

November 2013

Cognitive Activity Support Tools: Design of the Visual Interface

Paul Parsons

The University of Western Ontario

Supervisor

Kamran Sedig

The University of Western Ontario

Graduate Program in Computer Science

A thesis submitted in partial fulfillment of the requirements for the degree in Doctor of Philosophy

© Paul Parsons 2013

Follow this and additional works at: <https://ir.lib.uwo.ca/etd>

 Part of the [Cognition and Perception Commons](#), [Graphics and Human Computer Interfaces Commons](#), and the [Instructional Media Design Commons](#)

Recommended Citation

Parsons, Paul, "Cognitive Activity Support Tools: Design of the Visual Interface" (2013). *Electronic Thesis and Dissertation Repository*. 1708.

<https://ir.lib.uwo.ca/etd/1708>

This Dissertation/Thesis is brought to you for free and open access by Scholarship@Western. It has been accepted for inclusion in Electronic Thesis and Dissertation Repository by an authorized administrator of Scholarship@Western. For more information, please contact tadam@uwo.ca.

Cognitive Activity Support Tools: Design of the Visual Interface

(Thesis format: Integrated Article)

by

Paul Parsons

Graduate Program in Computer Science

A thesis submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

The School of Graduate and Postdoctoral Studies
The University of Western Ontario
London, Ontario, Canada

© Paul Parsons 2013

Abstract

This dissertation is broadly concerned with interactive computational tools that support the performance of complex cognitive activities, examples of which are analytical reasoning, decision making, problem solving, sense making, forecasting, and learning. Examples of tools that support such activities are visualization-based tools in the areas of: education, information visualization, personal information management, statistics, and health informatics. Such tools enable access to information and data and, through interaction, enable a human-information discourse. In a more specific sense, this dissertation is concerned with the design of the visual interface of these tools. This dissertation presents a large and comprehensive theoretical framework to support research and design. Issues treated herein include interaction design and patterns of interaction for cognitive and epistemic support; analysis of the essential properties of interactive visual representations and their influences on cognitive and perceptual processes; an analysis of the structural components of interaction and how different operational forms of interaction components affect the performance of cognitive activities; an examination of how the information-processing load should be distributed between humans and tools during the performance of complex cognitive activities; and a categorization of common visualizations according to their structure and function, and a discussion of the cognitive utility of each category. This dissertation also includes a chapter that describes the design of a cognitive activity support tool, as guided by the theoretical contributions that comprise the rest of the dissertation. Those that may find this dissertation useful include researchers and practitioners in the areas of data and information visualization, visual analytics, medical and health informatics, data science, journalism, educational technology, and digital games.

Keywords

Human-Centered Informatics, Visualization, Interaction Design, Interactivity, Visual Representations, Complex Cognition, Tasks and Activities, Human-Information Interaction, Visual Reasoning, Cognitive Tools, Epistemic Action

Co-Authorship Statement

Chapters 1 and 2 are my own original work in introducing the dissertation and providing a brief background. **Chapters 3, 4, 6, and 7** were a collaborative effort with my supervisor, Kamran Sedig. From early in my PhD studies, we worked very closely on developing the frameworks that are presented in this dissertation. Over many years of research, and through countless revisions, our ideas were blended into what is now the final product. **Chapter 5** was a collaborative effort with Kamran Sedig and two graduate students in our research group, Mark Dittmer and Robert Haworth. After an initial phase of conceptualization and writing, Mark and Robert were added to the project. Mark and Robert helped primarily by developing examples to illustrate some aspects of the framework. While doing so, they also helped to iron out some subtle terminological issues. Mark was also responsible for the creation of the figures and for coming up with the design scenario. **Chapter 8** is my own original work in describing an application of our research to the design of a cognitive activity support tool. **Chapter 9** is my own original work in drawing conclusions and summarizing the dissertation. To state my most consequential individual contribution to the research is difficult; however, it should be close to the following: the integration of seemingly disparate concepts into a unified conceptual foundation, with internal consistency and by using or creating common terminology, upon which a coherent theoretical framework for research and design could be built.

Acknowledgments

First and foremost, I would like to offer my sincerest thanks to my supervisor, Kamran Sedig. You have taught me how to be a scientist and a researcher, and what it means to do true interdisciplinary research. I am eternally grateful for your dedication. No one can hope for a better supervisor.

Special thanks goes to my examiners—Drs. Bob Mercer, Lu Xiao, Bethany White, and Judi McCuaig. Thank you for giving your time both before and during the examination, and for your helpful comments on the dissertation.

A special note of thanks goes to my beloved wife, Caity. Thank you for putting up with me these past few years when my research often left no time for other things! You are my best friend and my greatest supporter.

Finally, I offer the deepest gratitude to my parents, without whom I would not be where I am today. Thank you for your many years of support. Thank you for caring about my education, and for the many sacrifices you have made that enabled me to obtain a Ph.D.!

“In the temple of science are many mansions, and various indeed are they that dwell therein and the motives that have led them thither.”

Albert Einstein

Table of Contents

Abstract.....	ii
Co-Authorship Statement	iii
Acknowledgments	iv
Table of Contents	vi
List of Tables	ix
List of Figures.....	x
Chapter 1 Introduction.....	1
1.1 Motivation	1
1.2 Structure of the Dissertation	4
1.3 References	5
Chapter 2 Background and Terminology.....	7
2.1 Conceptual and Theoretical Background.....	7
2.2 The EDIFICE Framework.....	7
2.3 Terminology	8
2.4 Acronyms.....	9
2.5 Science, Design, and Creativity	10
2.6 References	11
Chapter 3 Interaction Design for Complex Cognitive Activities with Visual Representations: A Pattern-Based Approach	12
3.1 Introduction	12
3.2 Conceptual and Theoretical Foundations	18
3.2.1 Frameworks.....	18
3.2.2 Information and Information Space	19
3.2.3 Visual Representations	20
3.2.4 Complex Cognitive Activities, Tasks, Actions, and Events.....	22
3.2.5 Pragmatic vs. Epistemic Actions.....	24
3.2.6 Epistemic Action Patterns	25
3.2.7 Interactive Coupling and Complex Cognitive Activities	26

3.3	The EDIFICE-AP Framework	28
3.3.1	Characteristics of EDIFICE-AP	28
3.3.2	Methodology	36
3.3.3	Catalog of Action Patterns	41
3.3.4	Integrated Scenario: A Sense Making Activity	48
3.3.5	Comparison to Existing Work.....	56
3.4	Summary and Future Work	58
3.5	Acknowledgements	62
3.6	References	62
Chapter 4 Adjustable Properties of Visual Representations: Improving the Quality of Human-Information Interaction		86
4.1	Introduction	86
4.2	Interactivity: Quality of Interaction	92
4.3	Human-Information Interaction in Complex Cognitive Activities	94
4.3.1	Complex Cognitive Activities as Emergent Phenomena	95
4.3.2	Structure and Process of Human-Information Interaction in Complex Cognitive Activities	96
4.3.3	Role of Interactive VRs in Performing Complex Cognitive Activities.....	99
4.4	Related Work	101
4.5	The EDIFICE-PVR Framework	103
4.5.1	Rationale	103
4.5.2	Identification and Development of Properties.....	105
4.5.3	Properties.....	108
4.5.4	Integrated Scenario: Epidemiological Analysis	123
4.6	Discussion	128
4.6.1	Comparison to Existing Work.....	130
4.7	Summary and Future Work	132
4.8	Acknowledgments	134
4.9	References	135
Chapter 5 Human-centered interactivity of visualization tools: Micro- and macro-level considerations		149
5.1	Abstract	149

Chapter 6 Distribution of information processing while performing complex cognitive activities with visualization tools.....	151
6.1 Abstract.....	151
Chapter 7 Common Visualizations: Their Cognitive Utility	153
7.1 Abstract.....	153
Chapter 8 Research Application: Design of a Cognitive Activity Support Tool.....	155
8.1 Introduction and Motivation.....	155
8.2 Background and Context.....	157
8.2.1 Information Space	157
8.2.2 Tasks and Activities	158
8.2.3 Implementation Details	158
8.3 Design Process.....	159
8.3.1 Choice of Visual Representations	159
8.3.2 Interaction and Interactivity Design	160
8.4 Summary.....	171
8.5 References.....	171
Chapter 9 Summary, Contributions, and Future Work	173
9.1 Chapter Summaries and Contributions	173
9.2 General Contributions and Conclusions	177
9.2.1 Scientific and Research Contribution.....	177
9.2.2 Design Contribution	178
9.3 Future Work	178
9.3.1 Descriptive and Explanatory Models, Taxonomies, and Frameworks	179
9.3.2 Prescriptive Design Support.....	181
9.3.3 Empirical Studies	182
Chapter 10 Appendices.....	184
10.1 Additional Action Patterns	184
10.1.1 Unipolar Actions	184
10.1.2 Bipolar Actions	203
10.2 List of Examined CASTS for EDIFICE-PVR.....	213
Curriculum Vitae	216

List of Tables

Table 3-1 Catalog of epistemic action patterns.....	41
Table 4-1 Essential properties of interactive VRs, the values of which should be made adjustable to provide better support for the performance of complex cognitive activities.	108

List of Figures

Figure 3-1 Action choices operating as mental tentacles to reach into an information space.....	29
Figure 3-2 The hierarchical structure of a complex cognitive activity and its emergence over time.	30
Figure 3-3 The human-information interaction epistemic cycle.....	32
Figure 3-4 An implementation of the scoping pattern: Acting upon a VR of a 4D shape to explore its compositional structure.	44
Figure 3-5 An implementation of the translating pattern: Acting upon a VR to convert it from one form to another.	46
Figure 3-6 An implementation of the collapsing and expanding patterns: Acting upon a VR to fold in and fold out some of its constituent components.....	48
Figure 3-7 Filtering a VR to display only stocks with high relative activity.....	50
Figure 3-8 Comparing the Microsoft and IBM stocks.....	51
Figure 3-9 Arranging a VR to reorder it according to market capitalization (L) and trading activity (R).....	52
Figure 3-10 Translating the Treemap VR (L) to an alternative form (R).....	53
Figure 3-11 Different actions allow the user to operate on represented information in different ways, and to mentally 'reach into' an information space.....	55
Figure 3-12 Emergence of the overall sense making activity over time from the performance of actions, tasks, and activities.	56
Figure 4-1 The structure and process of CAST-mediated human-information interaction	99

Figure 4-2 The performance of a cognitive activity through information discourse that is mediated by a CAST.....	101
Figure 4-3 Adjusting the value of complexity of a VR.	111
Figure 4-4 Adjusting the value of configuration of a VR.....	113
Figure 4-5 Adjusting the value of density of a VR.....	114
Figure 4-6 Adjusting the value of geometric fidelity of a VR.....	117
Figure 4-7 Adjusting the value of fragmentation of a VR.....	118
Figure 4-8 Adjusting the value of interiority of a VR.	120
Figure 4-9 Adjusting the value of scope of a VR.	121
Figure 4-10 Adjusting the value of type of a VR.....	123
Figure 4-11 VR of disease occurrences and relationships (L). Adjusting the scope of the VR to locate the origin of the disease and determine its direction of spread (R).	125
Figure 4-12 Adjusting interiority value to encode latent information.	126
Figure 4-13 Adjusting values of properties during the performance of an analytical reasoning activity.....	127
Figure 4-14 Considering the properties of EDIFICE-PVR in an integrated manner for design and evaluation.....	127
Figure 8-1 The four VRs used in this tool to support the overall sense making activity.	160
Figure 8-2 The result of arranging the VR according to departments to which individuals belong.....	162
Figure 8-3 The result of multiple instances of an arranging action where the position of individual items is changed.....	162

Figure 8-4 Successive stages of a scoping action, showing growth of the network until 2009 (L), 2010 (TR), and 2011 (BR).....	163
Figure 8-5 An implementation of the searching pattern.	164
Figure 8-6 The result of the user translating the VR.	165
Figure 8-7 Adjusting the density setting of the VR to assist with identifying clusters of collaboration.	166
Figure 8-8 An implementation of the transforming pattern to adjust the appearance of the VR.	167
Figure 8-9 Adjusting the settings of the VR to increase the fragmentation (L to R).....	168
Figure 8-10 Combining filtering and scoping to show co-publications between two departments until 2010 (L) and 2012 (R).	170
Figure 9-1 Major aspects of the dissertation as components of a coherent framework..	176
Figure 10-1 An implementation of the annotating pattern: Acting upon a VR to add a layer of personal meta-information.....	186
Figure 10-2 An implementation of the cloning pattern: Acting upon a VR of a protein network to duplicate a portion of it.....	190
Figure 10-3 An implementation of the measuring pattern: Acting upon a VR to quantify one of its angles.	195
Figure 10-4 An implementation of the navigating pattern: Acting upon a VR to move across its components.	197
Figure 10-5 An implementation of the searching pattern: Acting upon a VR to seek out the existence of items related to 'neck pain'.....	198
Figure 10-6 An implementation of the transforming pattern: Acting upon a VR to fold it © 2010 IEEE.....	202

Figure 10-7 An implementation of the composing/decomposing patterns: Acting upon VRs to bind them to create a VR of the human foot or to break them into constituent components. 207

Figure 10-8 An implementation of the gathering/discarding pattern: Acting upon VRs to place them into a temporary collection. 208

Figure 10-9 An implementation of the linking/unlinking patterns: Acting upon VRs to explicitly establish relationships among them. 211

Chapter 1 Introduction

The general concern of this dissertation lies at the intersection of interactive computational technology, informatics, and human cognition. While residing within the domain of computer science, this dissertation draws from research in the following areas: cognitive psychology, educational psychology, information visualization, human-computer interaction, information science, and philosophy of mind. As a result of its interdisciplinary nature, ascribing a single, descriptive label to this dissertation is a difficult task. If one performs a search for the term *human-centered* (or *-centric*) within this dissertation, it will become evident that it is used consistently throughout to modify important concepts—e.g., as in human-centered: visualization, informatics, approach, perspective, research, and design. Thus, while this research is certainly concerned with technological issues, and may in particular contexts focus almost exclusively on them, the ultimate focus is always on how computational technology can best enhance and support the cognitive needs, preferences, and characteristics of its human users. Although the more particular concerns of this dissertation should become clear as one peruses its contents, this brief introduction will hopefully give the reader a general idea of what this dissertation is about.

1.1 Motivation

It is not uncommon nowadays to encounter concerns about how we manage and work with information, in both the popular and scholarly media and literature. Such concerns—often expressed idiomatically as *information overload*, *information explosion*, *information anxiety*, and others—are not new, however, and have been voiced

consistently throughout history. Two thousand years ago, Seneca complained about the “abundance of books”, suggesting that it was “a distraction” (Blair, 2010, p. 15).

Erasmus, living after the invention of the printing press, disdainfully longed for a place on earth that was exempt from the “swarms of new books” (Barker, 2001, p. 145). While their concerns were centered mostly on ‘inferior’ information being overabundant and more accessible than ‘useful’ information, such statements, along with a host of other recorded examples, attest to the enduring concern for how and why people access, manage, and use the information that is available to them in their own time.

Although historical antecedents exist, there seem to be at least two distinctive characteristics of the information concerns with which we are currently challenged: 1) A much larger segment of the population than in any previous time is engaged in information-intensive knowledge work in their daily lives. This includes, among others, scientists, clinicians, journalists, doctors, lawyers, librarians, students, engineers, policy makers, and analysts. While in previous times information overload was mostly the concern of scholars, this is perhaps the first time that such a concern is shared by and affects the general population. 2) The ubiquity of computational technology adds new dimensions to age-old information concerns. A large portion of the population—including, but not even limited to, the aforementioned ‘knowledge workers’—regularly uses computational devices to access and work with digital information. Related to the ubiquity of computational technology is the proliferation of devices that are capturing data at a pace never seen before. Making sense of and analyzing such data—whether in the realm of genomics, climate science, astronomy, healthcare, education, urban planning, agriculture, or otherwise—is becoming increasingly important for dealing with challenges of the 21st century.

Since the beginning of recorded history, human beings have utilized visual representations to preserve, access, communicate, and work with information. Indeed, the use of visual representations for such purposes—early examples include cave drawings and bone etchings—reportedly predates the systematic use of written natural language by approximately 25,000 years (Massironi, 2012). From the cave drawings of the early humans to the statistical graphics of the Enlightenment thinkers, one underlying feature

remains constant: the use of visual representations to communicate information and to support the performance of cognitive activities. Such cognitive activities range from the simple (e.g., identifying the location of a food source with a cave painting) to the more complex (e.g., making sense of the origin and spread of a disease with a geospatial map). While present-day visual representations share many characteristics with ancient cave drawings and Enlightenment-era charts, modern computational technology—on which visual representations are being increasingly displayed—adds some significant features: namely, information processing, automation, and interactivity. One could say that modern computational technology has brought visual representations to life. These additional features, as will be demonstrated throughout the dissertation, add great potential for visual representations to support human cognitive activities—especially those at the more complex end of the spectrum.

In today's information society, the aforementioned knowledge workers are constantly engaged in information-intensive, complex cognitive activities. Moreover, they regularly use interactive visual representations to support such activities. A quick survey of the literature of the past few years reveals a number of examples: social scientists using interactive visual representations to assist with social network analysis (e.g., Krempel, 2011); biologists using interactive visual representations for analysis of gene expressions (e.g., Melo et al., 2013); clinicians using interactive visual representations for decision support and promotion of evidence-based medicine (e.g., Mane et al., 2012); journalists using interactive visual representations for telling data-driven stories (e.g., Weber & Rall, 2012); policy makers using interactive visual representations for predicting climate change impacts and developing policy responses (e.g., Bennett et al., 2012); and many other examples too numerous to list here. While once a marginal interest of only a small group of computer scientists, psychologists, and statisticians, interactive visual representations are now entering the lives and discourse of seemingly all knowledge workers. Therefore, if we are to effectively deal with the information challenges of our time, we would do well to carefully investigate the use of interactive visual representations in supporting our information-intensive cognitive activities. Such is the intent of this dissertation.

1.2 Structure of the Dissertation

The rest of this dissertation is broken into 8 chapters as follows:

Chapter 2 briefly discusses the issue of conceptual and theoretical background for the dissertation, clarifies the use of some synonymous terms, and briefly discusses the intention of the research presented herein with regard to its scientific contribution and its role in supporting design.

Chapter 3 syncretizes a number of foundational concepts related to interaction and complex cognitive activities into a coherent theoretical framework. Included in the framework is a catalog of 32 fundamental epistemic action patterns, with each action pattern being characterized and examined in terms of its utility in supporting different complex cognitive activities.

Chapter 4 presents 10 properties of interactive visual representations that are essential, relational, and whose values can be adjusted through interaction. By adjusting the values of these properties, better coordination between humans and tools can be effected, leading to higher-quality performance of complex cognitive activities.

Chapter 5 presents a framework that analyzes interactivity, where interactivity is conceptualized as the quality of interaction. As interactivity is a broad and complex construct, it is categorized into two levels: micro and macro. Interactivity at the micro level emerges from the structural elements of individual interactions. Interactivity at the macro level emerges from the combination, sequencing, and aggregate properties and relationships of interactions as a user performs an activity. Twelve micro-level interactivity elements and five macro-level interactivity factors are identified and characterized.

Chapter 6 examines the issue of the distribution of information processing between humans and tools during the performance of complex cognitive activities. The chapter

identifies and elaborates upon some key concerns, integrates some fundamental concepts, and highlights some current research gaps that require future study.

Chapter 7 divides visual representations into six high-level categories, and discusses their perceptual and cognitive influences, with a concerted effort to identify utility for complex cognitive activities. Most typical visual representations are instantiations of one or a combination of multiple of these abstract categories.

Chapter 8 presents an application of the research in the previous chapters. In this chapter, the design of the visual interface of a cognitive activity support tool is described. This chapter demonstrates how the research in this dissertation can enable systematic and principled design of interactive tools for supporting complex cognitive activities.

Chapter 9 draws some conclusions from the research reported in the previous chapters, postulates on the contributions of this research to the wider scientific community, and suggests some possible lines of future work.

It should be noted that while the dissertation can be read sequentially from beginning to end, particular chapters of interest can be read in isolation. Chapters 3,4,5,6, and 7 have been published individually, and each one is thus self-contained and meant to be read on its own.

1.3 References

- Barker, W. (2001). *The Adages of Erasmus*. Toronto: University of Toronto Press
- Bennett, R., Senot, H., Pettit, C. J., Aurambout, J.-P., Sheth, F., Soste, L., & Sposito, V. (2012). Using digital globes to visualize climate change impact. In W. Shi, M. F. Goodchild, B. Lees, & Y. Leung (Eds.), *Advances in Geo-Spatial Information Science*, pp. 205-218. London, UK: Taylor & Francis.
- Blair, A. M. (2010). *Too Much to Know: Managing Scholarly Information before the Modern Age*. Newhaven, CT: Yale University Press.
- Krempel, L. (2011). Network Visualization. In J. Scott & P. J. Carrington (Eds.), *The SAGE Handbook of Social Network Analysis*, pp. 558-577. London, UK: Sage Publications.

- Mane, K. K., Bizon, C., Schmitt, C., Ownen, P., Burchett, B., Pietrobon, R. & Gersing, K. (2012). VisualDecisionLinc: A visual analytics approach for comparative effectiveness-based clinical decision support in psychiatry. *Journal of Biomedical Informatics* 45(1), 101-106.
- Massironi, M. (2002). *The Psychology of Graphic Images: Seeing, Drawing, Communicating*. Mahwah, NJ: Lawrence Erlbaum Associates.
- Melo, C., Orphanides, C., McLeod, K., Aufaure, M.-A., Andrews, S., & Burger, A. (2013). *A conceptual approach to gene expression analysis enhanced by visual analytics*. In Proceedings of the 28th Annual ACM Symposium on Applied Computing (SAC '13), Coimbra, Portugal, pp. 1314-1319. NY: ACM.
- Weber, W. & Rall, H. (2012). Data visualization in online journalism and its implications for the production process. In Proceedings of the 16th International Conference on Information Visualization (IV '12), Montpellier, France, pp. 349-356, Danvers, MA: IEEE.

Chapter 2 Background and Terminology

2.1 Conceptual and Theoretical Background

In this dissertation each chapter is self-contained. Therefore, each one provides a conceptual background that is appropriate for its own content. In addition, Chapter 3 likely provides adequate background information for any reader to proceed with the rest of the dissertation. Although customary to provide a background chapter in which fundamental concepts and assumptions are explicated, to repeat this information here is unnecessary and would likely make for tedious reading. The reader can simply proceed to Chapter 3 to gain a conceptual and theoretical background necessary for comprehending the remainder of the dissertation. However, if the reader is interested in a very thorough background, the following sections should be perused: 3.1, 3.2, 4.1-4.4, 5.1-5.3, 6.1-6.3, 7.1, and 7.2. It is worth noting here that there is some repetition across the chapters, mostly concentrated in the background sections listed above. Such is an inevitable result of having self-contained chapters.

2.2 The EDIFICE Framework

While all of the research contained in this dissertation is oriented toward the same general goal, three of the chapters have more particular goals, and are components of a large framework called EDIFICE (Epistemology and Design of human-InFormation Interaction in complex Cognitive activitiEs). The motivation behind developing EDIFICE was a lack of general theories and comprehensive frameworks concerned with human-information interaction for complex cognitive activities (see Sections 3.2.1, 3.3.1, 3.3.5, and 4.5.1 for

elaboration on this issue). Thus the goal of EDIFICE is a general, comprehensive, and syncretic theoretical framework that can facilitate systematic research and design. The three chapters that comprise EDIFICE are Chapters 3, 4, and 5. As components of EDIFICE, they are given identifying acronyms: EDIFICE-AP (Action Patterns), EDIFICE-PVR (Properties of Visual Representations), and EDIFICE-IVT (Interactivity of Visualization Tools), applying to Chapters 3, 4, and 5 respectively. Chapters 6 and 7, while not formal components of EDIFICE, are compatible with and complement the other chapters. A fourth component of EDIFICE, concerned with the systematic design of visual representations, is currently under development and should be available sometime in the near future.

2.3 Terminology

As each chapter of this dissertation was written for a particular audience and venue, different terms have been used to refer to the same underlying concepts. The main terms are listed below in an attempt to remove any confusion that may arise in the mind of the reader.

- **User, actor, human:** *User* and *actor* are particular categories relative to the universal *human*, and thus emphasize certain characteristics of the universal concept—namely, in the context of this dissertation, humans that use or make use of a tool, and humans that act and perform activities with tools (see Section 4.1 for a brief comparison of these two terms). When the term *human* is used—e.g., as in human-centered design—it is generally used to emphasize more universal characteristics of *humanness* (e.g., perceptual and cognitive characteristics) rather than the particular habits or preferences of a certain group of users or actors. For the most part, however, it would not do any great harm to think of these terms as synonymous while reading this dissertation.
- **Visualization, visual representation:** As discussed elsewhere in this dissertation, one of the problems with the current state of research is a lack of common and

consistent vocabulary. When the term *visualization* is used in the existing literature, it is often not clear whether it refers to a whole tool, to a process (as in the process of encoding, representing, or visualizing), or to an instance (i.e., a visual representation). In each chapter, distinctions have been made between visualization tool, visualization as a process, and visual representations (see also Section 7.2.1 for a brief discussion). The acronyms VT (Visualization Tool) and VR (Visual Representation) are frequently used. When the term *visualization* is used, the context should be sufficient to determine its meaning.

- **Visualization tool, cognitive activity support tool:** Section 3.1 describes the motivation for inventing (as far as we know) and using the term *cognitive activity support tool* (CAST). Because CAST is not a widely used term in the literature, we have also used the term visualization tool (VT) in certain chapters, as it was more appropriate for the publication venue and audience. While there are differences in these two terms, they can be treated as synonymous throughout the dissertation without any repercussions.

2.4 Acronyms

A complete list of acronyms used throughout the dissertation is given below.

