of Visual Languages and Computing,* 14**,** 503-541.

ANDRIENKO, N., ANDRIENKO, G., VOSS, H., BERNARDO, F., HIPOLITO, J. & KRETCHMER, U. (2002) Testing the usability of interactive maps in CommonGIS. *Cartography and Geographic Information Science,* 29**,** 325-342.

ARNHEIM, R. (1969) *Visual Thinking,* Berkeley, CA, University of California Press.

AUER, M. T. (2009) Explicitly representing geographic change in map animations with bivariate symbolization. *Geography.* University Park, PA, Penn State.

BEAUDOUIN-LAFON, M. (2004) Designing interaction, not interfaces. *Advanced Visual Interfaces.* Gallipoli, Italy, ACM.

BECKER, R. A. & CLEVELAND, W. S. (1987) Brushing scatterplots. *Technometrics,* 29**,** 127-142.

BERG, E. (1946) An objective technique for the measurement of flexibility in thinking. *Psychology Department.* Madison, WI, University of Wisconsin.

BERG, E. A. (1948) A simple objective for measuring flexibility in thinking. *Journal of General Psychology,* 39**,** 15-22.

BERTIN, J. (1967|1983) *Semiology of graphics: Diagrams, networks, maps,* Madison, WI, University of Wisconsin Press.

BERTRAND, J. T., BROWN, J. E. & WARD, V. M. (1992) Techniques for analyzing focus group data. *Evaluation Review,* 16**,** 198-209.

BHOWMICK, T., GRIFFIN, A. L., MACEACHREN, A. M., KLUHSMAN, B. C. & LENGERICH, E. J. (2008) Informing geospatial toolset design: Understanding the process of cancer data exploration and analysis. *Health & Place,* 14**,** 576-607.

BLOK, C. (2000) Monitoring Change: Characteristics of dynamic geo-spatial phenomena for visual exploration. IN FREKSA, C., HABEL, C., BRAUER, W. & WENDER, K. F. (Eds.) *Spatial Cognition II.* Berlin, Germany, Springer-Verlag.

BLOK, C., KOBBEN, B., CHENG, T. & KUTEREMA, A. A. (1999) Visualization in relationships between spatial patterns in time by cartographic animation. *Cartograpphy and Geographic Information Science,* 26**,** 139-151.

BOARD, C. (1967) Maps as models. IN CHORLEY, R. J. & HAGGETT, P. (Eds.) *Models in Geography.* London, UK, Methuen.

BOBA, R. (2005) *Crime analysis and crime mapping,* Thousand Oaks, CA, Sage.

BOULOS, M. N. K. & BURDEN, D. (2007) Web GIS in practice V: 3-D Interactive and real-time mapping in Second Life. *International Journal of Health Geographics,* 6**,** 51.

BOWMAN, D. A., GABBARD, J. L. & HIX, D. (2002) A survey of usability evaluation in virtual environments: Classification and comparison of methods. *Presence,* 11**,** 404-424.

BREWER, C. A. (1996) Prediction of simultaneous contrast between map colors with Hunt's model of color appearance. *Color Research and Application,* 21**,** 221-235.

BREWER, C. A. (2003) A transition in improving maps: The ColorBrewer example. *Cartography and Geographic Information Science,* 30**,** 159-162.

BREWER, C. A. & BUTTENFIELD, B. P. (2007) Framing guidelines for multi-scale map design using databases at multiple resolutions. *Cartography and Geographic Information Science,* 34**,** 3-15.

BREWER, C. A. & PICKLE, L. (2002) Evaluation of methods for classifying epidemiological data on choropleth maps in series. *Annals of the Association of American Geographers,* 92**,** 662-681.

BRIMICOMBE, A. J. (2008) Location-based services and geographic information systems. IN WILSON, J. P. & FOTHERINGHAM, A. S. (Eds.) *The handbook of geographic information science.* Malden, MA, Blackwell.

BUJA, A., COOK, D. & SWAYNE, D. F. (1996) Interactive high-dimension data visualization. *Journal of Computational and Graphical Statistics,* 5**,** 78-99.

BURIGAT, S. & CHITTARO, L. (2008) Interactive visual analysis of geographic data on mobile devices based on dynamic queries. *Journal of Visual Languages and Computing,* 19**,** 99-122.

BUXTON, W. (2001) Less-is-more (more or less). IN DENNING, P. (Ed.) *The invisible future: The seamless integration of technology in everyday life.* New York, NY, McGraw Hill.

CAIVANO, J. L. (1990) Visual texture as a semiotic system. *Semiotica,* 80**,** 239-252.

CAMERON, J. (2005) Focusing on the focus group. IN HAY, I. (Ed.) *Qualitative research methods in human geography.* Oxford, UK, Oxford University Press.

CARD, S. K., MACKINLAY, J. D. & SHNEIDERMAN, B. (1999) *Information Visualization: Using vision to think,* San Francisco, California, Morgan-Kaufmann.

CARD, S. K., MORAN, T. P. & NEWELL, A. (1980) The keystroke-level model for user performance time with interactive systems. *ACM Communications,* 23**,** 396-410.

CARD, S. K., MORAN, T. P. & NEWELL, A. (1983) *The psychology of human-computer interaction,* Hillsdale, NJ, L. Erlbaum Associates.

CARTWRIGHT, W. (1999) Extending the map metaphor using web delivered multimedia. *International Journal of Geographical Information Science,* 13**,** 335-353.

CARTWRIGHT, W., CRAMPTON, J., GARTNER, G., MILLER, S., MITCHELL, K., SIEKIERSKA, E. & WOOD, J. (2001) Geospatial information visualization user interface issues. *Cartography and Geographic Information Science,* 28**,** 45-60.

CHANDLER, D. (2002) *Semiotics: The basics,* New York, NY, USA, Routledge.

CHANG, R., ZIEMKIEWICZ, C., GREEN, T. M. & RIBARSKY, W. (2009) Defining insight for visual analytics. *Computer Graphics and Applications,* 29**,** 14-17.

CHAPARRO, B. S., HINKLE, V. D. & RILEY, S. K. (2008) The usability of computerized card sorting: A comparison of three applications by researchers and end users. *Journal of Usability Studies,* 4**,** 31-48.

CHASE, W. & SIMON, H. (1973) Perception in chess. *Cognitive Psychology,* 4**,** 55-81.

CHEN, J. (2006) Visual inquiry of spatio-temporal multivariate patterns. *Visual Analytics Science and Technology.* Baltimore, MD, IEEE.

CHEN, J., MACEACHREN, A. M. & GUO, D. (2008) Supporting the process of exploring and interpreting space-time multivariate patterns: The Visual Inquiry Toolkit. *Cartography and Geographic Information Science,* 35**,** 33-50.

CHI, E. H.-H. & RIEDL, J. T. (1998) An operator interaction framework for visualization systems. *Information Visualization.* Research Triangle Park, NC, IEEE.

CHI, E. H. (2000) A taxonomy of visualization techniques using the data state reference model. *Information Visualization.* Salt Lake City, UT, IEEE.

CHUAH, M. C. & ROTH, S. F. (1996) On the semantics of interactive visualizations. *IEEE Symposium on Information Visualization.* San Francisco, CA.

CLATWORTHY, J., BUICK, D., HANKINS, M., WEINMAN, J. & HORNE, R. (2005) The use and reporting of cluster analysis in health psychology: A review. *British Journal of Health Psychology,* 10**,** 329-358.

CONVERTINO, G., GANOE, C. H., SCHAFER, W. A., YOST, B. & CARROLL, J. M. (2005) A multiple view approach to support common ground in distributed and synchronous geo-collaboration. *Third International Conference on Coordinated & Multiple Views in Exploratory Visualization.* IEEE Computer Society.

COOKE, N. J. (1994) Varieties of knowledge elicitation techniques. *International Journal of Human-Computer Studies,* 41**,** 801-849.

COOPER, A. & REIMANN, R. (2003) *About Face 2.0: The essentials of interaction design,* Indianapolis, Wiley.

COUCLELIS, H. (2003) The certainty of uncertainty: GIS and the limits of geographic knowledge. *Transactions in GIS,* 7**,** 165-175.

CRAMPTON, J. W. (2002) Interactivity types in geographic visualization. *Cartography and Geographic Information Science,* 29**,** 85-98.

CRAMPTON, J. W. & KRYGIER, J. (2006) An introduction to critical cartography. *ACME - An International E-Journal of Critical Geographies,* 4**,** 11-33.

DAVIES, C. (1998) Analysing 'work' in complex system tasks: An exploratory study with GIS. *Behaviour and Information Technology,* 17**,** 218-230.

DAVIES, C., LI, C. & ALBRECHT, J. (2010) Human understanding of space. IN HAKLAY, M. (Ed.) *Interacting with geospatial technologies.* West Sussex, UK, Wiley-Blackwell.

DAVIES, C. & MEDYCKYJ-SCOTT, D. (1996) GIS users observed. *International Journal of Geographical Information Science,* 10**,** 363-384.

DENIL, M. (2011) The search for radical cartography. *Cartographic Perspectives,* 68**,** 7-28.

DEY, I. (1993) *Qualitative data analysis: A user-friendly guide for social scientists,* London, England, Routledge.

DIBIASE, D. (1990) Visualization in the Earth Sciences. *Bulletin of the College of Earth and Mineral Sciences,* 59**,** 13-18.

DIBIASE, D., MACEACHREN, A. M., KRYGIER, J. B. & REEVES, C. (1992) Animation and the role of map design in scientific visualization. *Cartographic and Geographic Information Systems,* 19**,** 201-214, 265-266.

DIX, A. & ELLIS, G. (1998) Starting simple - Adding value to static visualisation through simple interaction *Working Conference on Advanced Visual Interfaces.* L'Aquila, Italy, ACM.

DODGE, M., MCDERBY, M. & TURNER, M. (2008) The power of geographical visualizations. IN DODGE, M., MCDERBY, M. & TURNER, M. (Eds.) *Geographic Visualization: Concepts, tools, and applications.* West Sussex, England, John Wiley & Sons.

DOU, W., ZIEMKIEWICZ, C., HARRISON, L., JEONG, D. H., RYAN, R., RIBARSKY, W., WANG, X. & CHANG, R. (2010) Comparing different levels of interaction constraints for deriving visual problem isomorphs. *Visual Analytics Science & Technology.* Salt Lake City, UT, IEEE.

DOWNS, R. M., BEDNARZ, S. W., BJORK, R. A., DOW, P. B., FOOTE, K. E., GILBERT, J. F., GOLLEDGE, R. G., KASTENS, K. A., LEINHARDT, G., LIBEN, L. S., LINN, M. C., RIESER, J. J., STOKES, G. M. & TVERSKY, B. (2006) *Support for thinking spatially: Incorporation of geographic information science across the K-12 curriculum,* Washington, D.C., The National Academies Press.

DYKES, J. (2005) Facilitating interaction for geovisualization. IN DYKES, J., MACEACHREN, A. M. & KRAAK, M.-J. (Eds.) *Exploring Geovisualization.* Amsterdam, The Netherlands, Elsevier Science.

DYKES, J. A. (1997) Exploring spatial data representation with dynamic graphics. *Computers & Geosciences*, 23**,** 345-370.

ECK, J. E., CHAINEY, S., CAMERON, J. G., LEITNER, M. & WILSON, R. E. (2005) Mapping Crime: Understanding Hot Spots. Washington, D.C., National Institute of Justice.

EDSALL, R., ANDRIENKO, G., ANDRIENKO, N. & BUTTENFIELD, B. (2008) Interactive maps for exploring spatial data. IN MADDEN, M. (Ed.) *Manual of Geographic Information Systems.* Bethesda, MD, ASPRS.

EDSALL, R. M. (2003) Design and usability of an enhanced geographic information system for exploration of multivariate health statistics. *The Professional Geographer,* 55**,** 146-160.

EGAN, D. & SCHWARTZ, B. (1979) Chunking in recall of symbolic drawings. *Memory and Cognition,* 7**,** 149-158.

ELLIS, C. A., GIBBS, S. J. & REIN, G. L. (1991) Groupware: Some issues and experiences. *Communications of the ACM,* 34**,** 38-58.

ENGELBART, D. C. & ENGLISH, W. K. (1968) A research center for augmenting human intellect. *Fall Joint Computer Conference.* San Francisco, CA.

EVANS, B. (1997) Dynamic display of spatial data-reliability: Does it benefit the map user? *Computers & Geosciences,* 23**,** 409-422.

EVERITT, B. S. (2001) *Cluster analysis,* London, England, Arnold.

FABRIKANT, S. I. (2001) Building task-ontologies for geovisualization. *20th International Cartographic Conference, ICA Commission on Visualization and Virtual Enviroments Pre-Conference Workshop on Geovisualization on the Web.* Beijing, China.

FEKETE, J.-D. & PLAISANT, C. (1999) Excentric labeling: Dynamic neighborhood labeling for data visualization. *Human Factors in Computing Systems (CHI).* Pittsburgh, PA, ACM.

FITTS, P. M. (1954) The information capacity of the human motor system in controlling amplitude of movement. *Journal of Experimental Psychology,* 47**,** 381-391.

FLANNERY, J. J. (1971) The relative effectiveness of some common graduated point symbols in the presentation of quantitative data. *Canadian Cartographer,* 8**,** 96-109.

FRIEDMANNOVÁ, L., KONEČNÝ, M. & STANĚK, K. (2006) An adaptive cartographic visualization for support of the crisis management. *AutoCarto.* Vancouver, WA.

FUHRMANN, S., AHONEN-RAINIO, P., EDSALL, R. M., FABRIKANT, S. I., KOUA, E. L., TOBON, C., WARE, C. & WILSON, S. (2005) Making useful and useable geovisualization: Design and evaluation issues. IN DYKES, J., MACEACHREN, A. M. & KRAAK, M. J. (Eds.) *Exploring Geovisualization.* Amsterdam, The Netherlands, Elsevier Science.

GABBARD, J. L., HIX, D. & SWAN, J. E. (1999) User-centered design and evaluation of virtual environments. *IEEE Computer Graphics and Applications,* 19**,** 51-59.

GAHEGAN, M. (1999) Four barriers to the development of effective exploratory visualization tools for the gegeosciences. *International Journal of Geographical Information Science,* 13**,** 289-309.