- CAST: Cognitive Activity Support Tool
- EDIFICE: Epistemology and Design of human-InFormation Interaction in complex Cognitive activitiEs
- EDIFICE-AP: Action Patterns
- EDIFICE-PVR: Properties of Visual Representations
- EDIFICE-IVT: Interactivity of Visualization Tools
- VR: Visual Representation
- VT: Visualization Tool

2.5 Science, Design, and Creativity

One major goal of this research has been to encourage and facilitate a more scientific approach to the conceptualization and analysis of human-information interaction for complex cognitive activities, as well as to the design and evaluation of tools that support such activities. Accordingly, this dissertation shares the goals of all scientific endeavors—to systematically and coherently explain, describe, and/or predict the properties and relationships of some phenomena under investigation. Thus, although this research is intended to facilitate design, it is not geared towards purely subjective and arbitrary issues that tend to fall under the purview of the applied arts. However, although the concern here is with design based on scientific principles and coherent theoretical foundations, creativity in the design process is not precluded. In much the same way that an architect may use abstract principles of physics and mathematics to design a building, and yet still have infinite creativity at more concrete levels of design, designers of tools for supporting cognitive activities can use the research herein as a foundation for sound design, and still have a large degree of creativity at the level of implementation.

There is a long history in the area of design theory concerning the role of logic, rationality, and method in design (see Alexander, 1964, Cross, 1981, 2011; Gedenryd, 1998; Stolterman, 2008). Early attempts to turn design into a science seem to have given way to a more dichotomous attitude about the nature of science and design. As design theorist Nigel Cross has recently noted, designers and scientists have radically different goals: “Unlike the scientist, who searches for many cases to substantiate a rule, and then one case to falsify it, the designer can be gratified in being able to produce just one satisfactory case that gives an appropriate result.” (Cross, 2011, p. 28). This separation of goals does not, however, remove the possibility incorporating a scientific (i.e., systematic, disciplined, consistent) attitude into the design process. In addition, while surely some degree of successful design is based on intuition, careful study shows that there is usually an underlying repertoire of precedents from a designer’s experience that actually informs what is often perceived to be intuition (Cross, 2011). Furthermore, not only do designers need a repertoire of precedents to draw from, they also need some conceptual structure to support systematic design thinking and to canalize the design

process (Chapter 9 deals with this issue in more detail). A review of design studies suggests that designers appreciate and are inclined to use “frameworks that do not prescribe but that support reflection and decision-making”, and “high-level theoretical and/or philosophical ideas and approaches that expand design thinking” (Stolterman, 2008, p. 63). It is hoped that the research presented in this dissertation will not only motivate further scientific investigation, but will also inform designers and inspire them to create tools that extend the reaches of the human mind.

2.6 References

- Alexander, C. (1964). *Notes on the Synthesis of Form*. Harvard University Press. Cambridge, MA.
- Cross, N. (1981). Design method and scientific method. *Design Studies*, 2(4), 195-201.
- Cross, N. (2011). *Design Thinking: Understanding how Designers Think and Work*. Berg, Oxford, UK.
- Gedenryd, H. (1998). *How Designers Think*. Doctoral Dissertation. Lund University.
- Stolterman, E. (2008). The nature of design practice and implications for interaction design research. *International Journal of Design* 2(1), 55-65.

Chapter 3 Interaction Design for Complex Cognitive Activities with Visual Representations: A Pattern-Based Approach

This chapter has been published as Sedig, K. and P. Parsons (2013). Interaction Design for Complex Cognitive Activities with Visual Representations: A Pattern-Based Approach, *AIS Transactions on Human-Computer Interaction* 5(2), 84-133.

Please note that the format has been changed to match the format of the dissertation. Figure numbers mentioned herein are relative to the chapter number. For instance, “Figure 1” corresponds to Figure 3-1. Additionally, when the term “paper” is used, it refers to this particular chapter.

3.1 Introduction

Many common activities nowadays are information-intensive and involve complex human cognition (Funke, 2010; Sternberg and Ben-Zeev, 2001). Such activities include decision making, problem solving, sense making, learning, and analysing, all of which can be referred to as complex cognitive activities (see Ericsson and Hastie, 1994). Knauff and Wolf (2010) identified two essential characteristics of complex cognitive activities: 1) the use of complex psychological processes, and 2) the presence of complex conditions. That is, complex cognitive activities are emergent and rely on the combination and interaction of more elementary processes such as perception and

memory. Furthermore, they may involve many variables that exhibit a high level of interdependence and may change over time.

In recent years, computational tools and technologies have become deeply embedded in the performance of many complex cognitive activities (Dascal and Dror, 2005). These technologies play two important roles: *epistemic* and *ontic* (Brey, 2005). In their epistemic role, they act as tools that extend, partner, supplement, and support human cognitive faculties and functioning by maintaining, operating upon, and displaying digital information. In their ontic role, they act as tools that extend the world and simulate it. In this paper, we are concerned with the epistemic role of these computational tools, particularly as it relates to the aforementioned complex cognitive activities. In this role, depending on the context and activity for which they are used, different terms are used to refer to them, such as cognitive technologies, decision support systems, knowledge support systems, cognitive tools, learning support tools, mind tools, and the like (e.g., Markus et al., 2002; Fischer and Sharff, 1998; Kim and Reeves, 2007; Bhargava et al., 2007; Sedig and Liang, 2008). As the focus here is on tools that mediate and enable complex cognitive activities, we unify all of them under one umbrella term to emphasize their epistemic support role, and will henceforth refer to all such tools as *cognitive activity support tools* (CASTs). In this context, the term ‘support’ suggests that CASTs can partner, distribute, augment, amplify, canalize, guide, offload, cognize with, shape, and/or transform human activities and thinking. Additionally, we broadly refer to people who use these tools as users, even though other terms, such as knowledge worker, learner, problem solver, analyzer, planner, or decision maker, can be contextually more accurate.

To perform complex cognitive activities, different types of CASTs with varying degrees of complexity are used. Such tools include library and research collection tools, drug analysis tools, knowledge mapping tools, financial analysis tools, virtual science museums, genome analysis tools, mathematical investigation software, social network visualizations, geovisualization tools, crime analysis tools, public health informatics tools, and business modelling tools (see e.g., MacEachren et al., 2004; Fast and Sedig, 2011; Shannon et al., 2003; Wagner, 2003; Xu and Chen, 2005; Thomas and Cook, 2005;

Sedig et al., 2012b). The information with which users of CASTs interact can originate from all kinds of concrete or abstract sources, such as genes and other biological phenomena, historical records, scientific experiments, mathematical objects and processes, hospitals and medical clinics, research and social networks, library collections, and financial markets. For the purposes of this paper, the common feature of all CASTs is that they have a visually perceptible interface that mediates between a user and information. This is done by providing interaction mechanisms through which users can access and process displayed representations of information as well as input new information into the CASTs. Hence, these tools participate in the interplay between external representations of information and internal mental representations of users. Accordingly, the epistemic locus of CASTs is their information interface (Lovett and Shah, 2007; Sedig, 2008).

Viewed from this perspective, we can identify two main components that comprise the information interface of CASTs: representation and interaction (Sedig, 2004; Yi et al., 2007). Design of the representation component of CASTs is concerned with how information can and should be *encoded* and displayed. The purpose of this component is to support users in their perceptual as well as their cognitive processing of the information. Design of the interaction component of CASTs is concerned with what users can and should *do* with the represented information, what *actions* should be made available to them to work and think with the represented information, and what their subsequent *reactions* should be. The focus of interaction design, then, is on the discourse that takes place between users and the represented information. It is through interaction with the represented information that users can restructure and modify the form and amount of displayed information in order to optimize and enhance its epistemic utility for performing complex cognitive activities. Hence, the representation and interaction components of the interface are at the heart of the epistemic role that CASTs play. The proper and systematic design of both these components, then, determines the degree of epistemic utility of CASTs, and how well they support their users' cognitive processes and activities (Sedig et al., 2001, 2003, 2005; Liang and Sedig, 2010; Thomas and Cook, 2005).

Although some fundamental concepts and techniques regarding representation and interaction design have been in place for a while (e.g., Bertin, 1983; Beynon et al., 2001; Lohse et al., 1994; Shneiderman, 1991; Tufte, 1983; Yi et al., 2007), many researchers suggest that we do not yet have a generalized, principled, and systematic understanding of the representation and interaction components of CASTs, and how these two components should be analyzed, designed, and integrated to support complex cognitive activities. For instance, in their seminal report on visual analytics, Thomas and Cook (2005) stated that “we lack fundamental understanding of the basic principles for effectively conveying information using graphical techniques” (p. 70), and that “although a lot of isolated design work has been done in specific aspects of interaction science, little systematic examination of the design space has been done” (p. 76). While this was stated a number of years ago, numerous researchers have more recently suggested that this is an extant issue. Consider the following statements:

- “the process of stimulating and enabling human reasoning with the aid of interactive visualization tools is still a highly unexplored field.” (Meyer et al., 2010, p. 227);
- “with all of this research, there is still a lack of precedent on how to conduct research into visually enabled reasoning. It is not at all clear how one might evaluate interfaces with respect to their ability to scaffold higher-order cognitive tasks.” (Green and Fisher, 2011, p. 45);
- “we still know little about the effectiveness of graphic displays for space-time problem solving and behavior, exploratory data analysis, knowledge exploration, learning, and decision-making”. (Fabrikant, 2011, p. 1);
- “there is hardly ever an explanation of what these benefits [of interaction] actually are as well as how and why they work.” (Aigner, 2011, p. 18); and,
- “we have barely scratched the surface of this exciting new line of research [regarding interaction], and much work remains to be done.” (Elmqvist et al., 2011, p. 337).

What becomes evident from surveying existing literature is that research that does exist is insufficient, and that there are no *comprehensive frameworks* that support researchers and

practitioners in terms of understanding *how these two components relate in the context of performing complex cognitive activities*. The relevant body of research dealing with these components is fragmentary and scattered across a set of disciplines (such as cognitive and learning sciences, information visualization, educational technologies, visual analytics, and human-computer interaction), often involving minimal interaction and collaboration between them.

Many researchers concerned with different facets of human-information interaction have recently suggested that a necessary theoretical substrate is not well developed (e.g., Fidel, 2012; Kaptelinin and Nardi, 2012; Liu and Stasko, 2010; Purchase et al., 2008; Sedig et al., 2013). Such is to be expected, however, as this is a relatively young research area. Indeed, it is typically the case that the theoretical scope of any scientific discipline expands to become generally applicable and to encompass a wide range of phenomena only after an initial phase of specialization and division (Bohm and Peat, 1987). While discussing the development of scientific theories, von Baeyer suggests that “increased abstraction is the hallmark of growing maturity” (2004, p. 36) of any scientific discipline. Recent emphasis on the need for a more coherent and abstract theory of interaction and its related areas may signify an important stage in the evolution and growing maturity of human-information interaction research. The development of such a theoretical framework is one of the goals of this paper.

Throughout the past decade, a number of researchers have been working on the development of frameworks dealing with different aspects and levels of interaction design, such as benefits, costs, activities, techniques, and tasks (Amar et al., 2004; Amar and Stasko, 2005; Gotz and Zhou, 2008; Lam, 2008; Sedig and Sumner, 2006; Shrinivasan and van Vijk, 2008; Liu and Stasko, 2010; Nakakoji and Yamamoto, 2003; Yi et al., 2007; Pike et al., 2009; Fast and Sedig, 2011). Much of this research has been in the context of specific domains and tools, such as visual analytics and information visualization (e.g., Pike et al., 2009; Gotz and Zhou, 2008; Liu and Stasko, 2010). Being focused only on certain types of CASTs and domains, this research has analyzed a limited set of complex cognitive activities (e.g., analytical reasoning and sense making) and tasks (e.g., computing derived values, determining range, and finding extreme

values). As valuable as this research is, it has not been—and cannot be—generalized beyond these CASTs and their pertinent activities, tasks, representations, interactions, and users, to sufficiently address the theoretical need discussed above. For instance, an oft-quoted and valuable prescription “overview first, zoom and filter, details-on-demand” (Shneiderman, 1996), which is applicable to some information visualization tools, does not necessarily generalize to other types of CASTs and their related representations and complex cognitive activities (e.g., see Sedig et al., 2001).

This paper presents a framework that supports systematic thinking about interaction design for complex cognitive activities. The framework has been developed to have the following four important characteristics, which position it to address existing research gaps and challenges and to make a valuable contribution to the existing literature: 1) to be syncretic, unifying a number of previously disconnected ideas into a coherent theoretical model; 2) to be general, operating at a level of abstraction that is applicable to all kinds of technologies, activities, users, and visual representations; 3) to be comprehensive, identifying patterns that cover an extensive range of actions; and, 4) to be generative, possessing the ability to motivate design creativity as well as to stimulate further theoretical and applied research.

No one framework or paradigm can address all possible tasks and situations (Purchase et al., 2008; Thomas and Cook, 2005). Accordingly, this paper is not complete in its characterization, but is a part of a broader research agenda to develop a comprehensive, principled, and systematic framework concerned with the information interface of CASTs, called EDIFICE (Epistemology and Design of human-InFormation Interaction in complex Cognitive activitiEs). This paper complements the other components of EDIFICE, which include: 1) a framework dealing with the design of visual representations, 2) a framework dealing with the analysis of the ontological properties of visual representations that affect the performance of complex cognitive activities, and 3) a framework dealing with the detailed analysis of the anatomical structure of an individual interaction as well as the manner in which interactions are combined and integrated during the performance of complex cognitive activities. The component of EDIFICE that is developed in this paper deals with the interaction design of CASTs. The

interaction that takes place between a user and a CAST can be characterized at multiple levels of granularity (see Sedig et al., 2013). Such levels include macro-level activities, tasks, individual actions and reactions (i.e., interactions), and micro-level events. Even though this paper discusses interaction at all these levels, its focus is mainly on interaction at the level of individual actions and reactions, dealing primarily with pattern-based characterizations of actions and their utility in supporting complex cognitive activities. Because this framework is human-centered, focusing on the action component of interaction, and because it takes a pattern-based approach, we will henceforth refer to it as EDIFICE-AP (where AP stands for Action Patterns).

The rest of this paper is divided into 3 main sections: 1) conceptual and theoretical foundations; 2) the EDIFICE-AP framework; and 3) summary and future directions.

3.2 Conceptual and Theoretical Foundations

This section serves a twofold function. First, it examines the utility of, and need for, frameworks; second, it identifies and explicates a number of terms and concepts that are necessary for discussing human-information interaction in the context of CASTs. These terms and concepts have been used in different contexts often with different meanings and connotations. It is necessary, therefore, to characterize them and examine their relationships before presenting the EDIFICE-AP framework.

3.2.1 Frameworks

Since the time of Plato and Aristotle, frameworks and classification systems have played an important role in systematic and scientific exploration of phenomena (Darian, 2003). Conducting research to develop frameworks, taxonomies, and models is crucial to the advancement of any discipline, including the analysis and design of computational tools (Carroll, 1991; Heller et al. 2001; Hult et al., 2006). Bederson and Shneiderman (2003) enumerate five roles for this type of research: 1) *describe* (characterize objects and actions in a systematic manner to provide clear language and enable cooperation), 2)

explain (explain processes to support education), 3) *predict* (predict performance in different situations), 4) *prescribe* (suggest guidelines and best practices), and 5) *generate* (facilitate innovation). In the case of interaction design for CASTs, a framework concerned with epistemic action patterns can serve each of these roles. Moreover, by classifying the space of potential actions and characterizing these actions, a catalog of action patterns can provide a common language for referring to potential actions, and can provide opportunities for their systematic analysis and comparison. As we try to design CASTs that require attentive, mindful engagement with information, some researchers are highlighting the importance of careful study of the *transactions* that users make as they interact with these tools (e.g., Kim and Reeves, 2007; Brey, 2005; Dascal and Dror, 2005; Thomas and Cook, 2005). A framework such as EDIFICE-AP can provide investigators with a systematic support structure for thinking about these transactions. Without frameworks that organize and characterize fundamental aspects of the interaction design space, the approach to both research and practice must be largely ad-hoc and rely mostly on personal anecdotes and intuition.

3.2.2 Information and Information Space

Information can originate from many different sources (Bates, 2006). These sources can be concrete (e.g., a molecule), existing within a physical space, or abstract (e.g., financial markets), originating from a non-tangible, non-perceptible source. An information space is an environment, source, domain, place, or area of containment from which a body of information originates. The concept of information does not yet have a universally agreed-upon definition, and is defined in different ways depending on the context in which it is used (Marchionini, 2010). We adopt Bates' (2005, 2006) definition of information—that information is the pattern of organization of matter and energy—e.g., physical objects, energy fields and forces, conceptual structures, and semantic relationships. This definition of information is broad and encompasses all visible, invisible, concrete, and abstract organizational patterns and sources—micro entities (e.g., DNA structure of a cell), hard-to-reach entities (e.g., rocks on distant planets), and non-physical entities (e.g., scientific concepts). Information by itself does not have inherent meaning. Meaning must be *assigned* to it (Stonier, 1990). For instance, electromagnetic

waves travelling through space have no meaning until they are interpreted in a contextual setting. As such, giving meaning to information and integrating it into other pre-existing mental forms is an essential feature of any complex cognitive activity (Bates, 2005; Sternberg and Ben-Zeev, 2001).

When performing complex cognitive activities, users often need to access and combine information from different sources. For instance, an analyst reasoning about a financial event may need to access financial records, historical reports, legal information, and social or business networks. As CASTs can mediate access to any blending of different sources of information in a seamless manner, in this paper the term *information space* refers to any source of information, whether simple and from a single domain or complex and spanning multiple sources. It is important to note that in some research areas, the term information space refers to a dataset or the data records in a database. In this paper, however, we use the term in its broadest sense, encompassing datasets and data records—whether structured or unstructured, homogeneous or heterogeneous, dynamic or static—as well as web logs, images, videos, text documents, and any other item or collection of items that contains information. For instance, an analyst could be working with multiple datasets, streams of incoming data, unstructured text documents, audio and video recordings, and photographs, all of which are contained within the information space with which the analyst is concerned.

3.2.3 Visual Representations

Because CASTs are computational environments, all information within them, whether originating from concrete or abstract spaces, needs to be visually encoded in a representational form at the interface of the tool to be accessible to users. Therefore, a representation acts as a perceptible form within which an information space's items are encoded. Consequently, the representation, acting as a mental interface, can connect the human mind to the information space. In this paper, we refer to external representations displayed at the interface of CASTs as visual representations (VRs). Instances of VRs include diagrams, maps, photographs, glyphs, tables, scatter plots, node-link trees, text, and videos. Although VRs give information a tangible form, making it accessible at the

interface, they seldom encode the totality of an information space. VRs usually encode only *a subset* of an information space. To provide an example, an information space may consist of climate data from a 100-year period. A given VR would be unlikely to encode the whole space (information regarding temperature, humidity, rainfall, atmospheric pressure, meteorological measurements, and their trends, outliers, cycles, and changes, for example), but would be likely to encode only some subset of the whole space, such as trends in global temperature change or the relationship between temperature change and CO₂. When VRs are made interactive, however, users can act upon them to alter the manner in which information is encoded, such as by encoding hidden information, hiding encoded information, or interjecting new information.

In order to design, analyze, and evaluate VRs systematically, a common conceptualization and vocabulary is required. Moreover, to operate at a foundational level, it must account for all kinds of different VRs, whether used for educational, financial, scientific, or other purposes, in a logical and consistent manner. Towards this end, a useful lens through which VRs can be viewed is that of general systems theory. This theory analyzes structures and properties of all systems at a general level, regardless of the particular form or domain of application (Skyttner, 2005). Generally speaking, a system is an organized whole composed of parts that generate emergent properties through their interrelationships. VRs are organized wholes (e.g., treemaps, radial diagrams), composed of parts (e.g., encodings and visual marks) that generate (i.e., communicate) emergent properties of an information space (e.g., patterns, correlations). As VRs can be considered as systems, general systems theory can therefore serve as a foundation upon which a science of VRs can be built. Essentially, all systems are hierarchical in nature, and are composed of layers of sub-systems (also referred to as entities, elements, objects, components, or parts, depending on the level of analysis) that have properties and relations with one another. It is the relations among entities at one hierarchical level that give rise to emergent properties at the level above. Accordingly, viewing VRs as systems allows for their discussion and analysis at different hierarchical levels in a systematic fashion. Any VR that is not simple and atomic can be decomposed into a set of sub-VRs (i.e., sub-systems), each of which can be further decomposed into other sub-VRs, all the way down to the atomic level of the VR in which information

items are encoded as simple visual marks. Using general systems theory, researchers and designers can not only discuss the structure of VRs and how their sub-systems relate to communicate emergent features of an information space, but can also discuss interaction design in a precise manner. If a VR has a particular number of sub-VRs at different hierarchical levels, for instance, designers can think about sub-VRs with which a user should be able to interact, how such interaction should take place, how the overall state of the system will be affected in terms of its entities, properties, and relationships, and how emergent features of an information space are communicated.

3.2.4 Complex Cognitive Activities, Tasks, Actions, and Events

Similar to VRs, complex cognitive activities can be regarded as hierarchical and emergent in nature (Funke, 2010). In the context of CASTs, complex cognitive activities emerge from lower-level tasks, which emerge from lower-level actions, which emerge from lower-level events. In addition, each level may be classified at finer levels of granularity: a complex cognitive activity may include sub-activities, a task may include sub-tasks, and so on. For instance, the activity of triaging a set of documents to find out whether they are semantically related may be comprised of lower-level tasks such as scanning the documents, extracting information, building associations among similar information items, and comparing these items. The task of extracting information may involve such actions as selecting a document, opening it, navigating it, selecting some items in it, and copying some items from it. Each of these actions in turn can be implemented in many different ways and using different input techniques, all the way down to low-level events, such as mouse-clicks or gestures and touches at the physical level of the interface (see Sedig et al., 2013; Sedig et al., 2012a for a more detailed discussion of these different levels). In this paper, we are mainly concerned with actions and how different actions enable and facilitate higher-level tasks and activities.

To develop a more adequate understanding of how actions influence the performance of complex cognitive activities, particular activities must be identified and characterized. Researchers and practitioners require a sense of the characteristics of activities to determine how actions can and should support them. Some of the main complex

cognitive activities are: analytical reasoning, problem solving, planning, sense making, forecasting, knowledge discovery, decision making, and learning (Bransford et al., 2000; Fildes et al., 2006; Funke, 2010; Hogarth and Makridakis, 1981; Klein et al., 2006; Knauff and Wolf, 2010; LeBoeuf and Shafir, 2005; Leighton and Sternberg, 2004; Mason, 2002; Morris and Ward, 2005; Sternberg and Ben-Zeev, 2001). Although future research is needed to explicate these activities in the context of interaction design, we briefly characterize three of them (analytical reasoning, problem solving, and sense making) to demonstrate their particular characteristics.

Analytical Reasoning. Analytical reasoning is a special type of reasoning. Reasoning itself refers to an activity in which information is used to draw inferences or conclusions (Leighton, 2004). In other words, reasoning can be seen as a transformative process in which new information is derived from the old, given information (Gilhooly, 2004). Analytical reasoning is based on rational, logical analysis and evaluation of information. It is an umbrella term covering many different kinds of reasoning: inductive, deductive, analogical, probabilistic, hypothetico-predictive, heuristic, syllogistic, categorical, and others (Halpern, 2003; Leighton and Sternberg, 2004). Analytical reasoning is a core concern of visual analytics (Thomas and Cook, 2005). As opposed to other complex cognitive activities, such as sense making and knowledge discovery, analytical reasoning is a structured, disciplined activity. Moreover, it is usually an iterative and non-linear process that involves tasks such as determining which resources to use, tracing and identifying cause-effect relationships, assessing the state of an information space, predicting future states of an information space, asserting and testing key assumptions, testing biases, and identifying and assessing alternatives (Heuer, 1999; Thomas and Cook, 2005).

Problem solving. This activity is concerned with searching through an information space to discover a path that connects a current state of information to some desired, goal state (Newell and Simon, 1972). A problem is a gap between two information states that should be bridged. Due to human cognitive limitations with regard to the amount of information that can be processed in working memory, problem solving is often a step-by-step process of connecting a current state to a sub-goal and eventually reaching the

desired goal (Morris and Ward, 2005; Thagard, 2000). Problem solving typically begins by constructing a mental representation of the information space—i.e., a set of possible states of the problem, the current state, and possible goal states—as well as *identifying the possible actions that can be performed* to bridge the gap between information states (Fischer et al., 2012). Problem solvers then use strategies to reach desired goals or sub-goals, which involves changing their internal, mental representations and/or changing external representations—i.e., VRs (Fischer et al., 2012). A common heuristic strategy is means-end analysis, in which the goal or sub-goal is compared to the current state, the difference between them is assessed, and an action is chosen to reduce the difference and to gradually bridge the gap between information states (Sternberg and Ben-Zeev, 2001).

Sense making. This activity is concerned with developing a mental model of an information space about which one has insufficient knowledge (Dervin, 1992; Klein et al., 2006). Sense making often involves a sequential process of performing tasks such as scanning the information space, assessing the relevance of items within the space, selecting items for further attention, examining them in more detail, and integrating them into mental models (Pirolli and Card, 2005). Other interlocking tasks and sub-tasks include discovering the space's structure and texture (e.g., vocabulary, resources, missing items), establishing questions to be asked, determining how to organize the answers, searching for pieces of information, encoding information to answer task-specific questions, reducing operational costs, filtering aspects of information, and categorizing items of information (Qu and Furnas, 2005; Pirolli and Russell, 2011; Russell et al., 1993).

3.2.5 Pragmatic vs. Epistemic Actions

Kirsh and Maglio (1992, 1994) have identified two types of actions: *pragmatic* and *epistemic*. Pragmatic actions are taken to transform the external world to achieve a physical goal (e.g., cooking a piece of meat before eating it). Epistemic actions are taken to transform the world to facilitate mental information-processing needs (e.g., rotating a jigsaw piece to explore potential fit while solving a jigsaw puzzle). Epistemic actions, then, can play an important role in complex cognitive activities (e.g., for usage in

planning and sense making, see Clark, 1998a; Liang and Sedig, 2010). Performing external epistemic actions on visible VRs or latent parts of an information space (which is stored in computer memory) not only change and alter the VRs, but also affect and shape the information-processing functions of users of a CAST and help set and define new goals (Brey, 2005; Kirsh, 1997).

3.2.6 Epistemic Action Patterns

Although cognitive scientists have made a distinction between pragmatic and epistemic actions, they are not clear about the level at which such actions take place. In other words, it is not clear whether such phenomena occur at the level of tasks, actions, or events. While it may not be important to make such distinctions for cognitive science research, as discussed above, such distinctions are important to provide clarity and precision in the context of CASTs. In this paper, we are concerned with epistemic actions at the level of individual action-reaction pairs, rather than at the level of tasks—which typically involve many actions and reactions, or at the level of events—which involve physical occurrences at the interface. That is, for the purposes of this paper, epistemic actions occur between these two levels. In this context, epistemic actions are those actions that are performed with CASTs to facilitate mental information-processing needs. In this paper we are interested in epistemic actions at a level of abstraction that is independent of their physical performance, the manner in which they are implemented, the techniques that may be used to perform them, the users who perform them, and the technologies and tools that mediate their performance. A pattern can be defined as a regularity in some dimension (Salingaros, 1999). An epistemic action pattern, then, is a regularity in terms of an action-based characterization and its utility in the context of performing complex cognitive activities, and not necessarily in terms of other characteristics such as implementation and technological platform. In this sense, an epistemic action pattern is one that has a timeless, invariant quality in supporting human cognitive activities (see the framework section for more discussion of patterns and their utility).

3.2.7 Interactive Coupling and Complex Cognitive Activities

Over the past few decades, cognitive science research has increasingly emphasized the distributed nature of cognitive phenomena (e.g., Brey, 2005; Hollan et al., 2000; Salomon, 1993; Zhang and Norman, 1994). The theory of distributed cognition states that cognitive processes are not solely the product of the inner functionings of the brain. Rather, they result from relationships between internal mental representations and the external environment. These relationships with the external environment take place at several levels: relationships with culture, society, other individuals, computational artifacts, and external representations. Cognitive functions are, hence, emergent phenomena taking place *across* the brain, body, and these aforementioned levels. As such, the external environment aids the mind, becomes coupled with it, and can extend it (Clark, 1998a). When using CASTs, cognitive processes emerge from a coupling that is formed between the internal representations and processes of the user and external representations and processes at the interface (Kirsh, 2009). Numerous sources suggest that external representations and actions play an important role in facilitating the performance of all complex cognitive activities. For instance, VRs can facilitate learning (Greeno and Hall, 1997), and acting upon them is important in learning (Burdea and Coiffet, 2003; Cairncross and Mannion, 2001; Cobb and Fraser, 2005; Rogers and Scaife, 1997). The same is true of planning (Cox and Brna, 1995; Neuwirth and Kaufer, 1989; Morris and Ward, 2005); problem solving (Jonassen, 2003; Zhang, 2000); decision making (Beach and Connolly, 2005; Kleinmuntz and Schkade, 1993); sense making (Qu and Furnas, 2005; Sedig et al., 2005b); and knowledge discovery (Fayyad et al., 2002).

All the above activities involve processes through which VRs are decoded, linked, coordinated, and harmonized in the pursuit of reaching new goals and conclusions (Leighton, 2004). However, there are some factors that interfere with the proper execution of these activities, such as working with poorly-designed VRs, not having adequate mechanisms for manipulating and transforming the VRs, and not having appropriate ways for combining and integrating different VRs (Sloman, 2002). Another compounding factor is that people may see the same VR differently: some may see more detailed configurations of it, while others may see its more abstract structure (*ibid.*). At a

basic level, complex cognitive activities involve the performance of simple visual sub-tasks, such as identifying an item or locating two close information items. However, even with the best-designed VRs, beyond the performance of simple tasks, the form, structure, amount, degree of abstraction, complexity, density, and other properties pertaining to how information is encoded affect the quality and process of complex cognitive activities (Anderson et al., 2002; Blackwell et al., 2004; Hegarty et al., 2002; Parsons and Sedig, in press; Peterson, 1996; Shah and Miyake, 2005; Zhang and Norman, 1994). The features of a VR can create a perceptual and cognitive distance between the VR and a user's mental processes. This distance needs to be bridged for people to carry out mental activities using the VR. During these activities, it may be necessary to switch from one form of observation to another. Because processing VRs in the mind is not easy (Sloman, 2002), to support their mental activities, humans tend to externalize their mental processes by externally acting upon VRs (Clark, 2008; Kirsh, 2009; Sedig, 2009). As cognitive processes are intrinsically temporal and dynamic, interactive VRs potentially create a harmony and a tight temporal coupling with cognitive processes (Kirsh, 1997; 2005). As part of this dynamically coupled cognitive system, the user and the CAST each have a causal influence—in other words, the user and the CAST are continuously affecting and simultaneously being affected by each another (see Clark, 1998b).

Brey (2005) suggests that the distributed coupling between a user and a tool can be *weak* or *strong*. In the case of weak coupling, the external aids are usually tools (e.g., representational or physical) that do not actively participate in the information-processing functions of the mind. These tools do not necessarily need to be static. They can be dynamic, but not inviting of explicit action choices for human participation. In distributed cognitive phenomena, interactive engagement with an external tool can strengthen the coupling and create a dialogical relationship with it. In other words, in distributed complex cognitive activities, interaction can make the coupling stronger. Unlike ordinary representational or physical tools, since CASTs are made of interactive visual representations, they can provide stronger coupling in that they serve the mind by being more than just externalizers of information spaces. In addition to their representational function, they can have built-in designed choices and conditional algorithmic behaviors that allow their users to engage in active, elaborative participation. These special external

actions can be performed to support information-processing functions and complex cognitive activities—i.e., rather than performing “in-the-head operations,” external actions provide *emergent* “operational capabilities” (Clark, 1998a).

3.3 The EDIFICE-AP Framework

The presentation of EDIFICE-AP is divided into 5 sections: First, some of the characteristics of the framework will be examined. This includes a discussion of how such characteristics address many of the research needs previously identified. Second, the methodology for devising EDIFICE-AP will be examined. Third, EDIFICE-AP’s catalog of action patterns will be presented. Thirty-two epistemic action patterns are identified and characterized. For ease of reading, only four of the action patterns are elaborated upon in this section—that is, their utilities in supporting different complex cognitive activities are discussed, and examples of CASTs from different domains in which such actions have been and can be used are given. Readers are referred to Appendix 10.1 for detailed discussion of the additional 28 actions. Fourth, a scenario involving a sense making activity is used to demonstrate how EDIFICE-AP can help with the systematic analysis and design of epistemic actions in CASTs. Finally, in light of these four sections, some existing work is discussed to demonstrate how EDIFICE-AP is unique and novel.

3.3.1 Characteristics of EDIFICE-AP

As was mentioned in the introduction, EDIFICE-AP is intended to achieve a number of goals that address extant research needs: 1) to be syncretic, unifying a number of previously disconnected ideas into a coherent theoretical model; 2) to be general, operating at a level of abstraction that is applicable to all kinds of technologies, activities, users, and VRs; 3) to be comprehensive, identifying patterns that cover an extensive range of actions; and, 4) to be generative, possessing the ability to motivate design creativity as well as to stimulate further theoretical and empirical research. This section will elaborate upon each of these characteristics.

3.3.1.1 Syncretic

EDIFICE-AP is not simply a list of actions; rather, it unifies and integrates a number of ideas that are often discussed in isolation, in a logical and coherent manner, in order to provide a theoretical foundation that informs the conceptualization of human-information interaction in the context of complex cognitive activities.

As was discussed earlier, actions can be divided into two types: epistemic and pragmatic. Epistemic actions—those related to knowledge and knowing—are the concern of this paper. Just as different physical tools can extend one’s reach into a physical space, the action choices offered by a CAST can extend the human mind, like tentacles, to reach into an information space to perform operations upon it, such as by bringing into view portions of the information that have not been encoded and displayed by the VRs at the interface level, or by viewing information from different perspectives, or by reorganizing the information (see Figure 1).

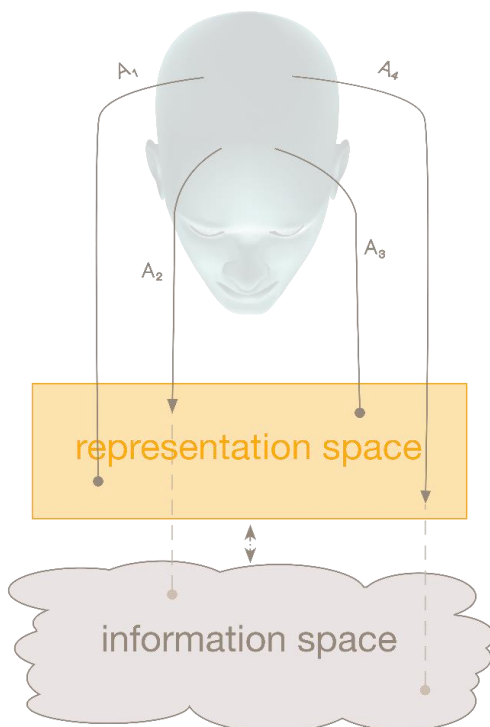


Figure 3-1 Action choices operating as mental tentacles to reach into an information space.

Note: Vector art adapted from www.vectoropenstock.com under the Attribution Creative Commons 3.0 license

Unlike simple structured tasks, complex cognitive activities do not usually follow a programmed, recipe-like model (Clark, 1998a; Thomas and Cook, 2005). Individuals deploy general, high-level strategies to operate upon an information space. In this process, they actively perform all kinds of epistemic actions upon the external environment to help them alter it, and as a result, transform and support their own cognitive functions to gradually achieve the overall goals of the activity. Therefore, complex cognitive activities emerge at a macro level while actions are occurring at a lower level. A sequence of epistemic actions creates a chain that represents the trajectory for the emergence of the macro-level activity (see Figure 2).

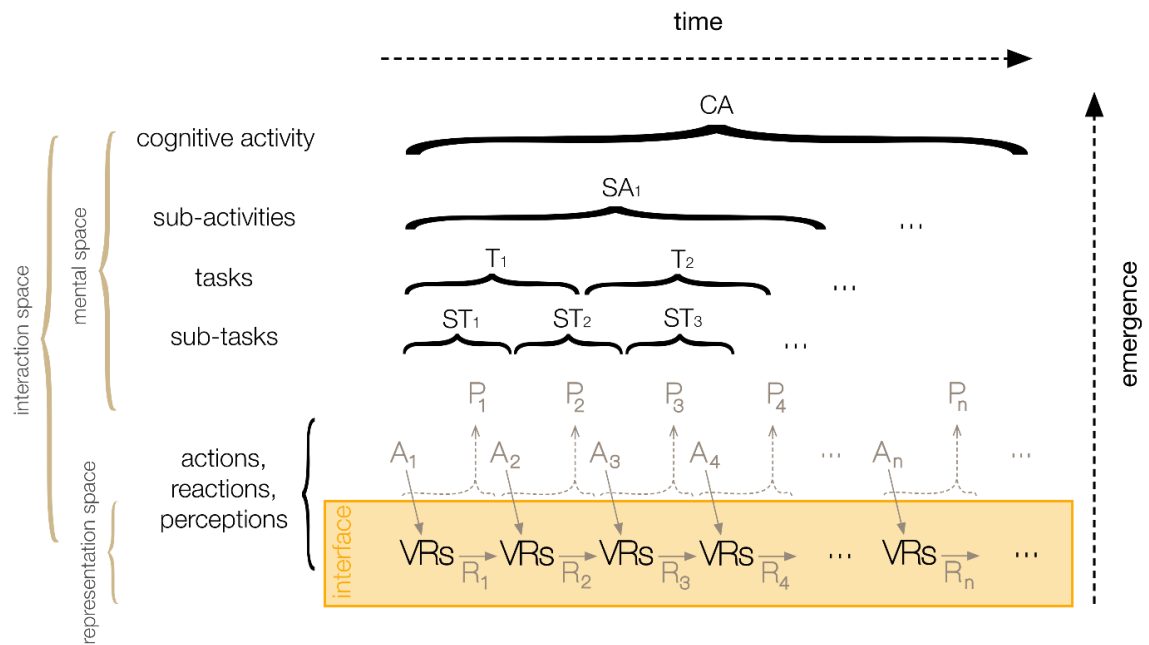


Figure 3-2 The hierarchical structure of a complex cognitive activity and its emergence over time.

The sequence of epistemic actions that allows users to carry out an information-based complex cognitive activity can be conceptualized as an epistemic cycle. Figure 3-3 depicts this cycle and its categorization into five spaces: information, computing, representation, interaction, and mental space (see Sedig et al., 2012a for more elaboration

on these spaces and their relationships). Information comes from some space or spaces and must be stored within a CAST. This aspect of a CAST can be conceptualized as computing space—the place where information is processed, stored, and prepared. This space may involve data cleaning, fusion, filtering and other pre-processing procedures, as well as data mining, transformation, and other mathematical procedures. Information must then be encoded in visual form to be made perceptually accessible to users—this is done in representation space. The information made available in this space through VRs is typically only a subset of the total information that is available. In addition, this space is often comprised of VRs of items from information space as well as VRs of aspects of interaction space (e.g., action possibilities and tools that are available to the user). The user perceives VRs and performs mental operations within mental space—the place in which internal mental events and operations (e.g., memory encoding, storage, and retrieval; apprehension; judgment; classification) take place. The user then selects an epistemic action from a set of available choices based on some overall epistemic goals and strategies, and acts upon VRs within representation space to effect some reaction. This space encompassing action and reaction can be considered as interaction space. The user then perceives the reaction, and the cycle repeats until the user is satisfied that a task or an overall activity is accomplished. In the context of design, allowing users to choose from a set of these epistemic actions means that designers must first know what kinds of actions exist and then build them into their designed CASTs.

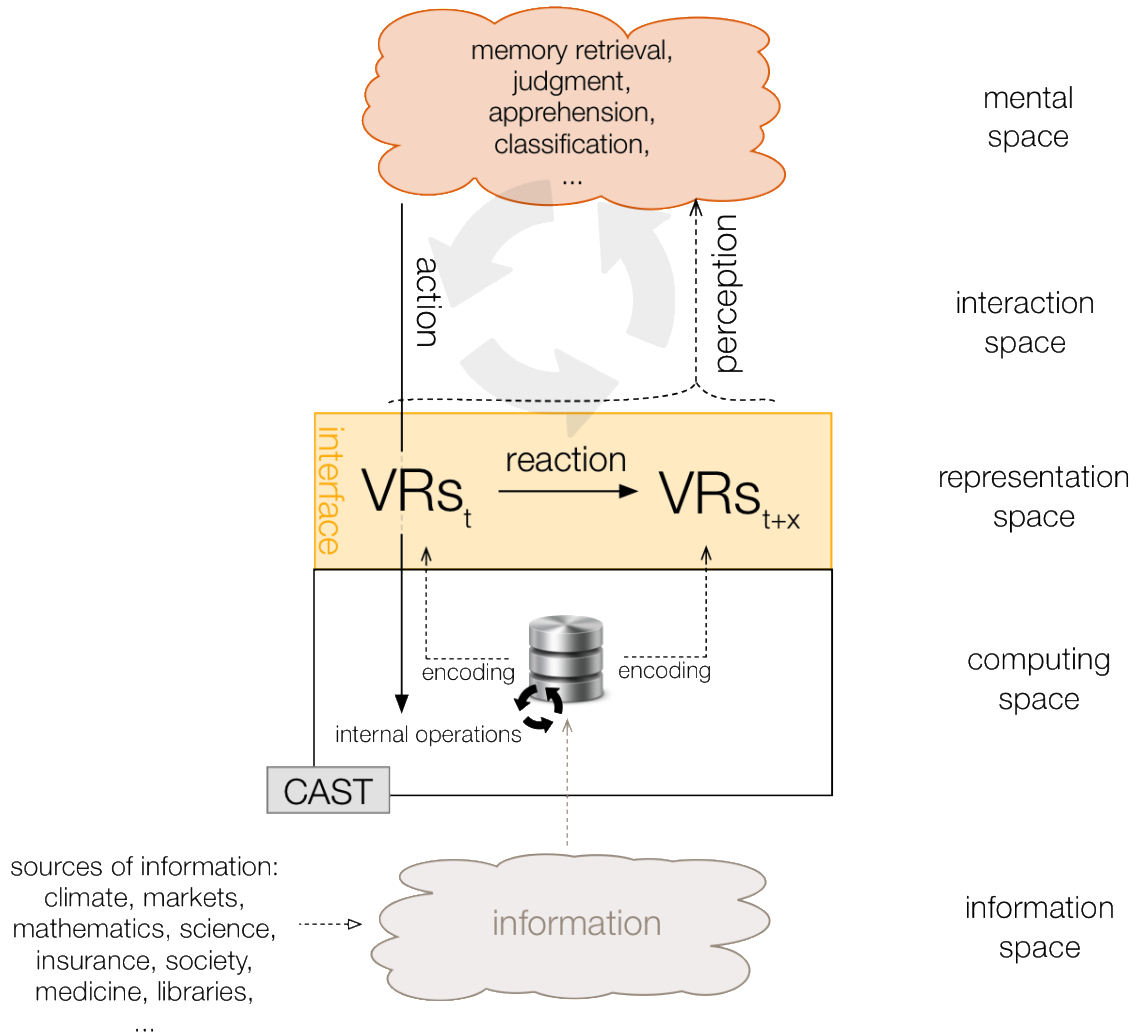


Figure 3-3 The human-information interaction epistemic cycle.

3.3.1.2 General

EDIFICE-AP abstracts beyond the details of techniques to identify action patterns that are applicable to diverse activities (e.g., sense making, problem solving), domains (e.g., science, education, business, gaming), and users (e.g., analysts, learners, researchers). A number of characteristics can be identified that contribute to the general nature of EDIFICE-AP:

Action-pattern-based rather than technique-based. EDIFICE-AP identifies and characterizes epistemic actions as general patterns rather than as technology- or implementation-dependent techniques. Even though interaction techniques can also be patterns, they are typically characterized at a lower level and are often technology-dependent. For example, one of the epistemic action patterns identified in EDIFICE-AP is drilling. Drilling is a general pattern that refers to all instances of acting upon VRs to drill into them and get more detail about latent, interior information that is not perceptually accessible—that is, it is latent in the information space and has not been encoded at the interface level. This is a conceptual, pattern-based characterization of the action and its utility that is not concerned with how the action is carried out. However, designers can develop many techniques to enable users to perform this action. Examples of these techniques include mouse-over, right-clicks, spatial proximity, semantic zooming, gestures, and digital probes. No matter what technique is used, by applying it to a VR, some of its hidden and latent information can be displayed.

Making the distinction between epistemic action patterns at this level and techniques at a lower level is crucial for two reasons. First, there are many existing techniques already, with all kinds of names and characterizations, and many more that can be developed in the future. Organizing many techniques under the umbrella of an action-pattern-based characterization makes it much easier to navigate the landscape of design possibilities by making the number of action possibilities manageable. Second, techniques vary in how they are characterized. By unifying many of them under one pattern, designers and researchers can focus on the conceptual utility of the action and worry about techniques and implementations later. Therefore, given a deep information space, a subset of whose items has been encoded by a VR, it can be easily predicted that at some stage of interaction with the tool users may need to drill into the VR to access latent information. This knowledge makes it easier for the designer to provide users with such an action choice. Indeed, the designer may choose to provide users with different implementations of the same action pattern. The pattern names we have selected are very close to the dictionary definition of the actions in order to be suggestive of what the actions do. For instance, the action pattern ‘scoping’ suggests that the action deals with the range, extent,

breadth, and/or scope of perception of an information space. Thus, pattern names suggest both the actions that may be needed as well as their epistemic utility.

Technology independent. The epistemic actions in EDIFICE-AP are independent of the technology through which complex cognitive activities are carried out. This is important—as technological platforms on which complex cognitive activities are performed change, EDIFICE-AP can remain resilient to these changes and still be applicable. Continuing with the drilling example, as new technological innovations (such as interactive tabletops, motion sensing input devices, virtual reality, augmented reality, and interactive surface projection environments) come into existence, these may result in the development of new techniques and methods for drilling into VRs. However, at a conceptual, general level, drilling will always exist as a distinct pattern of action with utility for performing complex cognitive activities, and designers will decide how to implement it using new technologies.

Activity independent. The epistemic actions in EDIFICE-AP are not directly linked to and dependent on the complex cognitive activities that they support. Since complex cognitive activities are emergent phenomena, combining different epistemic actions can result in countless trajectories of macro tasks and activities. Hence, whether the activity be sense making, decision making, planning, learning, knowledge discovery, or problem solving, a subset of the epistemic actions in EDIFICE-AP can be used to support it, depending on the contextual and situational needs of the activity and its users.

User independent. The epistemic actions in EDIFICE-AP can be performed by users of different ages and backgrounds. This is in contrast to techniques and implementations that can hinder some users from understanding how certain actions are carried out. For instance, while drilling, a young child may have difficulty doing a right-click and going down a menu to select an option. But the very same child may be able to use drilling techniques such as moving a mouse cursor over an object or pressing an object on a touch-screen surface. Additionally, the actions in EDIFICE-AP can be used in different situations whether they be single user, collaborative, or multi-user settings. Since the

actions are geared towards achieving activities, the activities can be carried out individually or collectively.

Processing-load independent. Since there is a joint epistemic partnership between the user and the CAST, when an epistemic action is performed its processing load is distributed across the mental, representation, interaction, and computing spaces—that is, between the CAST and the user (see Figure 3). This means that in some instances, the user may initiate an action, but most of the information processing load is carried out by the tool. It is up to researchers and the designers of the tool to determine how to distribute this load. This decision is dependent on several factors, such as the VRs that are used, the type of activity, and the users of the tool. For instance, in a CAST that is to be conducive to mindful reflection on the underlying relationships among the items in an information space when carrying out a learning activity, designers may need to let the users do most of the processing when performing an action (e.g., see Sedig et al., 2001; Liang et al., 2010). On the other hand, in a CAST that is designed to help users make time-critical decisions, for any given action there may be powerful algorithms and data mining features that shoulder most of the information processing load in the computing space.

3.3.1.3 Comprehensive

EDIFICE-AP is comprehensive in its scope. The 32 patterns that are identified are intended to cover the broad range of epistemic actions that are typically performed during sense making, problem solving, decision making, and other complex cognitive activities. The majority of interaction techniques, whether from information visualization, human-computer interaction, visual analytics, learning and knowledge technologies, digital libraries, or otherwise, are covered by EDIFICE-AP. However, although EDIFICE-AP is comprehensive, it is not necessarily exhaustive and may be expanded in the future.

3.3.1.4 Generative

EDIFICE-AP is generative in its nature. By providing a coherent conceptualization of the human-information interaction epistemic cycle and the emergent nature of complex cognitive activities, presenting a catalog of action patterns, discussing their utility for

performing complex cognitive activities, examining how they have been used in some existing CASTs, and identifying potential usage scenarios, EDIFICE-AP can facilitate systematic design of CASTs and can be used as a reference to help with design decisions. In his paper discussing models for interaction design, Beaudouin-Lafon (2004) noted that interaction models that are generative help designers “create richer and more varied design spaces from which to develop innovative solutions” (p. 17). By identifying patterns of action that are not dependent on particular implementation details, designers gain a support structure that allows them to think about the utility of an action, and then devise numerous innovative techniques and implementations that fit the particular context of use. In addition, because EDIFICE-AP is flexible and does not dictate any particular sequence of actions, designers can come up with different sequences of actions to be built into CASTs so as to most effectively support different tasks and activities. Furthermore, because the actions are identified in a conceptual, pattern-based fashion, designers can think about blending action patterns at a conceptual level to create new techniques. For instance, in many activities it may be beneficial to blend together the drilling and comparing action patterns. As a user acts upon two VRs, latent information is encoded and made visible while simultaneously identifying the degree of similarity between the two VRs. Another useful blending of patterns is that of sharing and cloning. A user may wish to share a VR to be used by a research team, for instance, but still keep a copy of the original. Indeed, action patterns can be blended in innumerable ways, each of which has distinct utility depending on the context of use. EDIFICE-AP is generative not only in the context of design; rather, its novel characteristics can also stimulate further theoretical research, and can motivate empirical studies that further examine the cognitive utility of the identified action patterns.

3.3.2 Methodology

This section describes the methodology for the construction of EDIFICE-AP, particularly in the context of achieving the desired characteristics discussed in the previous section. We describe the methods of achieving the following characteristics: 1) syncretic, 2) general, 3) comprehensive, and 4) generative, as well as the rationale and approach to the 5) characterization of interaction, action patterns, and VRs, 6) classification of action

patterns, and 7) validity of action patterns. These do not signify a series of sequential steps; rather, they are interwoven and complementary aspects of EDIFICE-AP's development.

Syncretic. To develop a coherent theoretical foundation for EDIFICE-AP, we have reviewed literature from numerous disciplines, including information science, cognitive and learning sciences, information systems, cognitive technologies, information behavior, information visualization and visual analytics, library science, human-computer interaction, computer science, psychology, and philosophy of mind. Observations made during this review suggested that there are deep connections among these different disciplines. Thus, we have identified relevant and related ideas from these different areas—e.g., epistemic vs. pragmatic actions from cognitive science; distributed cognition and extended mind theory from cognitive science and philosophy of mind; events, actions, tasks, and activities from information science, information behavior, and psychology; complex cognition and cognitive activities from learning sciences, information science, and cognitive science; interaction from cognitive and knowledge technologies and human-computer interaction; and, encoding and representation of information from psychology, information visualization, and visual analytics. By seeking out commonalities in these different research areas, important insights into how humans interact with information to perform complex cognitive activities can be gained. Thus, this aspect of the development of EDIFICE-AP represents a conscious attempt to syncretize related but underdeveloped and fragmented ideas into a coherent theoretical whole to inform the conceptualization, design, and evaluation of CASTs.