GARTNER, G., BENNETT, D. A. & MORITA, T. (2007) Towards ubiquitous cartography. *Cartography and Geographic Information Science,* 34**,** 247-257.
GOLDSBERRY, K. (2007) Real-time traffic maps for the Internet. *Geography.* Santa Barbara, University of California, Santa Barbara.
GOLDSBERRY, K. & BATTERSBY, S. (2009) Issues of change detection in animated choropleth maps. *Cartographica*, 44**,** 201-215.
GOLLEDGE, R. (1992) Do people understand spatial concepts: The case of first-order primitives. IN FRANK, A. U. & FORMENTINI, U. (Eds.) *Theories and methods of spatio-temporal reasoning in geographic space.* New York, NY, Springer.
GOODCHILD, M. F. (1988) Towards an enumeration and classification of GIS functions. *International Geographical Information Systems Symposium.* Washington, D.C., NASA.
GOODCHILD, M. F. (2010) Towards Geodesign: Repurposing Cartography and GIS? *Cartographic Perspectives,* 66**,** 7-21.
GOULD, M. D. (1993) Two views of the user interface. IN MEDYCKYJ-SCOTT, D. & HEARNSHAW, H. M. (Eds.) *Human Factors in Geographical Information Systems.* London, Belhaven Press.
GREIF, S. (1991) The role of German work psychology in the design of artefacts. IN CARROLL, J. M. (Ed.) *Designing Interaction: Psychology at the human-computer interface.* Cambridge, MA, Cambridge University Press.
GRIFFIN, A. (2002) Feeling it Out: The use of haptic visualization for exploratory geographic analysis. *Cartographic Perspectives***,** 12-29.
GRINSTEIN, G., KOBSA, A., PLAISANT, C., SHNEIDERMAN, B. & STASKO, J. T. (2003) Which comes first, usability or utility? *14th IEEE Visualization (VIZ '03).* Seattle, WA, IEEE Computer Society.
GUO, D. (2007) Visual analytics of spatial interaction patterns for pandemic decision support. *International Journal of Geographical Information Science,* 21**,** 859-877.
HABER, R. B. & MCNABB, D. A. (1990) Visualization Idioms: A conceptual model for scientific visualization systems. *Visualization in Scientific Computing.* IEEE Computer Society press.
HAKLAY, M. (2010) Computer-mediated communication, collaboration, and groupware. IN HAKLAY, M. (Ed.) *Interacting with geospatial technologies.* West Sussex, UK, Wiley-Blackwell.
HAKLAY, M. & LI, C. (2010) Single user environments: Desktop to mobile. IN HAKLAY, M. (Ed.) *Interacting with geospatial technologies.* West Sussex, UK, Wiley-Blackwell.
HAKLAY, M. & NIVALA, A.-M. (2010) User-centered design. IN HAKLAY, M. (Ed.) *Interacting with geospatial technologies.* West Sussex, UK, Wiley-Blackwell.
HAKLAY, M. & TOBÓN, C. (2003) Usability evaluation and PPGIS: Towards a user-centred design approach. *International Journal of Geographical Information Science,* 17**,** 577-592.
HAKLAY, M. & ZAFIRI, A. (2008) Usability engineering for GIS: Learning from a screenshot. *The Cartographic Journal,* 45**,** 87-97.
HANNAH, S. (2005) Sorting out card sorting: Comparing methods for information architects, usability specialists, and other practitioners. *Applied Information Management.* Portland, OR, University of Oregon.
HANRAHAN, P. (2009) Keynote Address: Systems of thought. *EuroVis.* Berlin, Germany.
HARDISTY, F. (2003) Strategies for designing coordinated geographic visualization software for enumerated data: A component-based approach. *Geography.* University Park, PA, The Pennsylvania State University.
HARDISTY, F. & ROBINSON, A. C. (2011) The GeoViz Toolkit: Using component-orented coordination methods for geographic visualization and analysis. *International Journal of Geographical Information Science,* 25**,** 191-210.
HARLEY, J. B. (1989) Deconstructing the map. *Cartographica,* 26**,** 1-20.
HARRIES, K. (1999) *Mapping crime: Principle and practice,* Washington, D.C., National Institute of Justice, Crime Mapping Research Center.
HARROWER, M. (2008) The Golden Age of Cartography is now. Axis Maps.

HARROWER, M. & BREWER, C. A. (2003) ColorBrewer.org: An online tool for selecting colour schemes for maps. *The Cartographic Journal,* 40**,** 27-37.

HARROWER, M. & FABRIKANT, S. (2008) The role of map animation in geographic visualization. IN DODGE, M., MCDERBY, M. & TURNER, M. (Eds.) *Geographic Visualization: Concepts, tools, and applications.* West Sussex, England, John Wiley & Sons.

HARROWER, M., HEYMAN, D., SHEESLEY, B. & WOODRUFF, A. (2008) Maker! Mapping the world's data. *NACIS Annual Meeting.* Missoula, MT.

HARROWER, M., KELLER, C. P. & HOCKING, D. (1997) Cartography on the Internet: Thoughts and a preliminary user survey. *Cartographic Perspectives,* 27**,** 27-37.

HARROWER, M., MACEACHREN, A. & GRIFFIN, A. L. (2000) Developing a geographic visualization tool to support earth science learning. *Cartography and Geographic Information Science,* 27**,** 279-293.

HARROWER, M. & SHEESLEY, B. (2005) Designing better map interfaces: A framework for panning and zooming. *Transactions in GIS,* 9**,** 77-89.

HARROWER, M. A. (2002) Visual Benchmarks: Representing geographic change with map animation. *Geography.* University Park, PA, Penn State.

HART, S. G. & STAVELAND, L. E. (1988) Development of NASA-TLX (task load index): Results of empirical and theoretical research. IN HANCOCK, P. A. & MESHKATI, N. (Eds.) *Human mental workload.* New York, NY, North-Holland.

HAUG, D., MACEACHREN, A. M., BOSCOE, F., BROWN, D., MARRARA, M., POLSKY, C. & BEEDASY, J. (1997) Implementing exploratory spatial data analysis methods for multivariate health statistics. *GIS/LIS.* Cincinnati, Ohio.

HAUG, D., MACEACHREN, A. M. & HARDISTY, F. (2001) The challenge of analyzing geovisualization tool use: Taking a visual approach. *20th International Cartographic Conference.* Beijing, China.

HAUNOLD, P. & KUHN, W. (1994) A keystroke level analysis of a graphics application: Manual map digitizing. IN ADELSON, B., DUMAIS, S. & OLSEN, J. (Eds.) *Conference on Human Factors in Computing Systems.* Boston, MA, ACM.

HERMANN, M. & PEARCE, M. (2011) "The would not take me there": People, places, and stories from Champlain's Travels in Canada 1603-1616. *Cartographic Perspectives,* 66**,** 41-46.

HOLLAN, J., HUTCHINS, E. & KIRSH, D. (2000) Distributed cognition: Toward a new foundation for human-computer interaction research. *ACM Transactions in Computer-Human Interaction,* 7**,** 174-196.

HOPE, S. & HUNTER, G. J. (2007) Testing the effects of thematic uncertainty on spatial decision-making. *Cartography and Geographic Information Science,* 34**,** 199-214.