General. In their comprehensive and critical review of human-computer interaction pattern languages, Dearden and Finlay (2006) suggested that an arguable weakness in many interaction design patterns is that they are strongly based on particular and current user interface paradigms, platforms, and/or technologies, and therefore do not embody a 'timeless quality' that is a necessary characteristic of good design patterns. Furthermore, they suggest that it is relatively easy to observe phenomena which could be put into a pattern-like form, but much more difficult to use these observations to develop and explicate good patterns. As Fincher (1999) noted, "practice can be captured at any scale,

but it is the combination of capture and abstraction that makes the presentation of the ideas coherent” (p. 339). During the development of the action-patterns portion of EDIFICE-AP, we have attempted to avoid such pitfalls and to identify patterns at a consistent level of abstraction that is useful for both research and practice. Furthermore, as discussed elsewhere, we have made a conscious effort to generalize beyond particular tools, tasks, domains, users, and technologies to contribute to a general theoretical framework for human-information interaction in complex cognitive activities.

Comprehensive. The intention to generalize by seeking similarities through abstraction had an influence on the development of EDIFICE-AP in general as well as on the process of pattern identification in particular. Generally speaking, patterns for design are derived empirically from observations, rather than from first principles (Salingaros, 2000). One commonly used method of identifying patterns is the process of ‘pattern mining’—extracting patterns by observing previous designs. This process is used in many fields, including software design, architecture, and interaction design (e.g., Gabriel, 1996; Meszaros, 1996; Jacob, 2011). To identify the 32 action patterns that are part of EDIFICE-AP, we took a twofold approach. First, we analyzed 130 existing tools that are used to support complex cognitive activities in different domains. These included: 20 educational tools, 40 data and information visualization tools, 20 visual analytics tools, 10 productivity tools, 20 digital games, 10 decision support tools, 5 digital library tools, and 5 personal information management tools. The second approach was to conduct an extensive analysis of literature that presented new interaction techniques, surveyed existing techniques, or provided interaction taxonomies and catalogs. During this analysis, we identified and recorded common characteristics and utilities of techniques. In order to identify fundamental action patterns, we abstracted beyond the details of each technique and implementation to categorize them according to fundamental features that were not dependent on particular tools, platforms, domains, or users. Although we do not claim that EDIFICE-AP’s action catalog is absolutely exhaustive, we do believe that it is comprehensive in that it accounts for the majority of interaction techniques that users perform in all of the aforementioned activities and domains.

Generative. As mentioned previously, by identifying patterns of action that are not dependent on particular implementation details, designers gain a support structure that allows them to think about the utility of an action, and then devise numerous innovative techniques and implementations that fit the particular context of use. One method we used for accomplishing this desired characteristic was to develop usage scenarios for each action pattern (see Appendix 10.1). It is well known from research on human creativity that new ideas are often generated through novel combinations of old ideas and access to new information (Lau, 2011). By devising usage scenarios, EDIFICE-AP provides designers with different contexts in which action patterns can be implemented, each of which may trigger mental associations and generate new design ideas. To position EDIFICE-AP to stimulate further research, we have proposed high-level models and ideas (e.g., emergence of complex cognitive activities using CASTs, distribution of information processing across different spaces, effects of action patterns) that require further theoretical and empirical research to more fully explain and describe their features in different contexts. In addition, we have explicitly suggested a number of future lines of research that may be undertaken to develop a better understanding of how to design and evaluate CASTs (see summary and future work section).

Characterization of interaction, action patterns, and VRs. To address the issue of ambiguity in existing literature, interaction in EDIFICE-AP is characterized as a complex phenomenon that must be categorized into multiple levels to discuss it in a coherent and meaningful fashion. In this paper, we are chiefly concerned with interaction at only one such level: that of individual actions performed by a user and the subsequent reactions from a CAST. Each action pattern is characterized in light of this categorization. In addition, much effort has been made to remain consistent in characterizing each action pattern at the same level. Furthermore, the names of all action patterns contain the suffix ‘*ing*’, suggesting that users are the ones initiating the action. On a separate but related note, in an attempt to bring more accuracy and precision to interaction design, we have used general systems theory to characterize VRs. This allows for thinking about and discussing interaction design in a precise manner. Existing research is often not clear about what the object of an action is—it is often suggested that users act upon VRs, for example, but there is no specificity with regard to what portion of a VR is receiving the

action. As VRs can be quite large and complex, this lack of precision can be problematic for research, design, and evaluation. Through the lens of general systems theory, any interface can be analyzed into its constituent components in a consistent manner. If VRs are conceptualized as systems comprised of sub-systems at multiple hierarchical layers, designers and researchers can think about sub-VRs with which a user should interact, how such interaction should take place, and how the overall state of the system will be affected. Although this portion of EDIFICE-AP's characterization is important, it is not fully developed in this paper and requires explication elsewhere. Keeping it in mind, however, can help bring more accuracy and exactness to interaction design.

Classification of action patterns. During examination of the literature and existing CASTs, we observed a pattern in the way that actions were and could be implemented in relation to one another: there are some action patterns in which an action is performed in one direction and there is no natural opposite action. After committing such an action, users can only typically reverse it by performing an 'undo' action. On the other hand, there are some patterns that are natural opposites of one another—when an action is performed, there is another natural opposite action. Therefore, to bring more order and clarity to the interaction design space, the action patterns in EDIFICE-AP have been classified into *unipolar* and *bipolar* action patterns. It was further observed that in many existing CASTs the bipolar patterns appear together. Thus, such a classification is useful not only for research and design, but also for evaluation. For instance, an evaluator can use this classification to determine whether two bipolar actions do or should appear together. Such a classification also helps us to see that some actions do not have a natural opposite. This classification is not the only valid one; it is possible that other classifications may be useful for different users, tasks, and contexts.

Validity of action patterns. The validity of the action patterns can be assessed from two angles: an ontological one and an empirical one. First, each action pattern has ontological validity. After characterizing each pattern, we give examples of several complex cognitive activities that are supported. Furthermore, in Table 1 as well as in Appendix 10.1, we provide examples of CASTs in which each action pattern is implemented. This is intended to demonstrate and validate the existence and necessity of the pattern.

Therefore, there is no need to perform experiments to find out whether the action pattern actually exists. What is in need of experimentation, however, is the role that the action pattern has in supporting complex cognitive activities. We have provided evidence supporting the empirical validity of the effects and utility of the patterns by noting relevant studies that have been previously conducted. These research studies, dealing with the cognitive and epistemic roles of actions in the performance of complex cognitive activities, are from diverse bodies of literature concerned with psychology, learning sciences, human-computer interaction, information science, computer science, and cognitive and knowledge technologies. The fact that we have gathered empirical validation, however, does not obviate the need for further precise studies that more fully explicate the effects and utility of the action patterns.

3.3.3 Catalog of Action Patterns

In Thomas and Cook's (2005) research agenda for visual analytics, they called for the development of "a science of interaction" and the need for "a *deep understanding of the different forms of interaction and their respective benefits*" (73, italics added). They further stated that the "*grand challenge of interaction is to develop a taxonomy to describe the design space of interaction techniques that supports the science of analytical reasoning*" (76, italics added). EDIFICE-AP presents a catalog of 32 epistemic action patterns that describe the interaction design space at the action-reaction level of human-information discourse. Table 1 lists all the epistemic action patterns in EDIFICE-AP, briefly characterizes each, and identifies some CASTs in which each action pattern is implemented. Following this, four patterns are characterized and the utility of each for performing complex cognitive activities is discussed in detail. These four are *scoping*, *translating*, *collapsing*, and *expanding*. For ease of reading, characterizations of and discussions about the rest of the patterns are appended (see Appendix 10.1).

Table 3-1 Catalog of epistemic action patterns

<i>Action</i>	<i>Characterization</i> acting upon VRs to ...	<i>Example CASTs</i>
---------------	---	----------------------

Unipolar	Annotating	augment them with additional visual marks and coding schemes, as personal meta-information	<i>GeoTime</i> (Eccles et al., 2008); <i>Mendeley</i> ; <i>Tableau</i>
	Arranging	change their ordering, either spatially or temporally	<i>Table Lens</i> (Rao and Card, 1994); <i>InfoZoom</i>
	Assigning	bind a feature or value to them (e.g., meaning, function, or behavior)	<i>NetLogo</i> (Wilensky, 1999)
	Blending	fuse them together such that they become one indivisible, single, new VR	<i>Microsoft Word</i>
	Cloning	create multiple identical copies	<i>Cytoscape</i> (Shannon et al., 2003)
	Comparing	determine degree of similarity or difference between them	<i>Multidatex</i> (Wu et al., 2006); <i>Panopticon</i>
	Drilling	bring out, make available, and display interior, deep information	<i>OECD eXplorer</i> , <i>Sunaeon</i>
	Filtering	display a subset of their elements according to certain criteria	<i>Film Finder</i> (Ahlberg and Shneiderman, 1994), <i>Tableau</i>
	Measuring	quantify some items (e.g., area, length, mass, temperature, and speed)	<i>GeoGebra</i>
	Navigating	move on, through, and/or around them	<i>K-Lattice Machine</i> (Sedig et al., 2005a); <i>CGV</i> (Tominksi et al., 2009)
	Scoping	dynamically work forwards and backwards to view compositional development and growth	<i>Polyvise</i> (Morey and Sedig, 2004); <i>Gephi</i> (Bastian et al., 2009)
	Searching	seek out the existence of or locate position of specific items, relationships, or structures	<i>Health Infoscape</i> ; <i>Vizster</i> (Heer and Boyd, 2005)
	Selecting	focus on or choose them, either as an individual or as a group	<i>EdgeMaps</i> (Dörk et al., 2011); <i>Dust & Magnet</i> (Yi et al., 2005)
	Bipolar	Sharing	make them accessible to other people
Transforming		change their geometric form	<i>Vizster</i> (Heer and Boyd, 2005)
Translating		convert them into alternative informationally- or conceptually-equivalent forms	<i>Archim</i> , <i>Panopticon</i>
Bipolar	Accelerating/ Decelerating	increase or decrease speed of movement of their constituent components	<i>OECD eXplorer</i> ; <i>NetLogo</i> (Wilensky, 1999)
	Animating/ Freezing	generate or stop motion in their constituent components	<i>Gapminder</i> , <i>Step</i>

Collapsing/ Expanding	fold in or compact them, or oppositely, fold them out or make them diffuse	<i>VisANT</i> (Hu et al., 2009); <i>Gephi</i> (Bastian et al., 2009)
Composing/ Decomposing	assemble them and join them together to create a new, whole VR, or oppositely, break whole entities up into separate, constituent components	<i>Hyperchem</i> , <i>SmartJigsaw3D</i> (Ritter et al., 2000)
Gathering/ Discarding	gather them into a collection, or oppositely, throw them away completely	<i>Microsoft Onenote</i> , <i>Gephi</i> (Bastian et al., 2009)
Inserting/ Removing	interject new VRs into them, or oppositely, get rid of their unwanted or unnecessary portions	<i>Visible Body</i> , <i>ModellingSpace</i> (Avouris et al., 2003)
Linking/ Unlinking	establish a relationship or association between them, or oppositely, dissociate them and disconnect their relationships	<i>MindJet</i> ; <i>DEMIST</i> (Ainsworth and van Labeke, 2001)
Storing/ Retrieving	put them aside for later use, or oppositely, bring stored VRs back into usage	<i>HARVEST</i> (Gotz et al., 2010); <i>Cytoscape</i> (Shannon et al., 2003)

3.3.3.1 Scoping

Characterization: Acting upon VRs to dynamically work forwards and backwards to view their compositional development and growth, either temporally or spatially. The term scope here is meant to signify the range, breadth, field, or amount of compositional information in view.

Utility: Among others, this action facilitates sense making, reasoning, investigating, and understanding (Chen and Morris, 2003; Chen, 2004; Card et al., 2006; Morey and Sedig, 2004; An et al., 2001). There are many situations in which users may want to discover the process or sequence of growth, development, or construction of an information space. Scoping can be useful for reasoning about the growth process of most complex phenomena, such as fractals, 3D structures, proteins, economic trends, and galaxies. Scoping the growth of such information spaces from elemental parts to more aggregate wholes can facilitate deeper understanding of the emergence of complex phenomena (Kaandorp, 1994). In general, the ability to analyze ideas by reasoning forward and backward and observing how information items are chained together is important in

analytical thinking (Shrinivasan and Wijk, 2008). Also, in many circumstances, being able to explain the prevalence of given structures within an information space depends upon identifying the temporal order in which relations occur (Moody et al., 2005). Examples of such information spaces are co-citation networks (see Chen and Morris, 2003; Chen, 2004) and social networks (see Moody et al., 2005). Working with static VRs of such information spaces can lead to false interpretations compared to when a user is able to act upon VRs to see the temporal growth (Moody et al., 2005). Therefore, scoping VRs of network-like information spaces can aid in investigating relationships, observing trends, and understanding how clusters are merged and split over time (Toyoda and Kitsuregawa, 2005). Moreover, in the context of research networks, understanding the evolution of a network can support the activity of forecasting research trends and studying a scientific community's life span (An et al., 2001).

An example of a CAST that implements the scoping pattern is *Polyvise* (Morey and Sedig, 2004), a tool for exploring the compositional structure and formation of complex 4D mathematical shapes. Figure 4 shows four successive stages of a scoping action being performed. By providing this action possibility, *Polyvise* allows users to gradually construct or deconstruct the VR to make reasoning about its composition more tractable. The temporal coupling that is formed between the user's mental space and the VR, through such interaction, can facilitate the development of an accurate mental model of the information space.

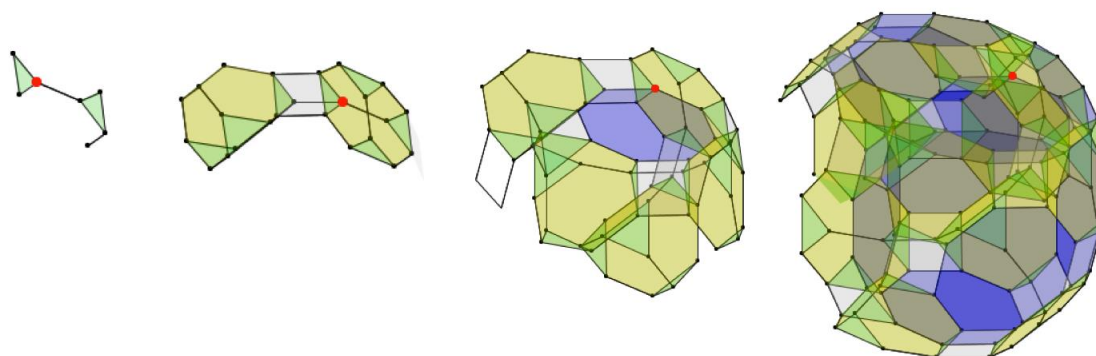


Figure 3-4 An implementation of the scoping pattern: Acting upon a VR of a 4D shape to explore its compositional structure.

3.3.3.2 Translating

Characterization: Acting upon VRs to convert them into alternative informationally- or conceptually-equivalent representations, each requiring different degrees and kinds of cognitive and perceptual processing.

Utility: Among others, this action facilitates problem solving, decision making, learning, reasoning, sense making, and understanding (Yi et al., 2007; de Jong et al., 1998; Spence, 2007; Peterson, 1996; Gotz and Zhou, 2008). In general, the effective acquisition and growth of knowledge depends on the use of appropriate representational forms (Peterson, 1996). However, the appropriateness of VRs depends on many factors related to the characteristics of the users, their tasks and activities, and the properties of VRs themselves (see Larkin and Simon, 1987; Peterson, 1996; Sedig and Liang, 2007). In the context of problem solving, sometimes one's understanding of a problem while working with a certain VR is poor, and translating to another VR of the same problem leads to insight (Robertson, 2001; Anderson, 2000). This is because inferential abilities are fundamentally affected by external representations (Cox and Brna, 1995; Larkin and Simon, 1987; Kaput, 1989). Translating can allow learners, for instance, to see relationships between the parts of the problem and understand its underlying structure, and can open up new paths through a problem space (Robertson, 2001). In one study, Bodner and Domin (2000) noticed that problem solvers who translated information into alternative representations were the most successful in making sense of concepts in organic chemistry. One benefit of a translating action, in the context of interactive VRs, is that users can go back-and-forth to compare and contrast alternative VRs to assimilate different aspects of an information space into their mental structures and increase understanding (see Spiro and Jehng, 1990; Godshalk et al., 2004). Overall, the translating action pattern has a high degree of utility for all activities, tasks, and users, since each informationally- or conceptually-equivalent VR enables different inferential abilities and reveals and emphasizes different aspects of an information space.

An example of a CAST that implements the translating pattern is *Gapminder*. Figure 5 shows two different states of the interface during the performance of an activity. In

Figure 5 (L), the scatterplot VR depicts the relationship between life expectancy and GDP per capita for a number of countries. Such a VR has certain benefits, such as facilitating the perception of anomalies, deviations, and outliers, and supporting the performance of complex cognitive activities that involve reasoning about trends and patterns within an information space (Parsons and Sedig, 2013a). Although each circle in the scatterplot represents a country, the location of which is encoded by color and corresponds to the map in the upper-right portion of the interface, the user may find it useful to translate the VR to the map-based VR shown in Figure 5 (R). In other words, although both VRs have very similar information content and are conceptually equivalent, certain tasks and inferences may be much more tractable using one VR over the other. Therefore, by providing the ability to translate the VR, the CAST can more effectively support the cognitive and contextual needs of its users.

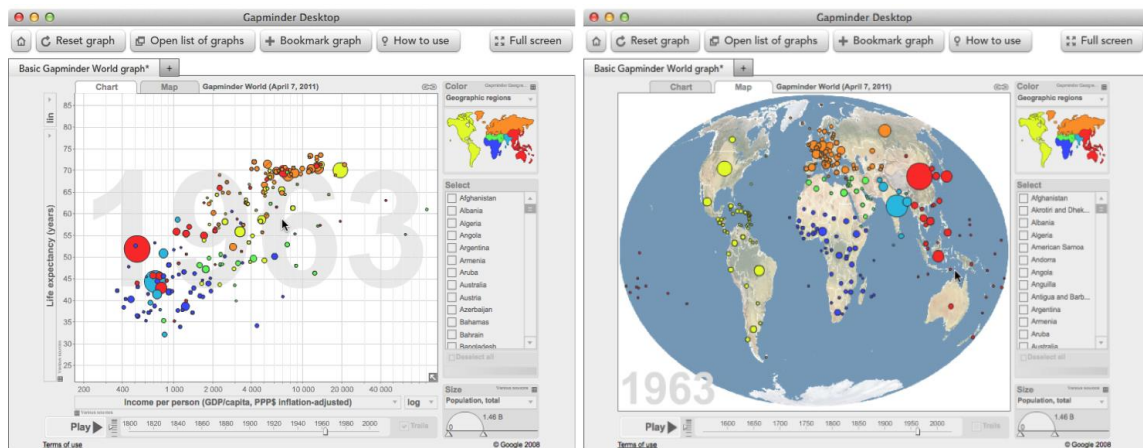


Figure 3-5 An implementation of the translating pattern: Acting upon a VR to convert it from one form to another.

Note: Free material from www.gapminder.org.

3.3.3.3 Collapsing/Expanding

Characterization: Acting upon VRs to fold them in and/or make them compact, or oppositely to fold them out and/or make them diffuse.

Utility: Among others, these actions facilitate sense making, reasoning, exploring, and investigating (Abello et al., 2006; Noel and Jajodia, 2004; Pinzger et al., 2008). Both folding and expanding representations are important in complex cognitive activities. Such actions can facilitate making sense of relationships among information items in complex information spaces by reducing and increasing detail when performing tasks (Pinzger et al., 2008). VRs with high degrees of density and/or complexity can place a large burden on users' perceptual and cognitive faculties and thus negatively influence the performance of tasks and activities (Demetriadis and Cadoz, 2005; Pirolli et al., 2001). VRs that are too dense, for instance, can place an unmanageable amount of the information-processing load on a user's working memory (Green and Petre, 1996). VRs with a lower degree of complexity have been empirically shown to have more correct responses to tasks as well as better reaction times while identifying trends in information spaces (see Cruz-Lemus et al., 2010; Huang et al., 2009; Meyer et al. 1997). Collapsing can allow users to condense a set of items into one, thereby reducing complexity and/or density and facilitating the comprehension of overall relationships and trends. Expanding, on the other hand, allows users to explore information spaces in a more diffused, opened-up fashion with more detail (Noel and Jajodia, 2004; Abello et al., 2006). When encoding a complex information space, there is always a trade-off between displaying low-level detail and high-level structure, and it is generally useful to provide users with access to both. Accordingly, expanding can be used along with collapsing to facilitate quick movement through spaces (Dachselt and Ebert, 2001). When dealing with complex VRs, expanding areas of interest while keeping other areas folded in helps manage information overload (Samp et al., 2008).

An example of a CAST that implements the collapsing and expanding patterns is *VisANT* (Hu et al., 2009), a tool that supports the exploration of protein complexes. In Figure 6, the representation space of *VisANT* is quite complex, as there are many items and relationships between them. Depending on the context, as discussed above, this may hinder the performance of perceptual and cognitive tasks. By implementing the collapsing pattern, *VisANT* provides users with the ability to act upon VRs to collapse them in order to reduce complexity and to make sense of higher-level relationships in the information space. Doing so may allow users to make sense of clusters within the

information space and identify major pathways between them. Users may need to repeatedly collapse (e.g., Figure 6 L to R) and expand (e.g., Figure 6 R to L) different portions of the VR to accomplish various tasks while performing a complex cognitive activity.

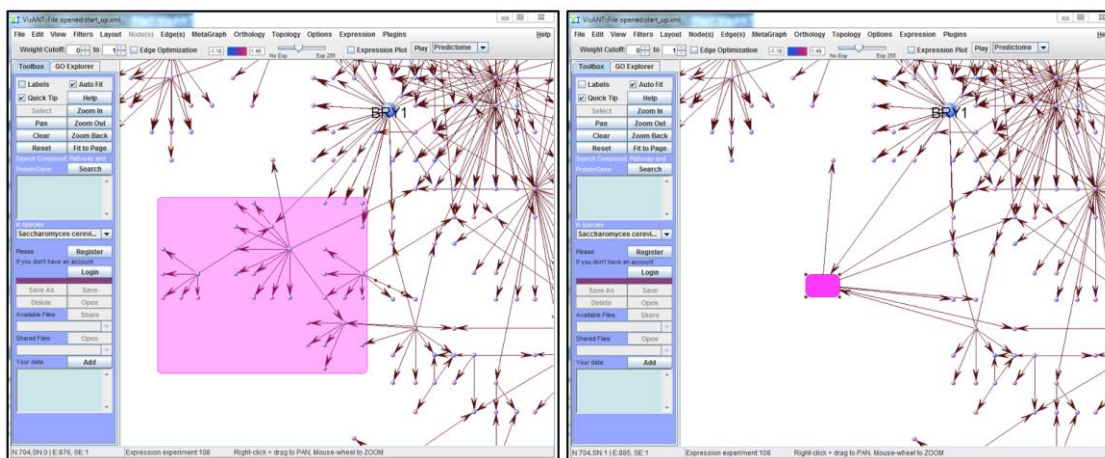


Figure 3-6 An implementation of the collapsing and expanding patterns: Acting upon a VR to fold in and fold out some of its constituent components.

3.3.4 Integrated Scenario: A Sense Making Activity

This section is intended to demonstrate how EDIFICE-AP can help with the systematic design and evaluation of epistemic actions in CASTs. A designer may identify characteristics of an information space and then consult EDIFICE-AP to become aware of relevant action patterns, which in turn can stimulate creativity in the design process. The designer can then implement desired actions in a systematic manner with their epistemic utility at the forefront of consideration. In a similar fashion, an evaluator may consult EDIFICE-AP to facilitate thinking about potential action patterns and subsequently assess how well a particular CAST is designed. The evaluator may also use EDIFICE-AP's catalog as a support structure for comparing CASTs based on their provision of action possibilities to evaluate how well they support given complex cognitive activities. Additionally, designers and evaluators can ask questions based on the actions identified in EDIFICE-AP to determine which action(s) should be included in a given CAST. For example, "Do users need to be able to see the compositional

development and growth of the information space, either spatially or temporally, to be able to perform the complex cognitive activity more effectively?” If the answer is ‘yes’ then the *scoping* pattern should be implemented in the CAST. A list of similar questions can be asked systematically, leading to decisions regarding the inclusion or non-inclusion of the other action patterns and their blending.

The scenario presented here involves a sense making activity, in which a financial analyst needs to make sense of stock market activity in the US. In such an activity, the user (she)¹ has insufficient knowledge of the information space and needs to develop a clearer mental model of it. Through a cycle of actions, her conceptualization of the space gradually evolves such that she can eventually develop an adequate mental model of the space. The rest of this section demonstrates how using EDIFICE-AP and thinking about the combination and integration of a number of different action patterns can facilitate design and evaluation of a CAST that supports the sense making activity.

As discussed previously, complex cognitive activities are hierarchical and emergent, resulting from the combination and interaction of a number of sub-activities, tasks, sub-tasks, actions, and events. While making sense of large and complex information spaces, users perform different sub-activities and gradually synthesize them once adequate connections between pieces of information can be made. One sub-activity that the user would likely perform in this scenario is knowledge discovery—exploring the information space to discover useful patterns within it. This sub-activity may involve the user browsing the information space to identify the distribution and dispersion of stocks and to distinguish between different categories of stocks. The user would also likely need to perform the task of organizing some of this information not only by identifying stocks and distinguishing between them, but also by ranking them according to different criteria. Consider the actions discussed below and how they facilitate the performance of such tasks and gradually lead to the emergence of activities.

¹ For ease of reading and consistency, in this section we will refer to the designer as ‘he’ as to the user as ‘she’.

While the user is browsing and trying to identify prominent features of the information space, one action that can facilitate such a task is *drilling*. The user can repeatedly drill into different stocks or industries to identify properties such as open and close values, turnover, and market capitalization. As the user begins to get a general sense of some of the main items within the information space, she will likely wish to identify and distinguish between items according to some particular criteria. One action pattern that facilitates such a task is *filtering*. Figure 7 shows a treemap VR² of the stock market information space. In Figure 7 (L), an overview of the information space is provided, with stocks categorized according to industry. Figure 7 (R), however, shows the result of the user filtering the VR to display only stocks with relative activity above 600%. Only a handful of stocks are now shown, and the user can easily identify stocks that have seen a very high amount of recent activity, which may stimulate hypothesis formulation, information searches, and outlier detection. The user may perform similar filtering actions according to other criteria such as market capitalization, turnover, and degree of change.



Figure 3-7 Filtering a VR to display only stocks with high relative activity

As the user progresses in the activity, she will need to organize all of the identified items to develop a richer mental model of the information space. One action pattern that can help in this regard is *comparing*. Figure 8 shows the user acting upon the VR to compare two stocks within the technology industry. Performance of this action allows the user to

² All figures in this section are screenshots of *Panopticon*, a CAST that supports visual analysis of numerous information spaces. Figures are used with kind permission from Panopticon (www.panopticon.com).

further distinguish between different stocks based on their properties, and to begin to develop an understanding of the rank and ordering of stocks based on their different properties. In addition, an action pattern that can further facilitate this task is that of *arranging*. By acting upon the VR to adjust its spatial arrangement, the user can easily perceive the ranking of all stocks based on their properties such as market capitalization and trading activity. Figure 9 depicts the user arranging the VR to reorder it according to market capitalization (L) and trading activity (R).

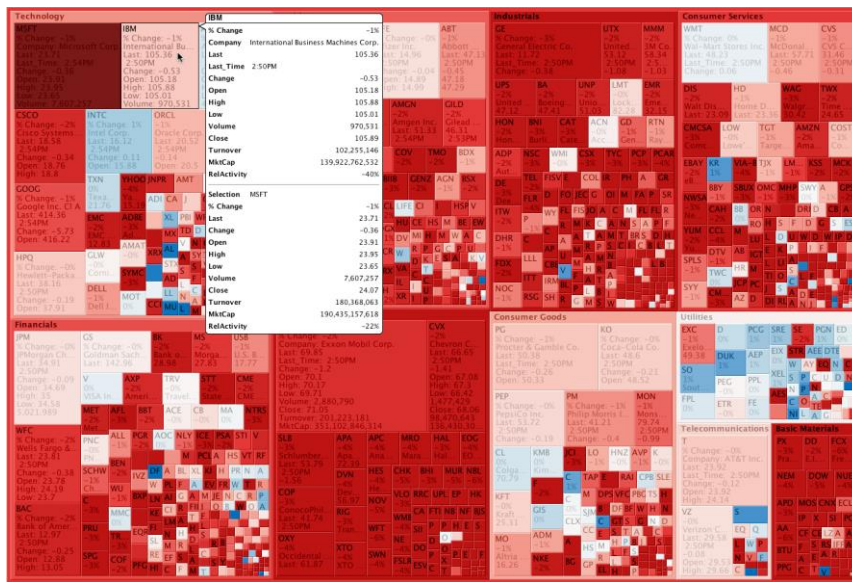


Figure 3-8 Comparing the Microsoft and IBM stocks.



Figure 3-9 Arranging a VR to reorder it according to market capitalization (L) and trading activity (R).

Although the treemap VR exploits certain perceptual features to facilitate tasks and activities, no one VR can sufficiently support all tasks and activities. Thus, a designer could predict that with such a complex information space the user would benefit from having access to different VRs of the same underlying information. A previously discussed action that has utility in most activities is *translating*. Figure 10 shows the user translating the treemap VR to an alternative form—a scatterplot VR. In this case, the information content of the scatterplot is very similar to that of the treemap. The form of the VR, however, exploits different perceptual features and facilitates tasks and activities in different ways than the treemap VR (see Parsons and Sedig, 2013a, for more discussion of the perceptual and cognitive utility of different VRs).



Figure 3-10 Translating the Treemap VR (L) to an alternative form (R).

Consulting the action catalog provided by EDIFICE-AP can help designers and evaluators to identify other action patterns that can further support the user in the performance of her sense making activity. For instance, consider the following action patterns from EDIFICE-AP in the context of the current scenario:

Gathering/Discarding. While interacting with the treemap VR, the user may become interested in a few particular stocks. For example, she may be surprised at the large gap in market value between certain stocks that she thought would have a similar market value. As a result, she may gather them into a temporary collection for subsequent analysis. She may then discard some that are not pertinent to a particular task.

Scoping. In order to identify relationships and temporal trends among stocks, industries, or sectors within the information space, the user can act upon the VR by scoping it. For instance, she may wish to see the growth of the oil and gas sector over the past few decades, particularly around specific events such as the 1973 oil crisis. Providing mechanisms for dynamically moving forwards and backwards to see the temporal growth and development of the VR may facilitate such tasks.

Navigating. The user may wish to identify connections within the information space that are not visible in the VR. For instance, given the VR in Figure 8, she could navigate it by traversing its stocks according to market value. This could allow the user to identify the

ranking of stocks while keeping the spatial layout of the VR consistent, so that she can identify their positions within the different sectors and industries.

Cloning. The user may wish to perform certain actions upon a VR, but may still wish to keep the original state of the VR. Additionally, she may wish to have both the new state and the original state simultaneously to compare or perform other tasks with them. As such, she can act upon one of the VRs in the plot that represents an individual stock to clone it and make a copy. She may then perform numerous actions on the cloned VR, such as assigning, annotating, or drilling.

Assigning. After cloning a VR of a stock, the user can assign a certain value or feature to the VR and perceive its effect. For example, she could assign a particular value to the stock to forecast how it may affect other stocks within the sector or to project its growth over a period of time.

Annotating. After cloning a VR and assigning certain properties to it, the user may want to make a record of what she has done, why she has done it, and any expectations, outcomes, or other observations that she has. If the CAST provides the ability to annotate VRs, she can act upon a VR to add such meta-information to it. Visiting the annotation at a later point in time may facilitate sense making and/or may provide insight into her thought processes.

Storing/Retrieving. At any point, especially after altering VRs by annotating, assigning, or cloning, the user may wish to store them. At some later point in time she can then retrieve them to continue with other activities or tasks.

Not only does EDIFICE-AP provide an action catalog that allows designers and evaluators to think about action possibilities in a systematic fashion, but it also provides a framework for thinking about the overall human-information discourse and the emergent nature of complex cognitive activities. More specifically, EDIFICE-AP helps in thinking about how actions allow users to mentally ‘reach into’ and perform operations on an information space, how the continual occurrence of actions, reactions, and perceptions

forms an epistemic cycle, and how complex cognitive activities emerge over time from the combination and interaction of actions and tasks (see Figures 1-3). Figure 11 demonstrates how the provision of different action patterns allows users to operate on represented information in different ways, and to ‘reach into’ an information space to access new information or modify or remove existing information. Figure 12 depicts how the sense making activity discussed in this section emerges at different levels over time.

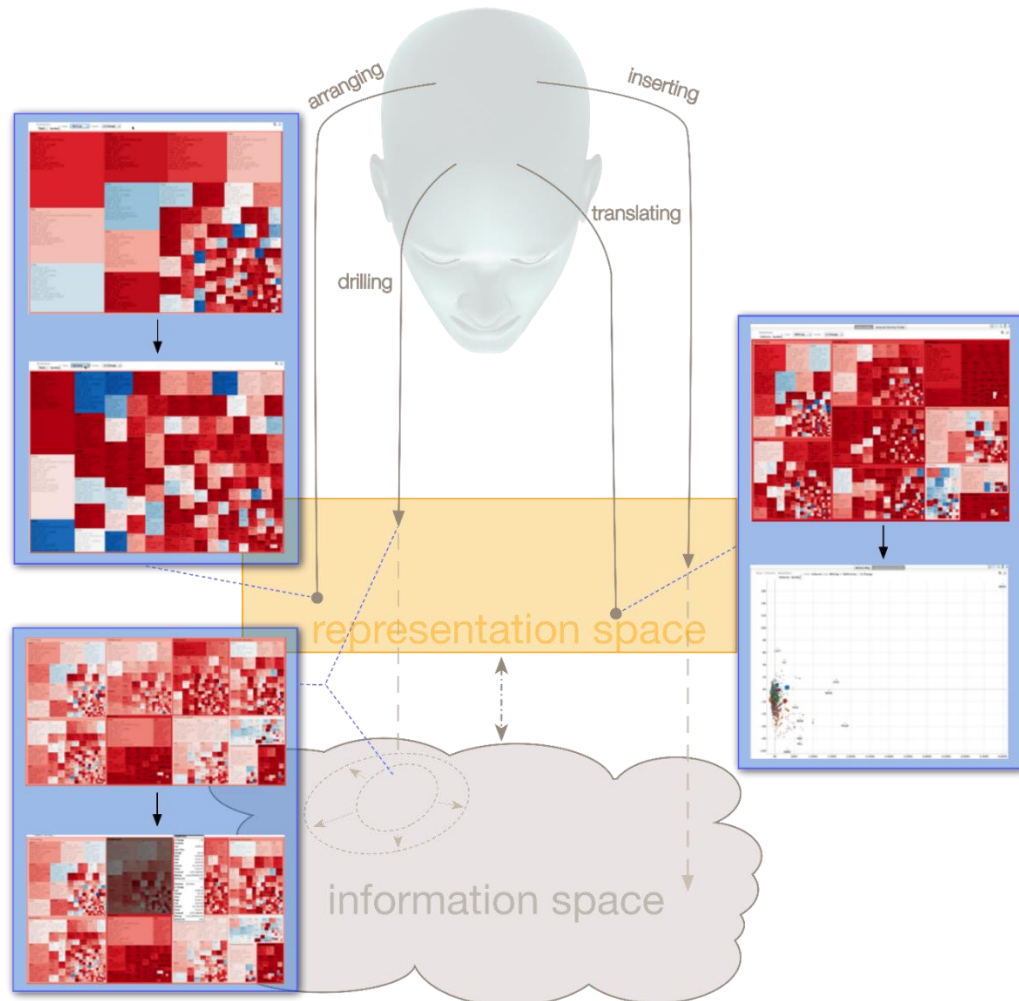


Figure 3-11 Different actions allow the user to operate on represented information in different ways, and to mentally 'reach into' an information space.

Note: Vector art adapted from www.vectoropenstock.com under the Attribution Creative Commons 3.0 license

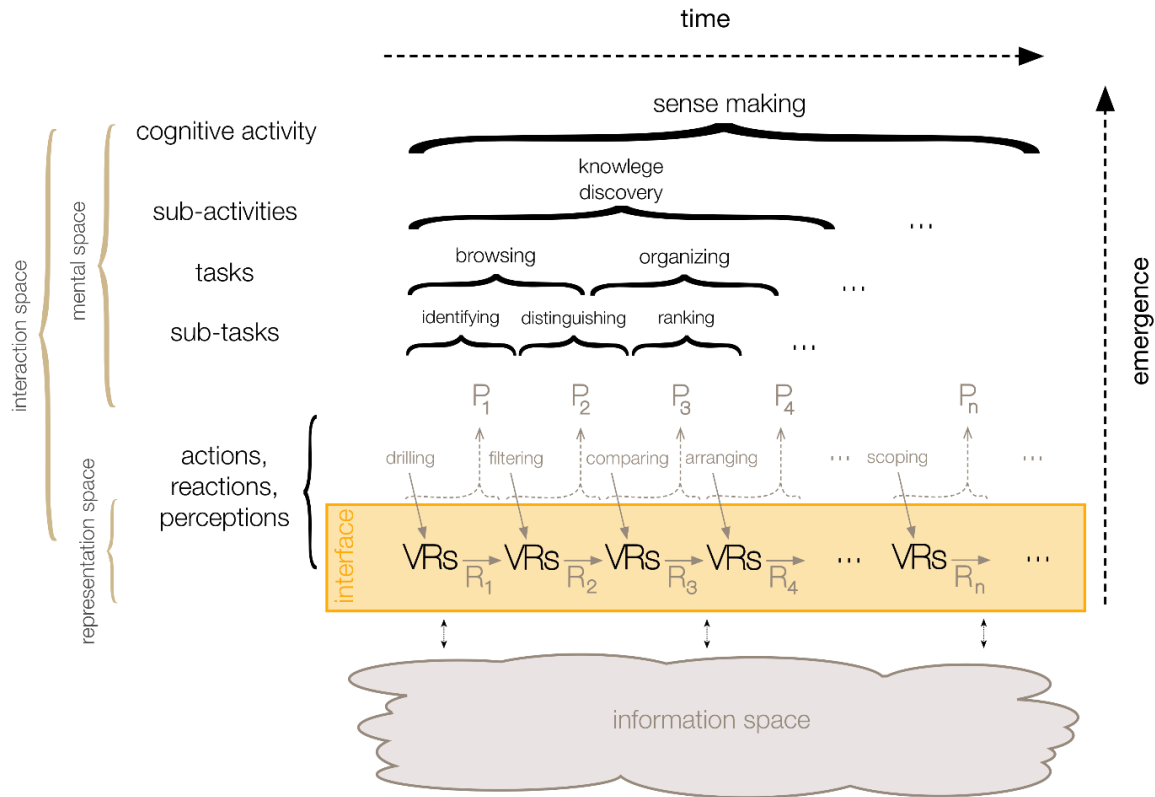


Figure 3-12 Emergence of the overall sense making activity over time from the performance of actions, tasks, and activities.

3.3.5 Comparison to Existing Work

The body of relevant existing research is fragmented and scattered across a number of disciplines. In addition, researchers are often concerned with only a particular group of users, a particular activity, or a particular domain. As a result, to develop a holistic and comprehensive understanding of interaction in the context of supporting complex cognitive activities, one must consult research from multiple disciplines, such as human-computer interaction, cognitive science, information visualization, visual analytics, information behavior, and learning technologies, and attempt to integrate such research into a coherent model. The manner in which EDIFICE-AP addresses this issue has been discussed in detail above and will not be repeated here.

Although there is a lack of general, comprehensive, and syncretic frameworks and models regarding human-information interaction in complex cognitive activities, researchers in the information visualization and visual analytics communities have been involved in developing one necessary component: interaction catalogs and taxonomies (e.g., Yi et al., 2007; Ward and Yang, 2003; Liu and Stasko, 2010; Gotz and Zhou, 2008; Heer and Shneiderman, 2012; Pike et al., 2009). Most of these, however, discuss only a small subset of possible actions and do not include actions identified in EDIFICE-AP such as animating, scoping, blending, assigning, and accelerating/decelerating, all of which are useful for complex cognitive activities mediated by different CASTs that are concerned with different information spaces. There are numerous information spaces and complex cognitive activities in which scoping, for instance, would be a desirable action, yet none of the existing work identifies and characterizes such an action and its utility. Another issue with existing work is that actions are sometimes presented without any characterization or examination of their utility. For instance, an action that has utility in many contexts (e.g., visual analytics, information visualization, decision support systems, and health informatics) is annotating. Much of the existing work does not identify, characterize, or describe the utility of annotating for performing complex cognitive activities. If annotating is identified (e.g., by Gotz and Zhou, 2008), its characterization is tied to a particular domain or activity, and therefore cannot inform a general framework concerned with interaction design.

In addition to these aforementioned issues, existing research often makes no clear distinction between different levels of interaction (i.e., activities, tasks, actions, events). As interaction is a complex phenomenon, such a distinction is crucial to establishing a consistent conceptualization and vocabulary for discussing interaction design. Yi et al. (2007), for example, identified 7 different interactions: select, explore, reconfigure, encode, abstract/elaborate, filter, and connect, each of which are characterized at different levels. For instance, *select* is a precise and low-level action. *Explore*, however, is a higher-level task that may actually involve lower-level actions such as selecting. In a similar fashion, Pike et al. (2009) identified *explore* as both a high-level task and an interaction; *select* as an interaction and *selection* as an interaction technique; and *filter* as both a low-level task and an interaction. In addition, they identified *correlate* and *cluster*

as low-level tasks, and *compare* as a high-level task, without any characterization of these tasks or justification as to their ascribed levels. In another contribution, Liu and Stasko (2010) also did not make a clear distinction between different levels of interaction with information. For instance, they identified both *explore* and *create* as actions but then characterized them as activities. They also identified both *save/load* and *explore* as actions; however, *save/load* is a low-level and precise action, whereas *explore* is a high-level and imprecise task or activity.

Although existing work can be scrutinized to identify areas of needed improvement, the aforementioned researchers have faced the difficult task of characterizing and classifying a wide range of phenomena, and have made valuable inroads into bringing order and coherence to the vast landscape of interaction design. If we are to develop a science of interaction, however, much further research is required to characterize, categorize, and explicate the concept of interaction. Such a task requires a coherent integration of numerous issues regarding, among others, information, visual representations, cognition, perception, interaction, events, tasks, and activities. As demonstrated in the preceding pages, EDIFICE-AP represents a major attempt to provide a coherent, methodical, and comprehensive framework that contributes to such a research need.

3.4 Summary and Future Work

Cognitive activity support tools (CASTs) mediate and supplement human cognitive faculties to enable high-level activities such as making sense of phenomena, making decisions, solving problems, discovering knowledge in a large body of data, analyzing information, and learning. They do so by maintaining and processing digital information, displaying visual information representations (VRs) at their interface, and providing mechanisms through which users can interact with VRs. Due to their interactive nature, CASTs allow users to perform epistemic actions on VRs that facilitate mental information processing functions. This creates a strong coupling between the user and a CAST, and allows the tool to become an active participant in the user's cognitive

processes. The action choices offered by a CAST can extend the human mind, allowing users to reach into an information space to perform operations upon it, such as by bringing into view portions of the information that have not been encoded and displayed by the VRs at the interface level, by viewing information from different perspectives, or by reorganizing the information. When using CASTs to perform complex cognitive activities, it is through a sequence of epistemic actions that such activities emerge. Users engage in an interaction cycle in which they perceive VRs, interpret them and perform other mental operations, act upon them, perceive the reaction, and so on. This cycle continues until the user is satisfied with a task or until an overall activity is accomplished. Accordingly, interaction design for CASTs is concerned with what users can and should do with VRs, what actions should be made available to them, and what their subsequent reactions should be. In other words, interaction design is concerned with the discourse that takes place between users and VRs at the interface of a tool.

Researchers have recently recognised a need for developing a science of interaction that can guide the analysis and design of all kinds of tools that support complex cognitive activities. Although work has been done in this area, no existing frameworks are comprehensive enough to be applicable to all types of users, activities, tools, complex cognitive activities, and VRs. This paper attempts to address this need, and is part of a larger research effort to develop a comprehensive framework of human-information interaction with CASTs called EDIFICE (Epistemology and Design of human-Information Interaction in complex Cognitive activities). Since this paper is largely concerned with the action part of EDIFICE, we have referred to it as EDIFICE-AP (where AP stands for Action Patterns). The focus of EDIFICE-AP is mainly on interaction at the level of individual actions and reactions, dealing mostly with pattern-based characterizations of actions and their utility in supporting complex cognitive activities.

Four major characteristics position EDIFICE-AP to address existing research needs. It is: 1) syncretic, unifying a number of previously disconnected ideas into a coherent theoretical model; 2) general, operating at a level of abstraction that is applicable to all kinds of technologies, activities, users, and VRs; 3) comprehensive, identifying patterns

that cover an extensive range of actions; and, 4) generative, possessing the ability to motivate design creativity as well as to stimulate further theoretical and empirical research.

EDIFICE-AP can offer a number of benefits for researchers, designers, and evaluators of CASTs. First, it provides suggestions for design while still allowing for creativity, flexibility, and innovation at the implementation level. Since a pattern-based characterization allows EDIFICE-AP to be tool- and technology-independent, this flexibility also extends to tools and technologies. Consequently, it is resilient to technological change and extensible to future technologies such as tablets, interactive tabletops, motion sensing input devices, virtual reality and augmented reality environments, and interactive surface projection environments. A second benefit of EDIFICE-AP is that it provides a high-level support structure for communicating and thinking about interaction design in a systematic fashion. For instance, designers and evaluators may not be aware of certain action patterns and their utilities. Using EDIFICE-AP, they can methodically examine each action pattern to think about its utility and whether or not a CAST would be enriched by such an action. This allows for communicating and thinking about a wide range of action possibilities, and how they might benefit a user, in a systematic and consistent manner. A third benefit is that EDIFICE-AP is applicable to all activities. In CASTs, activities are emergent phenomena that result from the combining and chaining of numerous individual actions. Hence, whether designing or evaluating a tool for sense making, planning, learning, knowledge discovery, or problem solving, a subset of the epistemic actions in EDIFICE-AP can be used to support the activity, depending on the contextual and situational needs of the activity and its users. A fourth benefit is that EDIFICE-AP is applicable to all users. Since EDIFICE-AP is pattern-based, interactions can be implemented in such a way that is suits all age groups, levels of experience, capabilities, and backgrounds. Similarly, it is also applicable to both single-user and multi-user environments.

EDIFICE-AP provides opportunities for much future research. One important future line of research, for instance, can involve the investigation of the degree of information processing that should take place in the different spaces of the human-information

interaction epistemic cycle for different types of CASTs and activities (see Figure 3). Currently, there is very little understanding of how processing load should be distributed among these spaces (see Parsons and Sedig, 2013b for a recent discussion of this issue). Another future line of research involves determining which action patterns complement one another in the performance of specific tasks and activities. Knowing which actions are complementary could allow for the creation of tools that support more coordinated and integrated tasks and activities. Another related line of research involves investigating the appropriate diversity and redundancy of actions for different tasks and activities. In other words, this line of research would be concerned with the number of actions that a CAST should offer, and whether users should be provided with multiple and diverse actions with which tasks and activities may be performed. Currently, we do not have a clear understanding of the implications of such considerations for interaction design. Future studies are required to develop a deep and structured understanding of these issues. Another possible area of research is in conducting empirical studies to develop a more detailed understanding of the utility of action patterns. In a general sense, each action pattern can support all kinds of activities; however, our knowledge of how and under what conditions each action pattern supports particular tasks and activities is still far from complete. Another possible area of future research involves categorizing interaction techniques according to the action pattern under which they fit. As there are hundreds of existing interaction techniques scattered across different disciplines, such a research effort could help to give more structure to the interaction design landscape. Additionally, such a categorization could add more of a prescriptive element to EDIFICE-AP and could provide a more robust palette of design rules and guidelines from which designers may make design decisions. Closely related to this is another line of action: that of devising new sets of different techniques and implementations under the same action pattern to compare, contrast and study their trade-offs. Furthermore, as EDIFICE-AP has presented many new action patterns, studies may be done to more accurately assess their relationships to particular tasks, users, tools, and complex cognitive activities.

3.5 Acknowledgements

This research has been supported financially by the Natural Sciences and Engineering Research Council of Canada. We would also like to express our gratitude to the reviewers of this paper for their constructive and helpful comments. This paper would not be in its current shape without their insightful suggestions.

3.6 References

- Abello, J., F. van Ham, and N. Krishnan (2006) "ASK-Graphview: A Large Scale Graph Visualization System," *IEEE Transactions on Visualization and Computer Graphics* (12) 5, pp. 669-676.
- Abrahamson, D. (2006) "Mathematical Representations as Conceptual Composites: Implications for Design," in S. Alatorre, J. L Cortina, M. Sáiz, and A. Méndez (Eds.), *Proceedings of the Twenty Eighth Annual Meeting of the North American Chapter of the International Group for the Psychology of Mathematics Education* (2), pp. 464-466.
- Abrams, D., R. Baecker, and M. Chignell (1998) "Information Archiving with Bookmarks: Personal Web Space Construction and Organization," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pp. 41-48.
- Ahlberg, C. and B. Shneiderman (1994) "Visual Information Seeking using the Filmfinder," in *Conference Companion on Human Factors in Computing Systems*, pp. 433-434.
- Aigner, W. (2011) "Understanding the Role and Value of Interaction: First Steps," in S. Miksch and G. Santucci (Eds.), *International Workshop on Visual Analytics*, pp. 17-20.
- Ainsworth, S. and N. van Labeke (2002) "Using a Multi-Representational Design Framework to Develop and Evaluate a Dynamic Simulation Environment," in *International Workshop on Dynamic Visualizations and Learning*, Tubingen, Germany.
- Amar, R. A. and J. T. Stasko (2005) "Knowledge Precepts for Design and Evaluation of Information Visualizations," *IEEE Transactions on Visualization and Computer Graphics* (11) 4, pp. 432-442.
- Amar, R. A., J. Eagen, and J. T. Stasko (2004) "Low-Level Components of Analytic Activity in Information Visualization," *IEEE Symposium on Information Visualization (INFOVIS 2005)*, pp. 111-117.