HOWARD, D. L. & MACEACHREN, A. M. (1996) Interface design for geographic visualization: Tools for representing reliability. *Cartography and Geographic Information Science,* 23**,** 59-77.

JONES, C. E., HAKLAY, M., GRIFFITHS, S. & VAUGHAN, L. (2009) A less-is-more approach to geovisualization: Enhancing knowledge construction across multidisciplinary teams. *International Journal of Geographical Information Science,* 23**,** 1077-1093.

KANG, H., PLAISANT, C. & SHNEIDERMAN, B. (2003) New approaches to help users get started with visual interfaces: Multi-layered interfaces and integrated initial guidance. *Annual National Conference on Digital Government Research.* Boston, MA, Digital Government Society of North America.

KEALY, W. A. & WEBB, J. M. (1995) Contextual influences of maps and diagrams on learning. *Contemporary Educational Psychology,* 20**,** 340-358.

KEEHNER, M., HEGARTY, M., COHEN, C., KHOOSHABEH, P. & MONTELLO, D. R. (2008) Spatial reasoning with external visualizations: What matters is what you see, not whether you interact. *Cognitive Science,* 32**,** 1099-1132.

KEIM, D. A. (2002) Information visualization and visual data mining. *Transactions on Visualization and Computer Graphics,* 7**,** 100-107.

KELLY, J. E. (1982) *Scientific managment, job redesign, and work performance,* London, UK, Academic Press.

KESSLER, F. (2000) Focus groups as a means of qualitatively assessing the U-Boat Narrative. *Cartographica,* 37**,** 33-60.

KLIPPEL, A. (2009) Topologically characterized movement patterns: A cognitive assessment. *Spatial Cognition and Computation,* 9**,** 233-261.

KLIPPEL, A. & HARDISTY, F. (2008) Visual analytics and the geometry of thought: Spatial intelligence through sapient interfaces. *Research and Training in Spatial Intelligence.* Evanston, IL.

KLIPPEL, A. & LI, R. (2009) The endpoint hypothesis: A topological-cognitive assessment of geographic scale movement patterns. IN HORNSBY, K. S., CLARAMUNT, C., DENIS, M. & LIGOZAT, G. (Eds.) *9th International Conference on Spatial Information Theory (COSIT).* Aber Wrac'h, France, Springer.

KLIPPEL, A., TAPPE, H., KULIK, L. & LEE, P. U. (2005) Wayfinding choremes: A language for modeling conceptual route knowledge. *Visual Languages & Computing,* 16**,** 311-329.

KOBUS, D. A., PROCTOR, S. & HOLSTE, S. (2001) Effects of experience and uncertainty during dynamic decision making. *International Journal of Industrial Ergonomics,* 28**,** 275-290.

KOCH, T. (2004) Opinion column. *Cartographic Perspectives,* 48**,** 4-6.

KOLÁČNÝ, A. (1969) Cartographic information-a fundamental concept and term in modern cartography. *Cartographic Journal,* 6**,** 47-49.

KOS, A. J. & PSENICKA, C. (2000) Measuring cluster similarity across methods. *Psychological Reports,* 86**,** 858-862.

KOSTELNICK, J. C., DOBSON, J. E., EGBERT, S. L. & DUNBAR, M. D. (2008) Cartographic symbols for humanitarian demining. *The Cartographic Journal,* 45**,** 18-31.

KOUA, E. L. & KRAAK, M.-J. (2004) Geovisualization to support the exploration of large health and demographic survey data. *International Journal of Health Geographics,* 3**,** 1-13.

KRAAK, M.-J. & BROWN, A. (2001) *Web Cartography: Developments and perspectives,* London, Taylor & Francis.

KRYGIER, J. (1994) Sound and geographic visualization. IN MACEACHREN, A. M. & TAYLOR, D. R. F. (Eds.) *Visualization in modern cartography.* Oxford, England, Elsevier.

LAKOFF, G. (1987) *Women, fire, and dangerous things,* Chicago, USA, University of Chicago Press.

LANDAUER, T. K. (1995) *The trouble with computers: Usefulness, usability, and productivity,* Cambridge, MA, MIT Press.

LEITNER, M. & BUTTENFIELD, B. P. (2000) Guidelines for the display of attribute certainty. *Cartography and Geographic Information Science,* 27**,** 3-14.

LESGOLD, A. (1984) Acquiring expertise. IN ANDERSON, J. R. & KOSSLYN, S. M. (Eds.) *Tutorials in learning and memory.* San Francisco, CA, Freeman.

LEWIN, K. (1951) *Field Theory in Social Science,* New York, NY, Basic Books.

LLOYD, D., DYKES, J. & RADBURN, R. (2008) Mediating geovisualization to potential users and prototyping a geovisualization application. *GIS Research UK.* Machester, UK.

LOBBEN, A. (2003) Classification and application of cartographic animation. *The Professional Geographer,* 55**,** 318-328.

LOBBEN, A. K. (2005) Identifying the needs of tactile map makers. *22nd International Cartographic Conference.* A Coruña, Spain, ICA.

LODHA, S. K. & VERMA, A. (1999) Animations of crime maps using Virtual Reality Modeling Language. *Western Criminology Review,* 1**,** [Online].

LUDÄSCHER, B., ALTINAS, I., BERKLEY, C., HIGGINS, D., JAEGER, E., JONES, M., LEE, E. A., TAO, J. & ZHAO, Y. (2006) Scientific workflow management and the Kepler system. *Concurrency and Computation: Practice and Experience,* 18**,** 1039-1065.

MACEACHREN, A. M. (1992) Visualizing uncertain information. *Cartographic Perspectives,* 13**,** 10-19.

MACEACHREN, A. M. (1994) Visualization in modern cartography: Setting the agenda. IN MACEACHREN, A. M. & TAYLOR, D. R. F. (Eds.) *Visualization in modern cartography.* Oxford, England, Pergamon.

MACEACHREN, A. M. (1995) *How maps work,* New York, NY, USA, The Guilford Press.

MACEACHREN, A. M. (2000) Cartography and GIS: Facilitating collaboration. *Progress in Human Geography,* 24**,** 445-456.

MACEACHREN, A. M. (2001) An evolving cognitive-semiotic approach to geographic visualization and knowledge construction. *Information Design Journal,* 10**,** 26-31.

MACEACHREN, A. M. (2005) Moving geovisualization toward support for group work. IN DYKES, J., MACEACHREN, A. M. & KRAAK, M.-J. (Eds.) *Exploring Geovisualization.* Amsterdam, The Netherlands, Elsevier Science.

MACEACHREN, A. M., BOSCOE, F. P., HAUG, D. & PICKLE, L. W. (1998) Geographic Visualization: Designing manipulable maps for exploring temporally varying georeferenced statistics. *Information Visualization.* Raleigh-Durham, NC, IEEE.

MACEACHREN, A. M., BUTTENFIELD, B. P., CAMPBELL, J. C. & MONMONIER, M. S. (1992) Visualization. IN ABLER, R., MARCUS, M. & OLSON, J. (Eds.) *Geography's inner worlds: Pervasive themes in contemporary american geography.* Rutgers, NJ, Rutgers University Press.

MACEACHREN, A. M., CAI, G., SHARMA, R., RAUSCHERT, I., BREWER, I., BOLELLI, L., SHAPARENKO, B., FUHRMANN, S. & WANG, H. (2005a) Enabling collaborative geoinformation access and decision-making through a natural, multimodal interface. *International Journal of Geographical Information Science,* 19**,** 293-317.