- An, Y., J. Janssen, and E., Milios (2001) "Characterizing and Mining the Citation Graph of the Computer Science Literature," *Knowledge and Information Systems* (6) 6, pp. 664-678.
- Anderson, J. (2000) *Cognitive Psychology and its Implications* (5th Ed.). NY: Worth Publishers.
- Anderson, M., B. Meyer, and P. Olivier (2002, Eds.) *Diagrammatic Representation and Reasoning*. London: Springer.
- Anderson, T. H., B. B. Armbruster, and B. Bonnie (1984) "Studying," Center for the Study of Reading Technical Report no. 155. University of Illinois at Urbana-Champaign, Center for the Study of Reading.
- Archim. www.archimiy.com
- Avouris, N., M. Margaritis, and C. Komis (2003) "Real-Time Collaborative Problem Solving: A Study on Alternative Coordination Mechanisms," in *Proceedings of the 3rd IEEE International Conference on Advanced Learning Technologies (ICALT'03)*, pp. 86-90.
- Barreau, D. K. (1995) "Context as a Factor in Personal Information-Management Systems," *Journal for the American Society of Information Science* (46) 5, pp. 327-339.
- Bastian M., S. Heymann and M. Jacomy (2009) "Gephi: An Open Source Software for Exploring and Manipulating Networks," in *International AAAI Conference on Weblogs and Social Media*, pp. 361-362.
- Bates, M. (2005) "Information and Knowledge: An Evolutionary Framework for Information Science," *Information Research* (10) 4.
- Bates, M. (2006) "Fundamental Forms of Information," *Journal of the American Society for Information Science and Technology* (57) 8, pp. 1033-1045.
- Bauer, S. W. and J. Wise (2004) *The Well-Trained Mind: A Guide to Classical Education at Home* (3rd Ed.). NY: W. W. Norton & Co.
- Beach, L. R. and T. Connolly (2005) *The Psychology of Decision Making*. Thousand Oaks, CA: Sage.
- Beaudouin-Lafon, M. (2004) "Designing Interaction, not Interfaces," in *Proceedings of the Working Conference on Advanced Visual Interfaces (AVI '04)*, pp. 15-22.
- Becker, R. A., W. S. Cleveland, and A. R. Wilks (1998) "Dynamic Graphics for Data Analysis," in W. S. Cleveland and M. E. McGill (Eds.). *Dynamic Graphics for Statistics*, pp. 1-49. Belmont, CA: Wadsworth.
- Bederson, B. B. and B. Shneiderman (2003, Eds.) "Theories for Understanding Information Visualization," in *The Craft of Information Visualization: Readings and Reflections*, pp. 349-351. San Francisco: Morgan Kaufmann
- Berka, K. (1983) *Measurement: Its Concepts, Theories, and Problems*. Dordrecht, Holland: D. Reidel Publishing.
- Bertin, J. (1983) *Semiology of Graphics*. Madison, WI: University of Wisconsin Press.

- Bétrancourt, M. (2005) "The Animation and Interactivity Principles," In R. E. Mayer (Ed.) *Handbook of Multimedia*, pp. 287-296. Cambridge: Cambridge University Press.
- Beynon, B., C. L. Nehaniv, and K. Dautenhahn (Eds., 2001) "Cognitive Technology: Instruments of Mind," in *Proceedings of the 4th International Cognitive Technology Conference*. Coventry, UK.
- Bhargava, H. K., D. J. Power, and D. Sun (2007) "Progress in Web-Based Decision Support Technologies," *Decision Support Systems* (43) 4, pp. 1083-1095.
- Bishop, A. (1991) *Mathematical Enculturation: A Cultural Perspective on Mathematics Education*. Dordrecht, Holland: Kluwer Academic.
- Blackwell, A. F., K. Marriott, and A. Shimojima (2004, Eds.) *Proceedings of the 3rd International Conference on Diagrammatic Representation and Inference*. Cambridge, UK: Springer.
- Bodner G. M. and D. S. Domin (2000) "Mental Models: The Role of Representations in Problem Solving in Chemistry," *University Chemistry Education* (4), pp. 24-30.
- Bohm, D. and D. F. Peat (1987) *Science, Order, and Creativity*. NY: Routledge.
- Bransford, J. D., A. L. Brown, and R. R. Cocking (2000) *How People Learn: Brain, Mind, Experience, and School*. Washington, DC: National Academies Press.
- Brey, P. (2005) "The Epistemology and Ontology of Human-Computer Interaction," *Minds and Machines* (15), pp. 383-398.
- Brown, M. (1998) *Human-Computer Interaction Design Guidelines*. Bristol, UK: Intellect Books.
- Buchel, O. and K. Sedig (2011) "Using Map-Based Visual Interfaces to Facilitate Knowledge Discovery in Digital Libraries," in *Proceedings of the American Society for Information Science and Technology* (48) 1, pp. 1-5.
- Burdea, G. C. and P. Coiffet (2003) *Virtual Reality Technology* (2nd Ed.). Hoboken, NJ: John Wiley and Sons.
- Cairncross, S. and M. Mannion (2001) "Interactive Multimedia and Learning: Realizing the Benefits," *Innovations in Education and Teaching International* (38) 2, pp. 156-164.
- Caraballo, A. (1985) "An Experimental Study to Investigate the Effects of Computer Animation on the Understanding and Retention of Selected Levels of Learning Outcomes," Doctoral Dissertation, Pennsylvania State University.
- Card, S., J. MacKinlay, and B. Shneiderman (1999) *Readings in Information Visualization: Using Vision to Think*. San Francisco: Morgan Kaufmann Publishers.
- Card, S., B. Suh, B. A. Pendleton, J. Heer, and J. W. Bodnar (2006) "Time Tree: Exploring Time Changing Hierarchies," *IEEE Symposium on Visual Analytics Science and Technology*, pp. 3-10.

- Carroll, J. M. (1991, Ed.) *Designing Interaction: Psychology at the Human-Computer Interface*. NY: Cambridge University Press
- Chen, C. (2004) "Searching for Intellectual Turning Points: Progressive Knowledge Domain Visualization," in *Proceedings of the National Academy of Sciences* (101) 1, pp. 5303-5310.
- Chen, C., and S. Morris (2003) "Visualizing Evolving Networks: Minimum Spanning Trees Versus Pathfinder Networks," in *Proceedings of the IEEE Symposium on Information Vizualization*, pp. 67-74.
- Clark, A. (1998a) *Being There: Putting Brain, Body, and World Together Again*. Cambridge, MA: MIT Press.
- Clark, A. (1998b) "Time and Mind," *The Journal of Philosophy* (95) 7, pp. 354-376.
- Clark, A. (2008) *Supersizing the Mind: Embodiment, Action, and Cognitive Extension*. Oxford: Oxford University Press.
- Clements, D. and M. Stephan (2004) "Measurement in PreK-2 Mathematics," in D. Clements, J. Sarama, and A. M. Di-Biase (Eds.), *Engaging Young Children in Mathematics: Standards for Early Childhood Mathematics Education*. Mahwah, NJ: Lawrence Erlbaum.
- Clements, D., M. Battista, J. Sarama, and S. Swaminathan (1997) "Development of Students' Spatial Thinking in a Unit on Geometric Motions and Area," *The Elementary School Journal* (98), pp. 171-186.
- Clements, D., D. Wilson, and J. Sarama (2004) "Young Children's Composition of Geometric Figures: A Learning Trajectory," *Mathematical Thinking and Learning* (6) 2, pp. 163-184.
- Cobb, S. and D. S. Fraser (2005) "Multimedia Learning in Virtual Reality," in R. E. Mayer (Ed.), *The Cambridge Handbook of Multimedia Learning*. NY: Cambridge University Press.
- Cohen, I. and D. Gordon (2008) "VS: A Surface-Based System for Topological Analysis, Quantization and Visualization of Voxel Data," *Medical Image Analysis* (13), pp. 245-256.
- Cooper, G. (1998) "Research into Cognitive Load Theory and Instructional Design at UNSW," Retrieved from http://education.arts.unsw.edu.au/CLT_NET_Aug_97.HTML.
- Cowan, N. (2001) "The Magical Number 4 in Short-Term Memory: A Reconsideration of Mental Storage Capacity," *Behavioral and Brain Sciences* (24) 1, pp. 87-114.
- Cox, R. and P. Brna (1995) "Supporting the Use of External Representations in Problem Solving: The Need for Flexible Learning Environments," *Journal of Artificial Intelligence in Education* (2) 3, pp. 239-302.
- Cruz-Lemus, J. A., A. Maes, M. Genero, G. Peols, and M. Piattini (2010) "The Impact of Structural Complexity on the Understandability of UML Statechart Diagrams," *Information Sciences*, (180) 11, pp. 2209-2220.

- Czerwinski, M., E. Horvitz and S. Wilhite (2004) "A Diary Study of Task Switching and Interruptions," *ACM SIGCHI Conference on Human Factors in Computing Systems*, pp. 175-192.
- Dahlbäck, N. (1998) "On Spaces and Navigation in and out of the Computer," in N. Dahlbäck (Ed.), *Exploring Navigation: Towards a Framework for Design and Evaluation of Navigation in Electronic Spaces*, pp. 13-30. SICS Technical Report T98:01.
- Dalgarno, B. (2004) "A Classification Scheme for Learner-Computer Interaction," in R. Atkinson, C. McBeath, D. Jonas-Dwyer and R. Phillips (Eds.), *Beyond the Comfort Zone: Proceedings of the 21st ASCILITE Conference*, pp. 240-248.
- Dansereau, D. F. (2005) "Node-Link Mapping Principles for Visualizing Knowledge and Information," in S-O. Tergan and T. Keller (Eds.), *Knowledge and Information Visualization: In Search of Synergies*, pp. 61-81. Heidelberg, Germany: Springer-Verlag.
- Darian, S. (2003) *Understanding the Language of Science*. Austin, TX: University of Texas Press.
- Dascal, M. and I. E. Dror (2005) "The Impact of Cognitive Technologies: Towards a Pragmatic Approach," *Pragmatics and Cognition* (13) 3, pp. 451-457.
- Dachselt, R. and J. Ebert (2001) "Collapsible Cylindrical Trees: A Fast Hierarchical Navigation Technique," *IEEE Symposium on Information Visualization*, pp. 79-86.
- Davenport, T. H. and L. Prusak (1998) *Working Knowledge*. Boston, MA: Harvard Business School Press.
- Davidson, J. E. (2003) "Insights about Insightful Problem Solving," in J. E. Davidson and R. J. Sternberg (Eds.), *The Psychology of Problem Solving*, pp. 149-175. NY: Cambridge University Press.
- De Jong, T., S. Ainsworth, M. Dobson, A. van der Hurst, J. Levonen, P. Reimann, J. A. Sime, M. W. van Someren, H. Spada, and J. Swaak (1998) "Acquiring Knowledge in Science and Mathematics: The use of Multiple Representations in Technology-Based Learning Environments," in M. W. van Someren, P. Reimann, P. A. Boshuizen, and T. de Jong (Eds.), *Learning with Multiple Representations*, pp. 9-41. Oxford, UK: Elsevier.
- Dearden, A. M. and J. Finlay (2006) "Pattern Languages in HCI: A Critical Review," *Human Computer Interaction* (21) 1, pp. 49-102.
- Demetriadis, S., and C. Cadoz (2005) "A Conceptual Framework for the Integrative Design of Adaptable Representations for Learning," in A. Mendez-Vilas, B. Gonzalez-Pereira, J. Mesa Gonzalez, and J. A. Mesa Gonzalez (Eds.), *Recent Research Developments in Learning Technologies*, pp. 1250-1255. Badajoz, Spain: Formatex.
- Dervin, B. (1977) "Useful Theory for Librarianship: Communication, Not Information," *Drexel Library Quarterly* (13) 3, pp. 16-32.

- Dervin, B. (1983) "An Overview of Sense Making Research: Concepts, Methods and Results to Date," Seattle: School of Communications, University of Washington.
- Dervin, B. (1992) "From the Mind's Eye of the Users: The Sense Making Qualitative-Quantitative Methodology," in J. D. Glazier and R. R. Powell (Eds.), *Qualitative Research in Information Management*, pp. 61-84. Englewood, CO: Libraries Unlimited.
- Dervin, B. (1997) "Given a Context by any Other Name: Methodological Tools for Taming the Unruly Beast," in *Proceedings of the International Conference on Information Seeking in Context*, pp. 13-38.
- Desimone, R., and J. Duncan (1995) "Neural Mechanisms of Selective Visual Attention," *Annual Review of Neuroscience* (18), pp. 193-222.
- Détienne, F., and F. Bott (2002) *Software Design—Cognitive Aspects*. London: Springer.
- Dörk, M., S. Carpendale, and C. Williamson (2011) "EdgeMaps: Visualizing Explicit and Implicit Relations," in *Proceedings of VDA 2011: Conference on Visualization and Data Analysis, IS&T/SPIE*, 12 pp.
- Dwyer, F. (1994) "One Dimension of Visual Research: A Paradigm and its Implication," in D. Moore and F. Dyer (Eds.), *Visual learning: A Spectrum of Visual Learning*. Englewood Cliffs, NJ: Educational Technology Publications.
- Eccles, R., T. K. Kapler, R. Harper, and W. Wright (2008) "Stories in GeoTime," *Information Visualization* (7) 3, pp. 3-17.
- Elmqvist, N., A. V. Moere, H.-C. Jetter, D. Cernea, H. Reiterer, and T. J. Jankun-Kelly (2011) "Fluid Interaction for Information Visualization," *Information Visualization* (10) 4, pp. 327-340.
- Elmqvist, N., Y. Riche, N. Henry-Riche, J.-D. Fekete (2010) "Mélange: Space Folding for Visual Exploration," in *IEEE Transactions on Visualization and Computer Graphics* (16) 3, pp. 468-483.
- Ericsson, K. A. and R. Hastie (1994) "Contemporary Approaches to the Study of Thinking and Problem Solving," in R. Sternberg (Ed.), *Thinking and Problem Solving*, pp. 37-80. San Diego, CA: Academic Press.
- Fabrikant, S. I. (2011) "Persistent Problem in Geographic Visualization: Evidence of Geovis(ual Analytics) Utility and Usefulness," in *ICA Geovis Commission ICC2011 Workshop*, Paris, France.
- Fast, K. V. and K. Sedig (2011) "Interaction and the Epistemic Potential of Digital Libraries," *International Journal on Digital Libraries* (11) 3, pp. 169-207.
- Fayyad, U., G. Grinstein, and A. Wierse (2002, Eds.) *Information Visualization in Data Mining and Knowledge Discovery*. London: Academic Press.
- Feltovich, P. J., M. J., Prietula, and K. A. Ericsson (2006) "Studies of Expertise from Psychological Perspectives," in K. A. Ericsson, N. Charness, P. J. Feltovich, and R. R. Hoffman (Eds.), *The Cambridge Handbook of Expertise and Expert Performance*, pp. 41-67. NY: Cambridge University Press.

- Fidel, R. (2012) *Human Information Interaction: An Ecological Approach to Information Behavior*. Cambridge, MA: MIT Press.
- Fildes, R., P. Goodwin, and M. Lawrence (2006) "The Design Features of Forecasting Support Systems and their Effectiveness," *Decision Support Systems* (42) 1, pp. 351-361.
- Fincher, S. (1999) "What is a Pattern Language?" *Patterns Workshop at INTERACT '99*, Edinburgh, Scotland, August 30-September 3, 1999.
- Fischer, A., F. Greiff, and J. Funke (2012) "The Process of Solving Complex problems," *The Journal of Problem Solving* (4) 1, pp. 19-42.
- Fischer, D. and C. Richards (1995) "Cinegrams for Self-Directed Learning," *Computers and Education* (25) 1, pp. 31-40.
- Fischer, G. and E. Sharff (1998) "Learning Technologies in Support of Self-Directed Learning," *Journal of Interactive Learning Media in Education* (98) 4, 32 pp.
- Foos, P. W., J. J. Mora, and S. Tkacz (1994) "Student Study Techniques and the Generation Effect," *Journal of Educational Psychology* (86) 4, pp. 567-576.
- Foster, G. and M. Stefik (1986) "Cognoter: Theory and Practice of a Collaborative Tool," in *Proceedings of the ACM Conference on Computer-Supported Cooperative Work*, pp. 7-15.
- Fraivillig, J. L., L. A. Murphy, and K. Fuson (1999) "Advancing Children's Mathematical Thinking in Everyday Mathematics Classrooms," *Journal for Research in Mathematics Education* (30), pp. 148-170.
- Frederickson, G. (2003) *Dissection: Plane and Fancy*. NY: Cambridge University Press.
- Funke, J. (2010) "Complex Problem Solving: A Case for Complex Cognition?" *Cognitive Processing* (11), pp. 133-42.
- Gabriel, R. P. (1996) *Patterns of Software: Tales from the Software Community*. Cambridge, MA: Oxford University Press.
- Gapminder. www.gapminder.org
- Gaslikova, I. (1999) "'Information Seeking in Context' and the Development of Information Systems," *Information Research* (5) 1.
- Gentner, D., J. Loewenstein, and B. Hung (2007) "Comparison Facilitates Children's Learning of Names for Parts," *Journal of Cognition and Development* (8), pp. 285-307.
- Gentner, D., J. Loewenstein, and L. Thompson (2003) "Learning and Transfer: A General Role for Analogical Encoding," *Journal of Educational Psychology* (95), pp. 393-405.
- GeoGebra. www.geogebra.org
- Gilhooly, K. J. (2004) "Working Memory and Reasoning," in J. P. Leighton and R. Sternberg (Eds.), *The Nature of Reasoning*, pp. 49-77. NY: Cambridge University Press.

- Global Council Interlinkage. www.janwillemtulip.com/worldeconomicforum/
- Gobet, F. (1998) "Memory for the Meaningless: How Chunks Help," in *Proceedings of the 20th Meeting of the Cognitive Science Society*, pp. 398–403.
- Gobet, F., P. Lane, S. Croker, P. Cheng, G. Jones, I. Oliver, and J. Pine (2001) "Chunking Mechanisms in Human Learning," *Trends in Cognitive Sciences* (5) 6, pp. 236-243.
- Godshalk, V. M., D. M. Harvey, and L. Moller (2004) "The Role of Learning Tasks on Attitude Change Using Cognitive Flexibility Hypertext Systems," *Journal of the Learning Sciences* (13) 4, pp. 507-526.
- Gotz, D., Z. When, J. Lu, P. Kissa, N. Cao, W. H. Qian, S. X. Liu, and M. X. Zhou (2010) "HARVEST: An Intelligent Visual Analytic Tool for the Masses," in *Proceedings of ACM IUI 2010 International Workshop on Intelligent Visual Interfaces for Text Analysis*, 4 pp.
- Gotz, D. and M. X. Zhou (2008) "Characterizing Users' Visual Analytic Activity for Insight Provenance," *IEEE Symposium on Visual Analytics Science and Technology*, pp. 123-130.
- Green, T. M. and B. Fisher (2011) "The Personal Equation Of Complex Individual Cognition During Visual Interface Interaction," in A. Ebert, A. Dix, N. Gershon, and M. Pohl (Eds.), *Human Aspects of Visualization*, LNCS 6431, pp. 38–57.
- Green, T. R. G. and M. Petre (1996) "Usability Analysis of Visual Programming Environments: A 'Cognitive Dimensions' Framework," *Journal of Visual Languages and Computing* (7), pp. 131-174.
- Greeno, J. G. and R. P. Hall (1997) "Practicing Representation: Learning with and about Representational Forms," *Phi Delta Kappan* (78) 5, pp. 361-167.
- Halpern, D. F. (2003) *Thought and Knowledge* (4th Ed.) Mahwah, NJ: Lawrence Erlbaum.
- Hannafin, M., S. Land, and K. Oliver (1999) "Open Learning Environments: Foundations, Methods, and Models," in C. M. Reigeluth, (Ed.), *Instructional-Design Theories and Models: A New Paradigm of Instructional Theory*, pp. 115-140. Mahwah, NJ: Lawrence Erlbaum Associates.
- Hannafin, M. J, and S. R. Hooper (1993) "Learning Principles," in M. Fleming and W. H. Levie (Eds.), *Instructional Message Design: Principles from the Behavioral and Cognitive Sciences* (2nd Ed.), pp. 191-231. Englewood Cliffs, NJ: Educational Technology Publications.
- Hao, M. C., M. Marwah, H. Janetzko, U. Dayal, D. A. Keim, D. Patnaik, N. Ramakrishnan, and R. K. Sharma (2012) "Visual Exploration of Frequent Patterns in Multivariate Time Series," *Information Visualization* (11) 1, pp. 71-83.
- Harel, G. and J. Confrey (1994, Eds.) *The Development of Multiplicative Reasoning in the Learning of Mathematics*. Albany, NY: SUNY Press.

- Harris, J. (1990) "Text Annotation and Underlining as Metacognitive Strategies to Improve Comprehension and Retention of Expository Text," Doctoral Dissertation, University of Arizona.
- Health InfoScape. <http://visualization.geblogs.com/visualization/network/>
- Heer, J. and D. Boyd (2005) "Vizster: Visualizing Online Social Networks," in *IEEE Symposium on Information Visualization (InfoVis '05)*, pp. 33-40.
- Heer, J. and B. Shneiderman (2012) "A Taxonomy of Tools that Support the Fluent and Flexible use of Visualizations," *ACM Queue* (10) 2, pp. 1-26.
- Hegarty, M. (2004) "Dynamic Visualizations and Learning: Getting to the Difficult Questions," *Learning and Instruction* (14), pp. 343-351.
- Hegarty, M., B. Meyer, and N. H. Narayanan (2002, Eds.) *Diagrams*, LNAI 2317. Berlin: Springer.
- Heller, R. S., D. Martin, N. Haneef, and S. Gievska-Krliu (2001) "Using a Theoretical Multimedia Taxonomy Framework," *ACM Journal of Educational Resources in Computing*, (1) 1es.
- Henry, N. and J.-D. Fekete (2006) "MatrixExplorer: A Dual Representation System to Explore Social Networks," *IEEE Transactions On Visualization and Computer Graphics* (12) 5, pp. 677-684.
- Henshaw, J. (2006) *Does Measurement Measure up?: How Numbers Reveal and Conceal the Truth*. Baltimore, MA: Johns Hopkins University Press.
- Heuer, R. (1999) *Psychology of Intelligence Analysis*. Washington, DC: Center for the Study of Intelligence.
- Hoadley, C. M., M. C. Linn, L. M. Mann, and M. J. Clancy (1996) "When, Why, and How do Novice Programmers Reuse Code?" in W. D. Gray and D. A. Boehm-Davis (Eds.), *Empirical Studies of Programmers: Sixth Workshop*, pp. 109-130. Oxford, UK: Intellect Books.
- Hogarth, R.M. and S. Makridakis (1981) "Forecasting and Planning: An Evaluation," *Management Science* (27) 2, pp. 115-138.
- Hollan, J., E. Hutchins, and D. Kirsh, D. (2000) "Distributed Cognition: Toward a New Foundation for Human-Computer Interaction Research," *ACM Transactions on Computer-Human Interaction* (7) 2, pp. 174-196.
- Hu, Z., J. H. Hung, Y. Wang, Y. C. Chang, C. L. Huang, M. Huyck, and C. DeLisi (2009) "VisANT 3.5: Multiscale Network Visualization, Analysis and Inference Based on the Gene Ontology," *Nucleic Acids Res* (37), W115-W121.
- Huang, W., P. Eades, and S-K. Hong (2009) "Measuring Effectiveness of Graph Visualizations: A Cognitive Load Perspective," *Information Visualization* (8) 3, pp. 139-152.
- Huffred-Ackles, K., K. Fuson, and M. G. Sherin (2004) "Describing Levels and Components of a Math-Talk Learning Community," *Journal for Research in Mathematics Education* (35), pp. 81-116.

- Hult, L., M. Irestig, and J. Lundberg (2006) "Design Perspectives," *Human-Computer Interaction* (21) 1, pp. 5-48.
- Hwang, W. and C. Wang (2004) "A Study on Application of Annotation System in Web-Based Materials," in *Proceedings of the 8th Global Chinese Conference on Computers in Education (GCCCE 2004)*. Hong Kong, China.
- Hwang, W. Y. and R. Shadiev (2008) "Investigating the Effect of Taking and Reviewing Annotations and Homework to Math Learning," in *Proceedings of the 8th IEEE International Conference on Advanced Learning Technologies*, pp. 544-548.
- Hynd, C. R., M. L. Simpson, and N. D. Chase (1990) "Studying Narrative Text: the Effects of Annotation vs. Journal Writing on Test Performance," *Reading Research and Instruction* (29), pp. 44-54.
- Hyperchem. <http://www.chemistry-software.com/hyperchem/index.html>
- Iacob, C. (2011) "A Design Pattern Mining Method for Interaction Design," in *Proceedings of the 3rd ACM SIGCHI Symposium on Engineering Interactive Computing Systems (EICS '11)*, pp. 217-222.
- InfoZoom. www.infozoom.com
- Jane, B. (2006) "Online Reflections about Tinkering in Early Childhood: A Socio-Cultural Analysis," in *Asia-Pacific Forum on Science Learning and Teaching* (7) 1, Article 5, 14 pp.
- Jonassen, D. H. (2000) *Computers as Mindtools for Schools: Engaging Critical Thinking* (2nd Ed.). Upper Saddle River, NJ: Merrill.
- Jonassen, D. H. (2003) "Using Cognitive Tools to Represent Problems," *Journal of Research on Technology in Education* (35) 3, pp. 362-382.
- Jonassen, D. H. and B. L. Grabowski (1993) *Handbook of Individual Differences, Learning, and Instruction*. Hillsdale, NJ: Lawrence Erlbaum.
- Jonassen, D. H. and S. Wang (1993) "Acquiring Structural Knowledge from Semantically Structured Hypertext," *Journal of Computer-Based Instruction* (20) 1, pp. 1-8.
- Jones, W. (2004) "Finders, Keepers? The Present and Future Perfect in Support of Personal Information Management," *First Monday* (9) 3.
- Jones, W. (2008) *Keeping Found Things Found: The Study and Practice of Personal Information Management*. Burlington, MA: Morgan Kaufmann.
- Jones, S. and M. Scaife (2000) "Animated Diagrams: An Investigation into the Cognitive Effects of Using Animation to Illustrate Dynamic Processes," in M. Anderson, P. Cheng, and V. Haarslev (Eds.), *Theory and Application of Diagrams (LNCS 1889)*, pp. 231-244. Berlin: Springer.
- Jordan, N. C., D. Kaplan, O. L. Nabors, and M. N. Locuniak (2006) "Number Sense Growth in Kindergarten: A Longitudinal Investigation of Children at Risk for Mathematics Difficulties," *Child Development* (77) 1, pp. 153-175.

- Jul, S. and G. W. Furnas (1997) "Navigation in Electronic Worlds: A CHI '97 Workshop," in *SIGCHI Bulletin* (29) 4, pp. 44-49.
- Kaandorp, J. A. (1994) *Modelling Growth Forms of Biological Objects using Fractals*. Berlin: Springer.
- Kahney, H. (2003) *Problem Solving: Current Issues* (2nd Ed.). Philadelphia, PA: Open University Press.
- Kaiser, M. K. and D. R. Proffitt (1987) *NASA Technical Memorandum 89430*. Moffett Field, CA.
- Kaptelinin, V. and B. Nardi (2012) *Activity Theory in HCI: Fundamentals and Reflections*. Bonita Springs, FL: Morgan & Claypool.
- Kaput, J. J. (1989) "Linking Representations in The Symbol Systems of Algebra," in S. Wagner and C. Kieran (Eds.), *Research Issues in the Learning and Teaching of Algebra*. Hillsdale, NJ: Erlbaum.
- Kastens, K. A., L. S. Liben, and S. Agrawal (2008) "Epistemic Actions in Science Education," in *Proceedings of the international Conference on Spatial Cognition VI: Learning, Reasoning, and Talking About Space*, pp. 202-215.
- Keller, P. R. and M. M. Keller (1993) *Visual Cues: Practical Data Visualization*. IEEE Computer Society Press.
- Kieran, C. (1989) "A Perspective on Algebraic Thinking," in G. Vernand, J., Rogalski, and M. Artigue (Eds.), *Proceedings of the 13th International Conference for the Psychology of Mathematics Education* (2), pp. 163-171.
- Kiewra, K. A. (1989) "A Review of Note-Taking: The Encoding-Storage Paradigm and Beyond," *Educational Psychology Review* (1), pp. 147-172.
- Kim, B. and T. C. Reeves (2007) "Reframing Research on Learning with Technology: In Search of the Meaning of Cognitive Tools," *Instructional Science* (35) 3, pp. 207-256.
- Kirschner, F., F. Paas, and P. A. Kirschner (2009) "A Cognitive Load Approach to Collaborative Learning: United Brains for Complex Tasks," *Educational Psychology Review* (21), pp. 31-42.
- Kirsh, D. (1995) "The Intelligent use of Space," *Artificial Intelligence* (73), pp. 31-68.
- Kirsh, D. (1997) "Interactivity and Multimedia Interfaces," *Instructional Science* (25) 2, pp. 79-96.
- Kirsh, D. (2005) "Metacognition, Distributed Cognition and Visual Design," in P. Gärdenfors and P. Johansson (Eds.), *Cognition, Education and Communication Technology*, pp. 1-22. Mahwah, NJ: Lawrence Erlbaum.
- Kirsh, D. (2009) "Interaction, External Representations and Sense Making," in *Proceedings of the 31st Annual Conference of the Cognitive Science Society*, pp. 1103-1108.
- Kirsh, D. and P. Maglio (1992) "Some Epistemic Benefits of Action: Tetris a Case Study," in *Proceedings of the 14th Annual Cognitive Science Society*.

- Kirsh, D. and P. Maglio (1994) "On Distinguishing Epistemic from Pragmatic Action," *Cognitive Science* (18), pp. 513-549.
- Klein, G., B. Moon, and R. Hoffman (2006) "Making Sense of Sensemaking 1: Alternative Perspectives," *IEEE Intelligent Systems* (21) 4, pp. 70-73.
- Klein, G., J. K. Philips, E. L. Rall, and D. A. Peluso (2007) "A Data-Frame Theory of Sensemaking," in R. Hoffman, R. (Ed.), *Expertise out of Context Proceedings of the 6th International Conference on Naturalistic Decision Making*, pp. 113-155. NY: Lawrence Erlbaum.
- Kleinmuntz, D. N. and D. A. Schkade (1993) "Information Displays and Decision Processes," *Psychological Science* (4) 4, pp. 221-227.
- Knauff, M. and A. G. Wolf (2010) "Complex Cognition: The Science of Human Reasoning, Problem-Solving, and Decision-Making," *Cognitive Processing* (11), pp. 99-102.
- Komis, V., N. Avouris, and C. Fidas (2002) "Computer-Supported Collaborative Concept Mapping: Study of Synchronous Peer Interaction," *Journal of Education and Information Technologies* (7) 2, pp. 169-188.
- Kuhlthau, C. (1993) *Seeking Meaning*. Norwood NJ: Ablex.
- Kurtz, K., C-H. Miao, and D. Gentner (2001) "Learning by Analogical Bootstrapping," *Journal of the Learning Sciences* (10), pp. 417-446.
- Lahtinen, V., K. Lonka, and S. Lindblom-Ylänne (1997) "Spontaneous Study Strategies and the Quality of Knowledge Construction," *British Journal of Educational Psychology* (67), pp. 13-24.
- Lam, H. (2008) "A Framework of Interaction Costs in Information Visualization," *IEEE Transactions on Visualization and Computer Graphics* (14) 6, pp. 1149-1156.
- Lamberty, K. and J. Kolodner (2002) "Exploring Digital Quilt Design using Manipulatives as a Math Learning Tool," in P. Bell, R. Stevens and T. Satwicz (Eds.), *Proceedings of ICLS '02*, pp. 552-553. Mahwah, NJ: Lawrence Erlbaum.
- Lamon, S. (1999) *Teaching Fractions and Ratios for Understanding: Essential Content Knowledge and Instructional Strategies for Teachers*. Mahwah, NJ: Lawrence Erlbaum.
- Lampert, M. (1990) "When the Problem is not the Question and the Solution is not the Answer: Mathematical Knowing and Teaching," *American Educational Research Journal* (27), pp. 29-63.
- Lane, P. C. R., F. Gobet and P. C-H. Cheng (2000) "What Forms the Chunks in a Subject Performance? Lessons from CHREST Computational Model of Learning," *Behavioral and Brain Sciences* (24), pp. 128-129.
- Larkin, J. H. and H. A. Simon (1987) "Why a Diagram is (Sometimes) Worth Ten Thousand Words," *Cognitive Science* (11), pp. 65-99.
- Lau, J. Y. F. (2011) *An Introduction to Critical Thinking and Creativity*. Hoboken, NJ: John Wiley & Sons.

- Lawless, K. A. and S. W. Brown (1997) "Multimedia Learning Environments: Issues of Learner Control and Navigation," *Instructional Science* (25) 2, pp. 117-131.
- Lawrence, A. W., A. M. Badre, and J. T. Stasko (1994) "Empirically Evaluating the use of Animations to Teach Algorithms," in *Proceedings of the IEEE Symposium on Visual Languages*, pp. 48-54.
- LeBoeuf, R. and E. Shafir (2005) "Decision Making," in K. Holyoak, and R. Morrison (Eds.), *The Cambridge Handbook of Thinking and Reasoning*. NY: Cambridge University Press.
- Leidner, D. E. and M. Fuller (1997) "Improving Student Learning of Conceptual Information: GSS Supported Collaborative Learning vs. Individual Constructive Learning," *Decision Support Systems* (20), pp. 149-163.
- Leighton, J. P. (2004) "Defining and Describing Reason," in J. P. Leighton and R. Sternberg (Eds.), *The Nature of Reasoning*, pp. 3-11. NY: Cambridge University Press.
- Leighton, J. and R. Sternberg (2004, Eds.) *The Nature of Reasoning*. NY: Cambridge University Press.
- Leung, Y. K. and M. D. Apperley (1994) "A Review and Taxonomy of Distortion-Oriented Presentation Techniques," *ACM Transactions on Computer-Human Interaction* (1) 2, pp. 126-160.
- Li, Y., J. Sun, C.-K. Tang, and H.-Y. Shum (2004) "Lazy Snapping," *ACM Transactions on Graphics* (23) 3, pp. 303-308.
- Liang, H-N. and K. Sedig (2009) "Characterizing Navigation in Interactive Learning Environments," *Interactive Learning Environments* (17) 1, pp. 53-75.
- Liang, H-N. and K. Sedig (2010) "Role of Interaction in Enhancing the Epistemic Utility of 3D Mathematical Visualizations," *International Journal of Computers for Mathematical Learning* (15) 3, pp. 191-224.
- Liang, H-N., P. Parsons, H-C. Wu, and K. Sedig (2010) "An Exploratory Study of Interactivity in Visualization Tools: 'Flow' of Interaction," *Journal of Interactive Learning Research* (21) 1, pp. 5-45.
- Liu, K. (2006) "Annotation as an Index to Critical Writing," *Urban Education* (4) 2, pp. 197-207.
- Liu, Z. and J. T. Stasko (2010) "Mental Models, Visual Reasoning and Interaction in Information Visualization: A Top-Down Perspective," *IEEE Transactions on Visualization and Computer Graphics* (16) 6, 999-1008.
- Lohse, G. L., H. Rueter, K. Biolsi, and N. Walker (1994) "A Classification of Visual Representations," *Communications of the ACM* (37) 12, pp. 36-49.
- Long, K. and C. Kamii (2001) "The Measurement of Time: Children's Construction of Transitivity, Unit Iteration, and Conservation of Speed," *School Science and Mathematics* (101) 3, pp. 125-132.

- Lonka, K., S. Lindblom-Ylänne, and S. Maury (1994) "The Effect of Study Strategies on Learning from Text," *Learning and Instruction* (4), pp. 253–271.
- Lovett, M. C. and P. ShaH (2007, Eds.) *Thinking with Data*. Mahwah, NJ: Lawrence Erlbaum.
- MacEachren, A. M., M. Gahegan, W. Pike, I. Brewer, G. Cai, E. Lengerich, and F. Hardistry (2004) "Geovisualization for Knowledge Construction and Decision Support," *Computer Graphics and Applications* (24) 1, pp. 13-17.
- MacKeracher, D. (2004) *Making Sense of Adult Learning*. Toronto: University of Toronto Press.
- Marchionini, G. (1997) *Information Seeking in Electronic Environments*. NY: Cambridge University Press.
- Marchionini, G. (2006) "Exploratory Search: From Finding to Understanding," *Communications of the ACM* (49) 4, pp. 41-46.
- Marchionini, G. (2010) *Information Concepts: From Books to Cyberspace Identities*. Bonita Springs, FL: Morgan & Claypool.
- Markman, A. B. (1999) *Knowledge Representation*. Mahwah, NJ: Lawrence Erlbaum.
- Markman, E. (1979) "Classes and Collections: Conceptual Organization and Numerical Abilities," *Cognitive Psychology* (11), pp. 395-411.
- Markus, M. L., A. Majchzrak, and L. Gasser (2002) "A Design Theory for Systems that Support Emergent Knowledge Processes," *MIS Quarterly* (26) 3, pp. 179-212.
- Marsh, B., P. M. Todd, and G. Gigerenzer (2004) "Cognitive Heuristics: Reasoning the Fast And Frugal Way," in J. P. Leighton and R. Sternberg (Eds.) *The Nature of Reasoning*, pp. 273-287. NY: Cambridge University Press.
- Marshall, C. (1997) "Annotation: From Paper Books to the Digital Library," in *Proceedings of the 2nd ACM International Conference on Digital Libraries*, pp. 131-140.
- Marshall, C. C., and W. Jones (2006) "Keeping Encountered Information," *Communications of the ACM—Personal Information Management* (49) 1, pp. 66-67.
- Mason, R. (2002) *How do People Learn?* London: CIPD Publishing.
- Masseti, B. (1996) "An Empirical Examination of the Value of Creativity Support Systems on Idea Generation," *MIS Quarterly* (20) 1, pp. 83-97.
- Mendeley. www.mendeley.com
- Meszaros, G. (1996) "Patterns for Decision Making in Architectural Design," in *Addendum to the Proceedings of OOPSLA '95 OOPS Messenger* (6) 4, pp. 132–137.
- Meyer, J., D. Shinar, and D. Leiser (1997) "Multiple Factors that Determine Performance with Tables and Graphs," *Human Factors* (39) 2, pp. 268-286.

- Meyer, J., J. Thomas, S. Diehl, and B. Fisher (2010) "From Visualization to Visually Enabled Reasoning," in H. Hagen (Ed.), *Scientific Visualization: Advanced Concepts*, pp. 227-245. Schloss Dagstuhl-Leibniz-Zentrum fuer Informatik: Germany.
- Miller, K. (1989) "Measurement as a Tool for Thought: The Role of Measuring Procedures in Children's Understanding of Quantitative Invariance," *Developmental Psychology* (25) 4, pp. 589-600.
- MindJet. www.mindjet.com
- Moody, J., D. McFarland, and S. Bender-deMoll (2005) "Dynamic Network Visualization," *American Journal of Sociology* (110) 4, pp. 1206-1241.
- Morey, J., and K. Sedig (2004) "Adjusting Degree of Visual Complexity: An Interactive Approach for Exploring Four-Dimensional Polytopes," *The Visual Computer: International Journal of Computer Graphics* (20), pp. 1-21.
- Morris, R. and G. Ward (2005, Eds.) *The Cognitive Psychology of Planning*. NY: Psychology Press.
- Munyofu, M., W. Swain, B. Ausman, H. Lin, K. Kidwai, and F. Dwyer (2007) "The Effect of Different Chunking Strategies in Complementing Animated Instruction," *Learning, Media and Technology* (32) 4, pp. 407-419.
- Nakakoji, K. and Y. Yamamoto (2003) "Toward A Taxonomy of Interaction Design Techniques for Externalizing in Creative Work," in *Proceedings of the 10th International Conference on Human-Computer Interaction (HCI2003)*, 5 pp.
- NCTM, National Council of Teachers of Mathematics. (2000) *Principles and Standards for School Mathematics*. Reston, VA: Author.
- Neuwirth, C. and D. Kaufer (1989) "The Role of External Representations in the Writing Process: Implications for the Design of Hypertext-Based Writing Tools," in *Hypertext '89 Proceedings*, pp. 319-341.
- Newell, A. (1994) *Unified Theories of Cognition*. Cambridge, MA: Harvard University Press.
- Newell, A. and H. A. Simon (1972) *Human Problem Solving*. Englewood Cliffs, NJ: Prentice Hall.
- Nickerson, R. S. (2004) "Teaching Reasoning," in J. P. Leighton and R. Sternberg (Eds.), *The Nature of Reasoning*, pp. 410-443. NY: Cambridge University Press.
- Noel, S. and S. Jajodia (2004) "Managing Attack Graph Complexity through Visual Hierarchical Aggregation," in *Proceedings of the 2004 ACM Workshop on Visualization and Data Mining for Computer Security*, pp. 109-118.
- Norback, J. and R. Love (1977) "Geometric Approaches to Solving the Traveling Salesman Problem," *Management Science* (23) 11, pp. 1208-1223.
- Norman, D. A. (1993) *Things that Make us Smart*. NY: Addison-Wesley.
- Novick, L. R. (1990) "Representational Transfer in Problem Solving," *Psychological Science* (1) 2, pp. 128-132.

- OECD Explorer. <http://stats.oecd.org/OECDregionalstatistics/>
- Olive, J. (2000) "Computer Tools for Interactive Mathematical Activity in the Elementary School," *International Journal of Computers for Mathematical Learning* (5) 3, pp. 241-262.
- Olton, M. and D. Johnson (1976) "Mechanisms of Incubation in Creative Problem Solving," *The American Journal of Psychology* (89) 4, pp. 617-630.
- Ormrod, J. E. (1995) *Human Learning* (2nd Ed.). Englewood Cliffs, NJ: Prentice Hall.
- Panopticon. www.panopticon.com
- Papadopoulos, I. and V. Dagdilelis (2008) "Students' use of Technological Tools for Verification Purposes in Geometry Problem Solving," *The Journal of Mathematical Behavior* (27), pp. 311–325.
- Park, O. and S. S. Gittleman (1992) "Selective use of animation and feedback in computer-based instruction," *Educational Technology Research and Development* (40) 4, pp. 27-38.
- Parsons, P. and K. Sedig (2013a) "Common Visualizations: Their Cognitive Utility," in W. Huang (Ed.), *Handbook of Human Centric Visualization*. New York: Springer, ch. 27.
- Parsons, P. and K. Sedig (2013b) "Distribution of Information Processing while Performing Complex Cognitive Activities with Visualization Tools," in W. Huang (Ed.), *Handbook of Human Centric Visualization*. New York: Springer, ch. 28.
- Parsons, P. and K. Sedig (in press) "Adjustable Properties of Visual Representations: Improving the Quality of Human-Information Interaction," *Journal of the American Society for Information Science & Technology*.
- Peng W. (2005) "Clutter-Based Dimension Reordering in Multi-Dimensional Data Visualization," Master's thesis. Worcester, MA: Worcester Polytechnic Institute.
- Peng, W., M. O. Ward, and E. A. Rundensteiner (2004) "Clutter Reduction in Multi-Dimensional Data Visualization Using Dimension Reordering," *IEEE Symposium on Information Visualization (INFOVIS 2004)*, pp.89-96.
- Peper, R. J. and R. E. Mayer (1986) "Generative Effects of Note-Taking During Science Lectures," *Journal of Educational Psychology* (78), pp. 34-38.
- Peterson, A. and P. Snyder (1998) "Using Mind Maps to Teach Social Problems Analysis," *Presented at the Annual Meeting of the Society for the Study of Social Problems*. San Francisco, CA.
- Peterson, D. (1996, Ed.) *Forms of Representation: An Interdisciplinary Theme for Cognitive Science*. Oxford, UK: Intellect Books.
- Phelps, T. and R. Wilensky (1997) "Multivalent Annotations," in *Proceedings of the 1st European Conference on Research and Advanced Technology for Digital Libraries*, pp. 287-303.

- Piaget, J., B. Inhelder, and A. Szeminska (1960) *The Child's Conception of Geometry*. London: Routledge.
- Pike, W. A., J. Stasko, R. Chang, and T. A. O'Connell (2009) "The Science of Interaction," *Information Visualization* (8) 4, pp. 263-274.
- Pimm, D. (1995) *Symbols and Meanings in School Mathematics*. NY: Routledge.
- Pinzger, M., K. Grafenhain, P. Knab, and H. C. Gall (2008) "A Tool for Visual Understanding of Source Code Dependencies," in *16th IEEE International Conference on Program Comprehension*, pp. 254-259.
- Pirolli, P. and S. K. Card (2005) "The Sensemaking Process and Leverage Points for Analyst Technology as Identified through Cognitive Task Analysis," *2005 International Conference on Intelligence Analysis*, 6 pp.
- Pirolli, P., S. K. Card and S. M. van Der Wege (2001) "Visual Information Foraging in a Focus + Context Visualization," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pp. 506-513.
- Pirolli, P. and R. Rao (1996) "Table Lens as a Tool for Making Sense of Data," in *Proceedings of the Workshop on Advanced Visual Interfaces*, pp. 67-80.
- Pirolli, P. and D. M. Russell (2011) "Introduction to this Special Issue on Sensemaking," *Human-Computer Interaction* (26), pp. 1-8.
- Pittenger, J. B. (1985) "Estimation of Pendulum Length from Information in Motion," *Perception* (14) 3, pp. 247-256.
- Plass, J. L., B. D. Homer and E. O. Hayward (2009) "Design Factors for Educationally Effective Animations and Simulations," *Journal of Computing in Higher Education* (21) 1, pp. 31-61.
- Preece, J., Y. Rogers and H. Sharp (2002) *Interaction Design: Beyond Human-Computer Interaction*. NY: John Wiley and Sons.
- Price, M., G. Golovchinsky, and B. Schilit (1998) "Linking By Inking: Trailblazing in a Paper-like Hypertext," in *Proceedings of Hypertext '98*, pp. 30-39.
- Proffitt, D. R., H. Hecht, I. Rock, and J. Schubert (1992) "Stereokinetic Effect and Its Relation to the Kinetic Depth Effect," *Journal of Experimental Psychology Human Perception and Performance* (18) 1, pp. 3-21.
- Purchase, H. C., N. Andrienko, T. J. Jankun-Kelly, and M. Ward (2008) "Theoretical Foundations of Information Visualization," in A. Kerren, J. T. Stasko, J-D. Fekete, and C. North (Eds.), *Information Visualization*, LNCS 4950, pp. 46-64. Berling: Springer-Verlag.
- Pylyshyn, Z. (2003) *Seeing and Visualizing: It's Not What You Think*. Cambridge, MA: The MIT Press.
- Qu, Y. and G. Furnas (2005) "Sources of Structure in Sense Making," *CHI Extended Abstracts 2005*, pp. 1989-1992.
- Radford, L. (2002) "On Heroes and the Collapse of Narratives: A Contribution to the Study of Symbolic Thinking," in *Proceedings of the 16th Conference of the*

- International Group for the Psychology of Mathematics Education, PME 26*, pp. 81-88.
- Radford, L. (2006) "Algebraic Thinking and the Generalization of Patterns: A Semiotic Perspective," in *Proceedings of the 28th North American Chapter of the International Group for the Psychology of Mathematics Education*, pp. 2-21.
- Rao, R. and S. K. Card (1994) "The Table Lens: Merging Graphical and Symbolic Representations in an Interactive Focus+Context Visualization for Tabular Information," in *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems*, pp. 1-7.
- Renkl, A. (1997) "Learning from Worked-Out Examples: A Study on Individual Difference," *Cognitive Science* (21), pp. 1–29.
- Reynolds, A. and G. Wheatley (1996) "Elementary Students' Construction and Coordination of Units in an Area Setting," *Journal for Research in Mathematics Education* (27) 5, pp. 564-581.
- Rieber, L. P. (1990) "Animation in Computer Based Instruction," *Educational Technology Research and Development* (38) 1, pp. 77-86.
- Rieber, L.P. and A. Kini (1991) "Theoretical Foundations of Instructional Applications of Computer-Generated Animated Visuals," *Journal of Computer-Based Instruction* (18) 3, pp. 83-88.
- Ritter, F., B. Preim, O. Deussen, and T. Strothotte (2000) "Using a 3D Puzzle as a Metaphor for Learning Spatial Relations", in *Proceedings of Graphics Interface*, pp. 171-178.
- Ritter, F. B. Berendt, B. Fischer, R. Richter, and B. Preim (2002) "Virtual 3D Jigsaw Puzzles: Studying the Effect of Exploring Spatial Relations with Implicit Guidance," in *Proceedings of Mensch & Computer*, pp. 363–372.
- Rittle-Johnson, B. and J. R. Star (2007) "Does Comparing Solution Methods Facilitate Conceptual and Procedural Knowledge? An Experimental Study on Learning to Solve Equations," *Journal of Educational Psychology* (99), pp. 561–574.
- Robertson, S. I. (2001) *Problem Solving*. Philadelphia, PA: Psychology Press.
- Rogers, Y. and M. Scaife (1997) "How can Interactive Multimedia Facilitate Learning?" in *Proceedings of the 1st International Workshop on Intelligence and Multimodalities in Multimedia*, pp. 123–142.
- Romberg, T. A. and J. J. Kaput (1999) "Mathematics Worth Teaching, Mathematics Worth Understanding," in E. Fennema and T. A. Romberg (Eds.), *Mathematics Classrooms That Promote Understanding*. Mahwah, NJ: Lawrence Erlbaum.
- Ross, B. (1987) "This is Like That: The use of Earlier Problems and the Separation of Similarity Effects," *Journal of Experimental Psychology: Learning, Memory, and Cognition* (13) 4, pp. 629-639.
- Rowley, J. and R. Hartley (2008) *Organizing Knowledge: An Introduction to Managing Access to Information* (4th Ed.). Burlington, VT: Ashgate Publishing.

- Rucker, R. (1987) *Mind Tools*. Boston, MA: Houghton Mifflin Company.
- Russell, D., M. Stefik, P. Pirolli, and S. K. Card (1993) "The Cost Structure of Sense Making," in *Proceedings of ACM Conference on Human Factors in Computing Systems*, pp. 269-276.
- Salingaros, N. A. (1999) "Architecture, Patterns, and Mathematics," *Nexus Network Journal* (1) 1-2, pp. 75-85.
- Salingaros, N. A. (2000) "The Structure of Pattern Languages," *Architectural Research Quarterly* (4), pp. 149-161
- Salomon, G. (1993, Ed.) *Distributed Cognitions: Psychological and Educational Considerations*. Cambridge, MA: Cambridge University Press.
- Samp, K., C. Basca, B. McDaniel, and S. Decker (2008) "Atom Interface—A Novel Interface for Exploring Browsing Semantic Space," in *Proceedings of the 5th International Workshop on Semantic Web User Interaction (SWUI 2008)*.
- Schilit, B. N., G. Golovchinsky, and M. N. Price (1998) "Beyond Paper: Supporting Active Reading with Free Form Digital Ink Annotations," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pp. 249-256.
- Schraefel, M. C., D. Modjeska, D. Wigdor, and Y. Zhu (2002) "Hunter Gatherer: Within-Web-Page Collection Making," in *CHI '02 Extended Abstracts on Human Factors in Computing Systems (CHI EA '02)*, pp. 498-499.
- Schwan, S. and R. Riempp (2004) "The Cognitive Benefits of Interactive Videos: Learning to Tie Nautical Knots," *Learning and Instruction* (14) 3, pp. 293-305.
- Schwan, S., B. Garsoffky, and F. W. Hesse (2000) "Do Film Cuts Facilitate the Perceptual and Cognitive Organization of Activity Sequences?" *Memory and Cognition* (28) 2, pp. 214-223.
- Sedig, K. (2004) "Need for a Prescriptive Taxonomy of Interaction for Mathematical Cognitive Tools," in *Proceedings of Interactive Visualization and Interaction Technologies (ICCS 2004)*, pp. 1030-1037.
- Sedig, K. (2008) "From Play to Thoughtful Learning: A Design Strategy to Engage Children With Mathematical Representations," *Journal of Computers in Mathematics and Science Teaching* (27) 1, pp. 65-101.
- Sedig, K. (2009) "Interactive Mathematical Visualizations: Frameworks, Tools, and Studies," in E. Zudilova-Seinstra, T. Adriaansen, and R. van Liere (Eds.), *Trends in Interactive Visualization: State-of-the-Art Survey*, pp. 343-363. London: Springer.
- Sedig, K., M. Klawe, and M. Westrom (2001) "Role of Interface Manipulation Style and Scaffolding on Cognition and Concept Learning in Learnware," *ACM Transactions on Computer-Human Interaction* (1) 8, pp. 34-59.
- Sedig, K. and H-N. Liang (2007) "On the Design of Interactive Visual Representations: Fitness of Interaction," in C. Seale and J. Montgomerie (Eds.), *Proceedings of the*

- World Conference on Educational Multimedia, Hypermedia, and Telecommunications*, pp. 999-1006.
- Sedig, K. and H-N. Liang (2008) "Learner-Information Interaction: A Macro-Level Framework Characterizing Visual Cognitive Tools," *Journal of Interactive Learning Research* (19) 1, pp. 147-173.
- Sedig, K., J. Morey and B. Chu (2002) "TileLand: A Microworld for Creating Mathematical Art," in *Proceedings of ED-MEDIA 2002: World Conference on Educational Multimedia and Hypermedia*, pp. 1778-1783.
- Sedig, K., J. Morey, R. Mercer, and W. Wilson (2005a) "Visualizing, Interacting and Experimenting with Lattices Using a Diagrammatic Representation," in G. Malcolm (Ed.), *Multidisciplinary Approaches to Visual Representations and Interpretations*, pp. 255-268.
- Sedig, K., P. Parsons, and A. Babanski (2012a) "Towards a Characterization of Interactivity in Visual Analytics," *Journal of Multimedia Processing Technologies, Special Issue on Theory and Application of Visual Analytics* (3) 1, pp. 12-28.
- Sedig, K., P. Parsons, M. Dittmer, and O. Ola (2012b) "Beyond Information Access: Support for Complex Cognitive Activities in Public Health Informatics Tools," *Online Journal of Public Health Informatics* (4) 3.
- Sedig, K., P. Parsons, M. Dittmer and R. Haworth (2013) "Human-Centered Interactivity of Visualization Tools: Micro- and Macro-Level Considerations," in W. Huang (Ed.), *Handbook of Human Centric Visualization*. New York: Springer, ch. 29.
- Sedig, K., S. Rowhani, and H-N. Liang (2003) "Application of Information Visualization Techniques to the Design of a Mathematical Mindtool: A Usability Study," *Information Visualization* (2) 3, pp. 142-159.
- Sedig, K., S. Rowhani, and H-N. Liang (2005b) "Designing Interfaces that Support Formation of Cognitive Maps of Transitional Processes: An Empirical Study," *Interacting with Computers* (17) 4, pp. 419-452.
- Sedig, K. and M. Sumner (2006) "Characterizing Interaction with Visual Mathematical Representations," *International Journal of Computers for Mathematical Learning* (11) 1, pp 1-55.
- Shah, P. and A. Miyake (2005, Eds.) *The Cambridge Handbook of Visuospatial Thinking*. Cambridge, UK: Cambridge University Press.
- Shannon, P., A. Markiel, O. Ozier, N. S. Baliga, J. T. Wang, D. Ramage, N. Amin, B. Schwikowski, and T. Ideker (2003) "Cytoscape: A Software Environment for Integrated Models of Biomolecular Interaction Networks," *Genome Research* (13) 11, pp. 2498-2504.
- Shneiderman, B. (1991) "A Taxonomy and Rule Base for the Selection of Interaction Styles," in B. Shackleton and S. J. Richardson (Eds.), *Human Factors for Informatics Usability*, pp. 325-342. NY: Cambridge University Press.