MACEACHREN, A. M., CRAWFORD, S., AKELLA, M. & LENGERICH, G. (2008) Design and implementation of a model, web-based, GIS-enabled cancer atlas. *The Cartographic Journal,* 45**,** 246-260.

MACEACHREN, A. M., GAHEGAN, M., PIKE, W., BREWER, I., CAI, G., LENGERICH, E. & HARDISTY, F. (2004) Geovisualization for knowledge construction and decision support. *Computer Graphics and Applications,* 24**,** 13-17.

MACEACHREN, A. M. & GANTER, J. H. (1990) A pattern identification approach to cartographic visualization. *Cartographica,* 27**,** 64-81.

MACEACHREN, A. M. & KRAAK, M.-J. (1997) Exploratory cartographic visualization: Advancing the agenda. *Computers & Geosciences,* 23**,** 335-343.

MACEACHREN, A. M. & KRAAK, M.-J. (2001) Research challenges in geovisualization. *Cartography and Geographic Information Science,* 28**,** 3-12.

MACEACHREN, A. M. & MONMONIER, M. (1992) Geographic visualization - Introduction. *Cartography and Geographic Information Science,* 19**,** 197-200.

MACEACHREN, A. M., ROBINSON, A., HOPPER, S., GARDNER, S., MURRAY, R., GAHEGAN, M. & HETZLER, E. (2005b) Visualizing geospatial information uncertainty: What we know and what we need to know. *Cartography and Geographic Information Science,* 32**,** 139-160.

MACEACHREN, A. M., WACHOWICZ, M., EDSALL, R., HAUG, D. & MASTERS, R. (1999) Constructing knowledge from multivariate spatiotemporal data: Integrating geographical visualization with knowledge discovery in database methods. *International Journal of Geographical Information Science,* 13**,** 311-334.

MAMALIAN, C. A. & LA VIGNE, N. G. (1999) Research preview: The use of computerized crime mapping by law enforcement: Survey results. Washington, DC, U.S.Department of Justice, National Institute of Justice.

MARGOLIS, E. & LAURENCE, S. (1999) *Concepts: Core readings,* Cambridge, MA, MIT Press.

MARSH, S. L. & DYKES, J. (2008) Using and evaluating HCI techniques in geovisualization: Applying standard and adapted methods in research and education. *GIS Research UK.* Machester, UK.

MARSH, S. L. & HAKLAY, M. (2010) Evaluation and deployment. IN HAKLAY, M. (Ed.) *Interacting with geospatial technologies.* West Sussex, UK, Wiley-Blackwell.

MASTERS, R. & EDSALL, R. (2000) Interaction tools to support knowledge discovery: A case study using Data Explorer and Tcl/Tk. *Visualization Development Environments.* Princeton, NJ.

MAURER, D. & WARFEL, T. (2004) Card sorting: A definitive guide.

MCCLEARY, G. F. (1975) In pursuit of the map user. *AutoCarto II.* Reston, VA.

MCCORMICK, B. H., DEFARANTI, T. A. & BROWN, M. D. (1987) Visualization in scientific computing - a synopsis. *IEEE Computer Graphics and Applications*, July**,** 61-70.

MCDONALD, J. E., DEARHOLT, D. W., PAAP, K. R. & SCHVANEVELDT, R. W. (1986) A formal interface design methodology based on user knowledge. *Human Factors in Computing Systems (CHI).* Boston, MA, ACM.

MCGEE, D. R., COHEN, P. R. & WU, L. (2000) Something from nothing: Augmenting a paper-based work practice via multimodal interaction. *Designing Augmented Reality (DARE).* Helsinor, Denmark, ACM.

MCGUINNESS, C. (1994) Expert/Novice use of visualization tools. IN MACEACHREN, A. M. & TAYLOR, D. R. F. (Eds.) *Visualization in modern cartography.* Oxford, England, Pergamon.

MCGUINNESS, C., WERSCH, A. V. & STRINGER, P. (1992) User differences in a GIS environment: A protocol study. *16th International Cartographic Conference.* Cologne, Germany, ICA.

MCHARG, I. L. (1969) *Design with nature,* Garden City, NY

Natural History Press.

MCMASTER, R. & MCMASTER, S. (2002) A history of Twentieth-Century American Academic Cartography. *Cartography and Geographic Information Science,* 29**,** 305-321.

MILES, M. B. & HUBERMAN, A. M. (1994) *Qualitative data analysis: An expanded sourcebook,* Thousand Oaks, CA, Sage Publications.

MILLER, R. B. (1968) Response time in man-computer conversational transactions. *Fall Joint Computer Conference.* AFIPS.

MITHAL, A. K. & DOUGLAS, S. A. (1996) Differences in movement microstructure of the mouse and the finger-controlled isometric joystick. *SIGCHI conference on human factors in computing systems.* Vancouver, BC.

MOELLERING, H. (1976) The potential uses of a computer animated film in the analysis of geographical patterns of traffic crashes. *Accident Analysis and Prevention,* 8**,** 215-227.

MONMONIER, M. (1989) Geographic brushing: Enhancing exploratory analysis of the scatterplot matrix. *Geographical analysis,* 21**,** 81-84.

MONMONIER, M. (1991) Ethics and map design: Six strategies for confronting the traditional one-map solution. *Cartographic Perspectives,* 10**,** 3-8.

MONMONIER, M. & GLUCK, M. (1994) Focus groups for design improvement in dynamic cartography. *Cartography and Geographic Information Science,* 21**,** 37-47.

MONTELLO, D. R. (2002) Cognitive map-design research in the twentieth century: Theoretical and empirical approaches. *Cartography and Geographic Information Science,* 29**,** p283-304.

MONTELLO, D. R., LOVELACE, K., GOLLEDGE, R. G. & SELF, C. (1999) Sex-related differences and similarities in geographic and environmental spatial abilities. *Annals of the Association of American Geographers,* 89**,** 515-534.

MORGAN, D. L. (1998) *Focus Group Kit,* Thousand Oaks, CA, Sage Publications.

MORRISON, J. L. (1974) A theoretical framework for cartographic generalization with the emphasis on the process of symbolization. *International Yearbook of Cartography,* 14**,** 115-127.

MUEHLENHAUS, I. A. (2010) Lost in visualization: Using quantitative content analysis to identify, measure, and categorize political cartographic manipulations. *Geography.* Minneapolis, MN, University of Minnesota.

MUEHRCKE, P. C. (1974) Map reading and abuse *Journal of Geography,* 73**,** 11-23.

MUEHRCKE, P. C. (1986) *Map use: Reading, analysis, and interpretation,* Madison, WI, JP Publications.

NIELSEN, J. (1993) *Usability Engineering,* San Francisco, CA, Morgan Kaufmann.

NIELSEN, J. (1994) Heuristic Evaluation. *Usability Inspection Methods.* New York, NY, John Wiley and Sons.

NIELSEN, J. (2004) Card Sorting: How many users to test.

NIELSEN, J. & SANO, D. (1995) SunWeb: User interface design for Sun Microsystem's internal Web. *Computer Networks and ISDN System,* 28**,** 179-188.

NORMAN, D. (1984) Stages and levels in human-machine interaction. *International Journal of Man-Machine Studies,* 21**,** 365-375.

NORMAN, D. A. (1988) *The design of everyday things,* New York, NY, Basic Books.

NORTH, C. (2006) Toward measuring visualization insight. *IEEE Computer Graphics and Applications,* 26**,** 6-9.

NOVAK, J. D. & CAÑAS, A. J. (2008) The theory underlying concept maps and how to construct and use them. Pensacola, FL, Florida Institute for Human and Machine Cognition (IHMC).

O'REILLY, T. (2007) What Is Web 2.0: Design Patterns and Business Models for the Next Generation of Software. *Communications & Strategies.*

O'SHEA, T. C. & NICHOLLS, K. (2003) Crime analysis in America: Findings and recommendations. Washington, D.C., Office of Community Oriented Policing Services, U.S. Department of Justice.

O'SULLIVAN, D. & UNWIN, D. J. (2003) *Geographic information analysis,* Hoboken, NJ, John Wiley & Sons.

OLSON, J. M. (2004) Cartography 2003. *Cartographic Perspectives,* 47**,** 4-12.

OLSON, J. M. & BREWER, C. A. (1997) An evaluation of color selections to accomodate map users with color vision impairments. *Annals of the Association of American Geographers,* 87**,** 103-134.

PARADIS, J. & BEARD, K. (1994) Visualization of spatial data quality for the decision-maker: A data-quality filter. *URISA Journal,* 6**,** 25-34.

PATTON, M. Q. (1990) *Qualitative evaluation and research methods,* Newbury Park, CA, Sage Publications.

PEARCE, M. & HERMANN, M. (2010) Mapping Champlain’s travels: Restorative techniques for historical cartography. *Cartographica,* 45**,** 33-48.

PERSSON, D., GARTNER, G. & BRUCHROITHNER, M. (2006) Towards a typology of interactivity functions for visual map exploration. IN STEFANAKIS, E., PETERSON, M. P., ARMENAKIS, C. & DELIS, V. (Eds.) *Geographic hypermedia: Concepts and systems.* Berlin, Germany, Springer.

PETCHENIK, B. B. (1983) A mapmaker's perspective on map design research 1950-1980. IN TAYLOR, D. R. F. (Ed.) *Graphic communication and design in contemporary cartography.* Chichester, UK, John Wiley & Sons.

PETERSON, M. P. (1998) That interactive thing you do. *Cartographic Perspectives,* 29**,** 3-4.

PEUQUET, D. J. (1994) It’s about time: A conceptual framework for the representation of temporal dynamics in geographic information systems. *Annals of the Association of American Geographers,* 84**,** 441-461.

PHILBRUCK, A. (1953) Towards a unity of cartographic terms and geographical content. *Professional Geographer,* 5**,** 11-15.

PICKLES, J. (2004) *A history of spaces: Cartographic reason, mapping, and the geo-coded world,* London, UK, Routledge.

PINDER, D. (1996) Subverting Cartography: The situationists and maps of the city. *Environment and Planning A,* 28**,** 405-427.

PIROLLI, P. & CARD, S. (2005) The sensemaking process and leverage points for analyst technology as identified through cognitive task analysis. *International Conference on Intelligence Analysis.* McLean, Va.

PIVAR, M., FREDKIN, E. & STOMMEL, H. (1963) Computer-compiled oceanographic atlas: An experiment in man-machine interaction. *Proceedings of the National Academy of Sciences,* 50**,** 396-398.

PLAISANT, C. (2004) The challenge of information visualization evaluation. *IEEE Advanced Visual Interfaces.* New York, NY, ACM Press.

RATCLIFFE, J. (2009a) Crime Mapping: Spatial and temporal challenges. IN PIQUERO, A. R. & WEISBURD, D. (Eds.) *Handbook of Quantitative Criminology.* New York City, NY, Springer Science.

RATCLIFFE, J. H. (2009b) The structure of strategic thinking. IN RATCLIFFE, J. H. (Ed.) *Strategic thinking in criminal intelligence.* 2nd ed. Sydney, Australia, Federation Press.

REICHENBACHER, T. (2003) Adaptive methods for mobile cartography. *21st International Cartographic Conference.* Durban, South Africa.

ROBERTS, J. C. (2008) Coordinated multiple views for exploratory geovisualization. IN DODGE, M., MCDERBY, M. & TURNER, M. (Eds.) *Geographic Visualization: Concepts, tools, and applications.* West Sussex, England, John Wiley & Sons.

ROBINSON, A. C. (2006) Highlighting techniques to support geovisualization. *ICA Workshop on Geovisualization and Visual Analytics.* Portland, OR.

ROBINSON, A. C. (2008a) Collaborative synthesis of visual analytic results. *Visual Analytics Science and Techology.* Columbus, OH, IEEE.

ROBINSON, A. C. (2008b) Design for synthesis in geovisualization. *Geography.* University Park, The Pennsylvania State University.

ROBINSON, A. C. (2009) Needs assessment for the design of information synthesis visual analytics tools. IEEE Computer Society.

ROBINSON, A. C. (2011) Challenges and opportunities for web-based evaluation of the use of spatial technologies. *International Cartographic Conference.* Paris, France.

ROBINSON, A. C., CHEN, J., LENGERICH, E. J., MEYER, H. G. & MACEACHREN, A. M. (2005) Combining usability techniques to design geovisualization tools for epidemiology. *Cartography and Geographic Information Science,* 32**,** 243-255.

ROBINSON, A. C., ROTH, R. E. & MACEACHREN, A. M. (2010) Challenges for map symbol standardization. *7th International Conference on Information Systems for Crisis Response and Management.* Seattle, WA.

ROBINSON, A. C., ROTH, R. E. & MACEACHREN, A. M. (2011) Understanding user needs for map symbol standardization in emergency management. *Journal of Homeland Security and Emergency Management,* 8**,** 33.

ROBINSON, A. C. & WEAVER, C. (2006) Re-Visualization: Interactive visualization of the process of visual analysis. *GIScience 2006, Workshop on Visual Analytics and Spatial Decision Support.* Muenster, Germany.

ROBINSON, A. H. (1952) *The look of maps: An examination of cartographic design,* Madison, WI, University of Wisconsin Press.

ROBINSON, A. H., MORRISON, J. L., MUEHRCKE, P. C., KIMERLING, A. J. & GUPTILL, S. C. (1995) *Elements of Cartography,* New York, NY, John Wiley & Sons.

RØD, J. K., ORMELING, F. & ELZAKKER, C. V. (2001) An agenda for democratising cartographic visualisation. *Norsk Geografisk Tidsskrift-Norwegian Journal of Geography,* 55**,** 38-41.

ROSS, K. S., MCCABE, C. A. & ROTH, R. E. (2009) A near real-time visualization for understanding spatio-temporal patterns of violent crime in the District of Columbia. *The Department of Homeland Security Summit.* Washington, D.C.

ROTH, R. E. (2008) The impact of user expertise on geographic risk assessment under uncertain conditions. *International Symposium on Automated Cartography (AutoCarto).* Shephardstown, WV.

ROTH, R. E. (2009a) The impact of user expertise on geographic risk assessment under uncertain conditions. *Cartography and Geographic Information Science,* 36**,** 29-43.

ROTH, R. E. (2009b) A qualitative approach to understanding the role of geographic information uncertainty during decision making. *Cartography and Geographic Information Science,* 36**,** 315-330.

ROTH, R. E., FINCH, B. F., BLANFORD, J. I., KLIPPEL, A., ROBINSON, A. C. & MACEACHREN, A. M. (2010a) The card sorting method for map symbol design. *International Symposium on Automated Cartography (AutoCarto).* Orlando, FL, ACSM/CaGIS.

ROTH, R. E., FINCH, B. G., BLANFORD, J. I., KLIPPEL, A., ROBINSON, A. C. & MACEACHREN, A. M. (2011) Card sorting for cartographic research and practice. *Cartography and Geographic Information Science,* 38**,** 89-99.

ROTH, R. E. & HARROWER, M. (2008) Addressing map interface usability: Learning from the Lakeshore Nature Preserve Interactive Map. *Cartographic Perspectives,* 60**,** 46-66.

ROTH, R. E., MACEACHREN, A. M. & MCCABE, C. A. (2009) A workflow learning model to improve geovisual analytics utility. *24th International Cartographic Conference.* Santiago, Chile.

ROTH, R. E. & ROSS, K. S. (2009) Extending the Google Maps API for event animation mashups. *Cartographic Perspectives,* 64**,** 21-40.

ROTH, R. E., ROSS, K. S., FINCH, B. G., LUO, W. & MACEACHREN, A. M. (2010b) A user-centered approach for designing and developing spatiotemporal crime analysis tools. *GIScience 2010.* Zurich, Switzerland.

RUGG, G. & MCGEORGE, P. (2005) The sorting techniques: A tutorial paper on card sorts, picture sorts, and item sorts. *Expert Systems,* 22**,** 94-107.

SACK, R. (1997) *Homo geographicus,* Baltimore, Maryland, The John Hopkins University Press.

SARAIYA, P., NORTH, C. & DUCA, K. (2004) An evaluation of microarray visualization tools for biological insight. *IEEE Symposium on Information Visualization (INFOVIS '04).* Austin, Texas, IEEE Computer Society.

SARJAKOSKI, L. T. (2007) Conceptual models of generalization and multiple representation. IN MACKANESS, W. A., RUAS, A. & SARJAKOSKI, L. T. (Eds.) *Generalisation of geographic information: Cartographic modelling and applications.* Elsevier.

SCAIFE, M. & ROGERS, Y. (1996) External cognition: How do graphical representations work? *International Journal of Human-Computer Studies*, 45**,** 185-213.

SCHIENKE, E. W. (2003) Who's Mapping the Mappers? Ethnographic Research in the Production of Digital Cartography. IN HARD, M., LOSCH, A. & VERDICCHIO, D. (Eds.) *Transforming Spaces, The Topological Turn in Technology Studies.* Darmstadt, Germany.

SCHUURMAN, N. (2006) Formalization matters: Critical GIS and ontology research. *Annals of the Association of American Geographers,* 96**,** 726-739.

SHEPHERD, I. D. H. (1995) Putting time on the map: Dynamic displays in data visualization and GIS. IN FISHER, P. F. (Ed.) *Innovations in GIS 2.* London, UK, Taylor & Francis.

SHNEIDERMAN, B. (1996) The eyes have it: A task by data type taxonomy for information visualization. *IEEE Conference on Visual Languages.* Boulder, CO, IEEE Computer Society Press.

SHNEIDERMAN, B. & PLAISANT, C. (2006) Strategies for evaluating information visualization tools: multi-dimensional in-depth long-term case studies *2006 BELIV workshop.* Venice, Italy ACM Press.

SHNEIDERMAN, B. & PLAISANT, C. (2010) *Designing the user interface: Strategies for effective human-computer interaction,* Boston, MA, Addison-Wesley.

SIMONS, D. J. & LEVIN, D. T. (1997) Change blindness. *Trends in Cognitive Sciences,* 1**,** 261-267.

SLOCUM, T. A., BLOK, C., JIAN, B., KOUSSOULAKOU, A., MONTELLO, D. R., FUHRMANN, S. & HEDLEY, N. R. (2001) Cognitive and usability issues in geovisualization. *Cartography and Geographic Information Science,* 28**,** 61-75.

SLOCUM, T. A., SLUTER, R. S., KESSLER, F. C. & YODER, S. C. (2004) A qualitative evaluation of MapTime, a program for exploring spatiotemporal point data. *Cartographica,* 59**,** 43-68.

SOLOW, R. M. (1987) We'd better watch out. *The New York Times.* New York, NY.

SPENCER, D. (2009) *Card Sorting: Designing usable categories,* Brooklyn, NY, Rosenfield Media.

STOHR, E. A. & ZHAO, J. L. (2001) Workflow automation: Overview and research issues. *Information Systems Frontiers,* 3**,** 281-296.

SUCHAN, T. A. & BREWER, C. A. (2000) Qualitative methods for research on mapmaking and map use. *Professional Geographer*, 52**,** 145-154.

SUI, D. Z. & GOODCHILD, M. F. (2003) A tetradic analysis of GIS and society using McLuhan's law of the media. *Canadian Geographer,* 47**,** 5-17.

SUTHERLAND, E. H., CRESSEY, D. R. & LUCKENBILL, D. F. (Eds.) (1992) *Principles of Criminology*, Landhan, MD, AltaMira Press.

SWEENEY, M., MAGUIRE, M. & SHACKEL, B. (1993) Evaluating user-computer interaction: A framework. *International Journal of Man-Machine Studies,* 38**,** 689-711.

TAKATSUKA, M. & GAHEGAN, M. (2002) GeoVISTA Studio: A codeless visual programming environment for geoscientific data analysis and visualization. *Computers & Geosciences,* 28**,** 1131-1144.

TANAKA, M. & ICHIKAWA, T. (1988) A visual user interface for map information retrieval based on semantic significance. *Transactions on Software Engineering,* 14**,** 666-670.

THOMAS, J. J., COOK, K. A., BARTOLETTI, A., CARD, S., CARR, D., DILL, J., EARNSHAW, R., EBERT, D., EICK, S., GROSSMAN, R., HANSEN, C., JONES, D., JOY, K., KASIK, D., LAIDLAW, D., MACEACHREN, A., PLAISANT, C., RIBARSKY, B., STASKO, J., STONE, M., TURNER, A., WARD, M., WHITE, D., WONG, P. C., WOODS, D., WRIGHT, B., FISHER, B., HETZLER, B., PEUQUET, D., WHITING, M. & WHITNEY, P. (2005) *Illuminating the path: The research and development agenda for visual analytics,* Los Alametos, CA, IEEE CS Press.

TOMASZEWSKI, B. M. & MACEACHREN, A. M. (2006) A distributed spatiotemporal cognition approach to visualization in support of coordinated group activity. IN WALLE, B. V. D. & TUROFF, M. (Eds.) *3rd International ISCRAM Conference.* Newark, NJ.

TUAN, Y.-F. (2011) Cartography and Humanism: Concordances and Discordances. *Glimpse,* 8**,** 66-73.

TUKEY, J. W. (1977) *Exploratory data analysis,* Reading, MA, Addison-Wesley.

TUKEY, J. W. (1980) We need both exploratory and confirmatory. *The American Statistician,* 34**,** 23-25.

TULLIS, T. & WOOD, L. (2004) How many users are enough for a card-sorting study? *Usability Professionals Association.* Minneapolis, MN.

TURNER, A. J. (2006) *Introduction to neogeography,* O'Reilly.

TWOHIG, P. L. & PUTNAM, W. (2002) Group interviews in primary care research: Advancing the state of the art or ritualized research? *Family Practice,* 19**,** 278-284.

VALENTINE, G. (1997) Tell me about...: using interviews as a research methodology. IN FLOWERDEW, R. & MARTIN, D. (Eds.) *Methods in human geography: A guide for students doing research projects.* Essex, England, Addison Wesley Longman Limited.

VINCENTE, K. J. & WILLIGES, R. C. (1988) Accommodating individual differences in searching a hierarchical file system. *International Journal of Man-Machine Studies,* 29**,** 647-668.

WALLACE, T. R. (2011) A new map sign typology for the GeoWeb. *International Cartographic Conference.* Paris, France, International Cartographic Association.

WANG, X., MILLER, E., SMARICK, K., RIBARSKY, W. & CHANG, R. (2008) Investigative visual analysis of global terrorism. *IEEE Symposium on Visualization*, 27**,** 919-926.

WANG, Y., LIU, Y., CHEN, X. & CHEN, Y. (2001) Adaptive Geovisualization: An approach towards the design of intelligent geovisualization systems. *Journal of Geographical Sciences,* 11**,** 1-11.

WARD, M. & YANG, J. (2003) Interaction spaces in data and information visualization. IN BRUNET, P. & FELLNER, D. (Eds.) *Joint Eurographics/IEEE TCVG Symposium on Visualization.* Grenada, Spain.

WARD, M. O. (1997) Creating and manipulating n-dimensional brushes. *Joint Statistical Meeting.* Anaheim, CA.

WARDLAW, J. (2010) Principles of interaction. IN HAKLAY, M. (Ed.) *Interacting with geospatial technologies.* West Sussex, UK, Wiley-Blackwell.

WEAVER, C. (2004) Building highly-coordinated visualizations in Improvise. *Information Visualization.* Austin, TX, IEEE.

WEHREND, S. (1993) Appendix B: Taxonomy of visualization goals. IN KELLER, R. P. & KELLER, M. M. (Eds.) *Visual cues: Practical data visualization.* Los Alamitos, CA, IEEE Computer Society Press.

WEHREND, S. & LEWIS, C. (1990) A problem-oriented classification of visualization techniques. *Visualization.* San Francisco, CA, IEEE.

WHITE, J. (2009) Multi-touch interfaces and map navigation. *Geography.* Madison, WI, UW-Madison.

WHITEFIELD, A., ESCGATE, A., DENLEY, I. & BYERLEY, P. (1993) On distinguishing work tasks and enabling tasks. *Interacting with Computers*, 5**,** 333-347.

WOOD, D. (1992) *The power of maps,* New York, NY, USA, The Guilford Press.

WOOD, D. (2003a) Cartography is dead (Thank God!). *Cartographic Perspectives*, 45**,** 4-7.

WOOD, J. R. & WOOD, L. E. (2008) Card Sorting: Current practices and beyond. *Journal of Usability Studies,* 4**,** 1-6.

WOOD, M. (1993) Interacting with maps. IN MEDYCKYJ-SCOTT, D. & HEARNSHAW, H. M. (Eds.) *Human Factors in Geographical Information Systems.* London, Belhaven Press.

WOOD, M. (2003b) Some personal reflections on change...The past and future of cartography. *The Cartographic Journal*, 40**,** 111-115.

YI, J. S., KANG, Y. A., STASKO, J. T. & JACKO, J. A. (2007) Toward a deeper understanding of the role of interaction in information visualization. *Transactions on Visualization and Computer Graphics,* 13**,** 1224-1231.

ZAPF, D., BRODBECK, F. C., FRESE, M., PETERS, H. & PRUMPER, J. (1992) Errors in working with office computers: A first validation of a taxonomy for observed errors in a field setting. *International Journal of Human-Computer Interaction,* 4**,** 311-339.

ZHOU, M. X. & FEINER, S. K. (1998) Visual task characterization for automated visual discourse synthesis. *CHI '98.* Los Angeles, CA, ACM.

Vita: Robert Emmett Roth

Robert Emmett Roth is an educator and researcher interested in the topics of Cartography, Geovisualization, and Geovisual Analytics. Roth completed his doctoral studies in The Pennsylvania State Department of Geography (2007-2011) under the direction of Dr. Alan MacEachren. While at Penn State, Roth was a research assistant at the Penn State GeoVISTA Center and a researcher at the Peter R. Gould Center for Geography Education and Outreach. Roth completed his Bachelors (2002-2005) and Masters (2005-2007) studies at the University of Wisconsin-Madison Department of Geography under the direction of Dr. Mark Harrower. While at UW-Madison, Roth was a project assistant at the UW-Madison Sea Grant Institute and a cartographer at the UW-Madison Cartography Laboratory. Starting Fall 2011, Roth will be returning to the University of Wisconsin-Madison Department of Geography as an Assistant Professor of Cartography in the University of Wisconsin-Madison Department of Geography

Roth is broadly trained in the discipline of Geography with specialization in the sub-discipline of GIScience. Roth's core research areas within Cartography, Geovisualization, and Geovisual Analytics include interactive cartography, web-based mapping, cartographic design, spatiotemporal visualization, human-computer interaction (and human-map interaction), user-centered design and usability engineering, and map-supported human reasoning and decision-making, particularly under conditions of uncertainty. Roth's research has practical applications and broader impacts to domains of Crime Analysis & Crime Mapping, Environmental Science & Human-Environment Geography, Emergency Response & Crisis Management, History & Historical Geography, Intelligence Analysis, News & New Media, Resource Management, and Spatial Epidemiology & Public Health.

Roth is an active contributor to the GIScience community, coordinating multiple university and national activities and participating in a variety of academic and professional societies. At the time of submitting the dissertation, Roth served as the Assistant Editor of *Cartographic Perspectives* and the Academic Director of the Cartography Specialty Group of the Association of American Geographers. Roth also is an active member in the International Cartographic Association Commissions on Geovisualization and Use and User Issues as well as the North American Cartographic Information Society (NACIS). Among other awards and distinctions, Roth was named recipient of the 2002 Wisconsin Academic Excellence Scholarship, the 2006 CaGIS Student Scholarship, the 2007 AAG-CSG Masters Thesis Research Grant, the 2007-2008 Anne C. Wilson Graduate Fellowship (Penn State), and the 2009 USGIF Graduate Scholarship as well as winner of the 34th Annual (2006) ACSM-CaGIS Map Design Competition, the 2007 Association of American Geographers Best Website Award, the 2007 UW-Madison Geography Outstanding Teaching Assistant Award, the 2008 E. Willard Miller Award in Geography, the 2009 AAG CSG/GISSG/RSSG Illustrated Poster Competition, and the 2011 Penn State Geography Outstanding Research Assistant Award.

Roth was born in Janesville, WI (USA) and grew up in Elkhorn, WI (USA). Roth currently resides in Madison, WI.