- Shneiderman, B. (1996) "The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations," in *Proceedings of 1996 IEEE Conference Visual Languages*, pp. 336-343.
- Shrinivasan, Y. and J. Wijk (2008) "Supporting the Analytical Reasoning Process in Information Visualization," in *Proceeding of the 26th Annual SIGCHI Conference on Human Factors in Computing Systems*, pp. 1237-1246.
- Siirtola, H. (1999) "Interaction with the Reorderable Matrix," in *IEEE International Conference on Information Visualization*, pp. 272-277.
- Silver, E. A., H. Ghouseini, D. Gosen, C. Charalambous, and B. Strawhun (2005) "Moving from Rhetoric to Praxis: Issues Faced by Teachers in Having Students Consider Multiple Solutions for Problems in the Mathematics Classroom," *Journal of Mathematical Behavior* (24), pp. 287-301.
- Simon, H. (1978) "Information-Processing Theory of Human Problem Solving," in W. Estes (Ed.), *Handbook of Learning and Cognitive Processes* (Vol. 5), pp. 271-295. Hillsdale, NJ: Erlbaum.
- Skyttner, L. (2005) *General Systems Theory: Problems, Perspectives, Practice* (2nd Ed.). Hackensack, NJ: World Scientific.
- Slooman, A. (2002) "Diagrams in the Mind?" in M. Anderson, B. Meyer, and P. Olivier (Eds.), *Diagrammatic Representation and Reasoning*, pp. 7-28. London: Springer.
- Slotte, V. and K. Lonka (1999) "Review and Process Effects of Spontaneous Note-Taking on Text Comprehension," *Contemporary Educational Psychology* (24) 1, pp. 1-20.
- Smith, E. E. and D. L. Medin (1981) *Categories and Concepts*. Cambridge, MA: Harvard University Press.
- Smith, S. M. (1995) "Fixation, Incubation, and Insight in Memory and Creative Thinking," in S. M. Smith, T. B. Ward, and R. A. Finke (Eds.), *The Creative Cognitive Approach*, pp. 135-156. The MIT Press.
- Spence, R. (1999) "A Framework for Navigation," *International Journal of Human-Computer Studies*, 51, pp. 919-945.
- Spence, R. (2007) *Information Visualization: Design for Interaction* (2nd Ed.). Essex, UK: Pearson.
- Spiro, R. J. and J-C. Jehng (1990) "Cognitive Flexibility and Hypertext: Theory and Technology for the Nonlinear and Multi-Dimensional Traversal of Complex Subject Matter," in D. Nix and R. J. Spiro (Eds.), *Cognition, Education and Multi-media: Exploring Ideas in High Technology*, pp. 163-205. Hillsdale, NJ: Erlbaum.
- Star, J. and B. Rittle-Johnson (2009) "It Pays to Compare: An Experimental Study on Computational Estimation," *Journal of Experimental Child Psychology* (102), pp. 408-426
- Step. <http://edu.kde.org/step/>

- Sternberg, R. J. and T. Ben-Zeev (2001) *Complex Cognition: The Psychology of Human Thought*. NY: Oxford University Press.
- Stolte, C., D. Tang, and P. Hanrahan (2002) "Polaris: A System for Query, Analysis, and Visualization of Multidimensional Relational Databases," in *IEEE Transactions on Visualization and Computer Graphics* (8) 1, pp. 52-65.
- Stone, M., K. Fishkin, and E. Bier (1994) "The Movable Filter as User Interface Tool," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems: Celebrating Interdependence*, pp. 306-312.
- Stonier, T. (1990) *Information and the Internal Structure of the Universe: An Exploration into Information Physics*. London: Springer.
- Strode, S. L. (1991) "Teaching Annotation Writing to College Students," *Forum for Reading* (23), pp. 33-44.
- Strothotte, T. (1998) *Computational Visualization: Graphics, Abstraction, and Interactivity*. Berlin: Springer.
- Sunaeon. www.sunaeon.com
- Tableau. <http://www.tableausoftware.com/solutions/government>
- Thagard, P. (2000) *Mind*. Cambridge, MA: MIT Press.
- Thomas, J. and K. Cook (2005, Eds.) *Illuminating the Path: The Research and Development Agenda for Visual Analytics*. NY: IEEE Press.
- Todd, J. T. and J. F. Norman (1991) "The Visual Perception of Smoothly Curved Surfaces from Minimal Apparent Motion Sequences," *Perception and Psychophysics* (50), pp. 509-523.
- Tominksi, C., J. Abello, H. Schumann (2009) "CGV—An Interactive Graph Visualization System," *Computers and Graphics* (33), pp. 660-678.
- Toyoda, M. and M. Kitsuregawa (2005) "A System for Visualizing and Analyzing the Evolution of the Web with a Time Series of Graphs," in *Proceedings of the 16th ACM Conference on Hypertext and Hypermedia*, pp. 151-160.
- Tsotsos, J. K. (1990) "Analyzing Vision at the Complexity Level," *Brain and Behavioral Sciences* (13) 3, pp. 423-469.
- Tufte, E. R. (1983) *The Visual Display of Quantitative Information*. Cheshire, CT: Graphics Press.
- Tversky, B., J. B. Morrison, and M. Bétrancourt (2002) "Animation: Can it Facilitate?" *International Journal of Human Computer Studies* (57), pp. 247-262.
- Ullman, S. (1979) *The Interpretation of Visual Motion*. Cambridge, MA: MIT Press.
- Uren, V., S. Buckingham Shum, M. Bachler, and G. Li (2006) "Sensemaking Tools for Understanding Research Literatures: Design, Implementation and User Evaluation," *International Journal of Human Computer Studies* (64) 5, pp. 420-445.
- VisANT (2011) <http://visant.bu.edu>

- von Baeyer, H. C. (2004) *Information: The New Language of Science*. London: Phoenix.
- Wagner, D. (2003) "Analysis and Visualization of Social Networks," in K. Jansen, M. Margraf, M. Mastrolilli, and J. Rolim (Eds.), *Experimental and Efficient Algorithms, LNCS, 2647/2003*, pp. 261-266.
- Ward, M. O. and J. Yang (2004) "Interaction Spaces in Data and Information Visualization," in *Joint Eurographics/IEEE TCVG Symposium on Visualization*, pp. 137-145.
- White, R. and R. Gunstone (1992) *Drilling Understanding*. NY: The Falmer Press.
- Wilensky, U. (1999) "NetLogo," <http://ccl.northwestern.edu/netlogo/>. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.
- Wolfe, J. L. and C. M. Neuwirth (2001) "From the Margins to the Center: The Future of Annotation," *Journal of Business and Technical Communication* (15), pp. 333.
- Wolfe, J. M. (1998) "Visual Search," in H. E. Pashler (Ed.), *Attention*. London: University College London Press.
- Wong, A. Y. K. (1994) "The use of Animation in Computer-Assisted Instruction," Doctoral Dissertation. Ottawa: Carleton University.
- Wu, A., X. Zhang, G. Convertino, and J. M. Carroll (2009) "CIVIL: Support Geo-Collaboration with Information Visualization," in *Proceedings of the ACM 2009 International Conference on Supporting Group Work*, pp. 273-276.
- Wu, H. and P. Shah (2004) "Exploring Visuospatial Thinking in Chemistry Learning," *Science Education* (88) 3, pp. 465-492.
- Wu, H-C., H-N. Liang, and K. Sedig (2006) "Exploring Correlations in Multivariate Datasets using Integrated Interactive Visualizations," in *Proceedings of the International British HCI, Combining Visualization and Interaction to Facilitate Scientific Exploration and Discovery Workshop*.
- Wu, H-K., J. S. Krajcik, and E. Soloway (2000) "Promoting Conceptual Understanding of Chemical Representations: Students' use of a Visualization Tool in the Classroom," *Journal of Research in Science Teaching* (38) 7, pp. 821-842.
- Wycoff, J. (1991) *Mindmapping: Your Personal Guide to Exploring Creativity and Problem Solving*. NY: Berkely Books.
- Xu, J. J. and H. Chen (2005) "CrimeNet Explorer: A Framework for Criminal Network Knowledge Discovery," *ACM Transactions on Information Systems* (23) 2, pp. 201-226.
- Yang, J., W. Peng, M. O. Ward, and E. A. Rundensteiner (2003) "Interactive Hierarchical Dimension Ordering, Spacing and Filtering for Exploration of High Dimensional Datasets," in *Proceedings of IEEE Symposium on Information Visualization*, pp. 105-112.

- Yi, J. S., Y. A. Kang, J. Stasko, and J. Jacko (2007) "Toward a Deeper Understanding of the Role of Interaction in Information Visualization," *IEEE Transactions on Visualization and Computer Graphics* (13), pp. 1224–1231.
- Yi, J. S., R. Melton, J. Stasko, and J. Jacko (2005) "Dust and Magnet: Multivariate Information Visualization using a Magnet Metaphor," *Information Visualization* (4) 4, pp. 239-256.
- Zhang, J. (2000) "External Representations in Complex Information Processing Tasks," in A. Kent (Ed.), *Encyclopedia of Library and Information Science*, (Vol. 68), pp. 164-180. NY: Marcel Dekker.
- Zhang, J. and D. A. Norman (1994) "Representations in Distributed Cognitive Tasks," *Cognitive Science* (18) 1, pp. 87-122.
- Zull, J. E. (2002) *The Art of Changing the Brain*. Sterling, VA: Stylus.

Chapter 4 Adjustable Properties of Visual Representations: Improving the Quality of Human-Information Interaction

This chapter has been published as Parsons, P. & Sedig, K. (2013). Adjustable Properties of Visual Representations: Improving the Quality of Human-Information Interaction. *Journal of the American Society for Information Science and Technology*

Please note that the format has been changed to match the format of the dissertation. Figure numbers mentioned herein are relative to the chapter number. For instance, “Figure 1” corresponds to Figure 4-1. Additionally, when the terms “paper” or “article” are used, they refer to this particular chapter.

4.1 Introduction

Scientists, analysts, decision makers, doctors, and other knowledge workers are constantly engaged in activities that involve complex cognition (Sternberg & Ben-Zeev, 2001). Such activities include, among others, decision making, problem solving, sense making, planning, analytical reasoning, and learning. To emphasize both the active and the complex nature of such activities, they can be referred to as complex cognitive activities (see, e.g., Baddeley, 2007; Sedig & Parsons, 2013). Two essential characteristics of complex cognitive activities can be identified: 1) the use of complex psychological processes—such activities rely on the combination and interaction of more elementary processes such as perception and memory; and 2) the presence of complex

conditions—the environment may be dynamic, the outcome of actions may be uncertain, objects or states may be only partially observable, and/or many variables may exhibit a high level of interdependence (Knauff & Wolf, 2010; Schmid, Ragni, Gonzalez, & Funke, 2011). Complex cognitive activities can be contrasted with simple cognitive activities. Examples of simple cognitive activities include perceiving and recognizing colors and reading and understanding words in a book. Examples of complex cognitive activities, on the other hand, are making sense of global climate change patterns, analyzing genomic data to discover unknown patterns, and making decisions about resource allocation and organizational strategies.

The performance of complex cognitive activities involves active and goal-directed information processing by human beings (Funke, 2010). This information processing consists of humans using and working with some given information to derive new information (Knauff & Wolf, 2010). That is, humans interact with information to support their information-intensive thinking processes that are focused on solving problems, making decisions, and performing other complex cognitive activities. In this paper, we refer to humans who interact with information to perform complex cognitive activities as *actors*. Using this term has a number of benefits over using other terms that are often used such as users, clients, or patrons. Such benefits include placing emphasis on the activity aspect of human-information interaction; situating interaction with information in the context of the performance of activities; and shifting the focus from the system to the person or people that are using the system (Fidel, 2012).

Nowadays, actors typically use interactive computational tools to mediate their interaction with information and to support their complex cognitive activities. Examples of such tools include information visualization, personal information management, visual analytics, knowledge discovery, and educational tools. This paper is concerned with all such tools that mediate human-information interaction (HII) and support complex cognitive activities. As these tools have different meanings and connotations depending on the context and discipline in which they are used, we will use the umbrella term Cognitive Activity Support Tools (CASTs) to encompass all such tools and to emphasize their role in supporting the performance of complex cognitive activities. CASTs have

many components, including displays, sensors, and other input and output devices, storage mechanisms, algorithms for processing and manipulating information, and interfaces that connect to humans or to other machines. The component that is of primary concern in this paper is their visually perceptible information interface that serves as a meeting point between information and the human visual system. Such interfaces communicate and provide access to information through visual representations (VRs). Research in cognitive science has repeatedly demonstrated the fundamental role that VRs play in the performance of complex cognitive activities (see Kirsh, 2010; Zhang & Patel, 2006). For instance, research has demonstrated that certain types of VRs are more appropriate for some tasks and activities than for others (Peterson, 1996; Stenning & Oberlander, 1995).

Although not yet a prevalent endeavor in most disciplines concerned with VRs, such as information visualization and visual analytics, researchers in related fields have long been concerned with ontological analysis of their domains of research—i.e., analysis of their nature and structure, which involves, among other things, identifying concepts, categories, and entities, as well as their properties and relationships; conceptual modeling; clarifying subtle distinctions in terminology; distinguishing between essential and non-essential, abstract and concrete, and other ontological dichotomies; and constructing taxonomies to organize such entities, properties, concepts, and so on. For instance, researchers concerned with designing, evaluating, and modeling information systems have been aware of the need to identify and characterize ontological properties, and to generally engage in ontological analysis of their domains, for at least two decades (see, e.g., Wand & Weber, 1990). Scholars concerned with artificial intelligence and knowledge representation have also engaged in such research (e.g., Guarino, 1995). In a similar manner, the information systems and information science communities have long recognized and emphasized the importance of metadata (i.e., an ontological aspect of the domain) in conceptualization, design, evaluation, and in scientific discovery and communication. For example, Hert, Denn, Gillman, Oh, Pattuelli, and Hernández (2007) stress the integral role of metadata in conceptualization and design of information systems. While examining the importance of metadata in scientific communication and discovery, Willis, Greenberg, and White (2012) argue that discipline-specific metadata

schemes have contributed to establishing artificial barriers to data discovery and reuse across disciplines, and, furthermore, such schemes interfere with interdisciplinary scientific progress. Just as the development of metadata schemes and the process of ontological analysis are of vital importance for research, design, evaluation, and communication in some well-established disciplines, ontological analysis of the domain that encompasses the intersection of humans, information, VRs, interaction, computational tools, and complex cognitive activities is necessary if we are to develop a more scientific approach to this area of research—a need suggested by multiple researchers (e.g., Green & Fisher, 2011; Thomas & Cook, 2005; Meyer et al., 2010). Moreover, to design and evaluate CASTs in a systematic fashion, models and frameworks that are based on such analyses are needed. Such models and frameworks bring order and coherence to the landscape of relevant concepts, constructs, hypotheses, and research findings, scaffold thinking for design and evaluation, and can enable consistent communication for interdisciplinary research.

One aspect of ontological analysis is concerned with identifying entities and properties that exist within a domain and, furthermore, determining whether such properties are essential or non-essential, intrinsic or relational (i.e., extrinsic). In this paper, we are mostly concerned with actors and VRs, rather than with other components of CASTs. More specifically, we are concerned with a particular subset of VRs—interactive VRs. We analyze interactive VRs to identify their essential properties that influence cognitive processes and visual reasoning. By focusing on essential properties, we are concerned with properties of interactive VRs that are *present in all instances*. In other words, all interactive VRs, regardless of the context in which they are instantiated, have such properties. In addition, we are not concerned with all essential properties of interactive VRs, but only those that influence cognitive processes and visual reasoning and whose values can be adjusted by actors through interaction. While all instances of a category have the same essential properties, it is the values of such properties that are variable. For example, the category of ‘human’ has certain essential properties, one of which is height. All instances of this category (i.e., all humans) have this property; however, in each instance the value of the height property is variable (e.g., 5 feet, 6 feet, and so on). In a similar manner, the category of ‘interactive VR’ has certain essential properties, each of

which has a value. These values do not have to be quantitative, but can be qualitative or categorical as well. In any instance of this category (i.e., any VR) these properties are existent, and their values influence cognitive processes and visual reasoning of the actor. In the case of interactive VRs, the values can be adjusted. Because the ideal values in any instance are dependent on the actor (e.g., his or her cognitive abilities, preferences, and prior knowledge and experience), the complexity of the activity, and other contextual factors, these essential properties are also relational. That is, their ideal values (i.e., those best suited to a task or activity) do not depend only on VRs, but depend on both VRs and actors. To summarize, we are concerned with properties of interactive VRs that influence cognitive processes and are present in all instances (they are essential); the ideal values of these properties are dependent on both the actor and CAST (they are relational); and the values of these properties can be adjusted by the actor through interaction. To provide an example, density is a property of interactive VRs that is present in all instances, whether in the context of decision support and visual analytics, analytical reasoning and intelligence analysis, or any other combination of actors, activities, and contexts. In any given VR, the value of the density property exists along a continuum from low to high (e.g., a VR may have a very high degree of density with thousands of encoded entities, or a low degree with only a few entities). This value influences an actor's cognitive processing and visual reasoning with the encoded information (e.g., too many entities can result in perceptual overload and errors in reasoning). The actors should thus be able to adjust the value (e.g., decrease it so a lower number of entities are encoded). This last aspect is what makes the focus of this paper human-centered. Such an approach is indeed the core of human-centered informatics—researching, designing, and evaluating according to human cognitive and perceptual characteristics, being flexible rather than rigid, being context-sensitive and adaptable to human needs, and measuring effectiveness in terms of human rather than system benefits (Kulik, Kosara, Urquiza, & Wassink, 2007; Zhang, Patel, Johnson, Smith, & Malin, 2002). In this paper, 10 of these previously described properties are identified, characterized, and examined in the context of their cognitive influences and adjustment possibilities.

Although interactive VRs have numerous advantages over static VRs, previous research has shown that simply making VRs interactive does not ensure that CASTs will

effectively support the performance of complex cognitive activities; rather, an additional necessary concern is the *quality of interaction*—also referred to as *interactivity* (e.g., see Sedig, Klawe, & Westrom, 2001; Liang, Parsons, Wu, & Sedig, 2010). Sedig, Parsons, Dittmer, & Haworth (2013) have recently developed a framework that explicates many of the elements and factors that contribute to the quality of interaction between an actor and a visualization-based CAST, and which must be considered to ensure proper and optimal performance of complex cognitive activities. One of these identified factors is concerned with the range and availability of options that allow actors to adjust properties of the CAST to suit their needs and goals. In this paper we address this one aspect of interactivity partially (as we are concerned with only a subset of all such adjustable properties). This paper is part of a larger research plan aimed at establishing a comprehensive framework that can bring systematicity to research, design, and evaluation of CASTs. This comprehensive framework is named EDIFICE (Epistemology and Design of human-InFormation Interaction in complex Cognitive activitiEs). This paper presents a framework that complements other aspects of the EDIFICE framework, and can thus be considered a component of EDIFICE. We will henceforth refer to as EDIFICE-PVR, where PVR stands for Properties of Visual Representations. Although EDIFICE-PVR can be used as an independent framework, it is most useful when combined with other components of EDIFICE.

The rest of the paper is organized into five main sections as follows. The first two sections provide some conceptual and theoretical foundations by examining the concept of interactivity, the emergent nature of complex cognitive activities, the structure and process of CAST-mediated HII, and the role of interactive VRs in the performance of complex cognitive activities. The third section briefly examines some related work. The fourth section presents EDIFICE-PVR: its rationale and development, and a detailed treatment of each property in terms of its cognitive and perceptual influences. The fourth section provides an integrated scenario to demonstrate the utility of EDIFICE-PVR for systematic design and evaluation of CASTs. Finally, the fifth section provides a summary and discusses some potential future research directions.

4.2 Interactivity: Quality of Interaction

The concept of interactivity lacks a coherent and commonly agreed upon characterization (see Aigner, 2011; Sedig, Parsons, & Babanski, 2012; Sedig et al., 2013). One of the problems in discussing interactivity is that the terms ‘interaction’ and ‘interactivity’ are often used loosely and interchangeably. Although these two terms are similar, they are conceptually distinct. In this paper, interaction refers to the dialogue that takes place between an actor and information through the mediation of a CAST. Interactivity, however, by adding the suffix ‘ity’, denotes the *quality of the interaction*. This distinction is important—a tool may be interactive, but if the quality of interaction is not good, it will not effectively support complex cognitive activities. For example, an actor can interact with a VR of a chemical compound to make sense of a chemical reaction. As such a process involves a transformation from one state to another, it may take place in many different ways—it may be instantaneous or it may take place gradually; it may require one mouse click or may require a chain of events; it may or may not allow the actor to control certain parameters of the transformation; and so on. In each case, the interaction is the same: the actor is acting upon a VR to effect a transformation. The quality of the interaction, however, is what changes.

Another difficulty for discussing interactivity is that it is a complex and emergent construct. It is a construct in the sense that it is an abstraction for which there is no single, directly observable referent. It is complex in the sense that the factors that contribute to the construct are many, are dynamic, and are themselves complex (e.g., the human cognitive and perceptual system). Furthermore, it is emergent in the sense that it is the result of the interaction of multiple components and cannot be reduced to the properties of the components themselves. While performing complex cognitive activities, a connection is formed between an actor and a CAST that results in a joint, coordinated cognitive system (Brey, 2005; Kirsh, 2005; Parsons & Sedig, 2013b). Within this cognitive system, there is continuous and reciprocal causal influence between the actor and the CAST (Clark, 1998; Kirsh, 2005). Such a reciprocal causal influence gives rise to properties that are not reducible to its components in isolation. In other words,

interactivity is an emergent property of the cognitive system that is created by an interactive coupling between an actor and a CAST.

The factors that contribute to the interactivity construct are many, and they can be examined at different levels of abstraction and granularity. At the micro-level, the manner in which the action and reaction components of a single interaction are operationalized affects the quality of interaction (see Liang et al., 2010; Sedig et al., 2013). At the macro-level, where multiple interactions are put together to perform tasks and activities, there are a number of factors that affect the quality of interaction. These include: the number and diversity of interactions that are available to the actor; the harmonious and reciprocal relationships among interactions; the appropriateness of interactions for given VRs, tasks and activities, and characteristics of actors; the types of interactions available to actors—whether interactions allow actors to access information, annotate information, modify existing information, insert new information, or any combination thereof; and, the range and availability of adjustability options that allow actors to adjust properties of the CAST to suit their needs and goals (see Sedig et al., 2013, for a more detailed examination of these micro- and macro-level considerations). The final consideration—regarding the range and availability of adjustability options—is the issue with which this paper is concerned.

An analogy may facilitate thinking about how adjusting the values of properties can affect the quality of interaction. Two people may interact with one another through verbal communication. When one person speaks, information is being communicated through speech—an auditory representation of information. The auditory information representation has a number of properties—volume, speed, pitch, clarity, language, and so on. These properties have values: volume can be high, low, or in between; clarity can be good, bad, or in between; language can be English, French, or some other language; and so on. Additionally, in this context these properties should be conceptualized as relational, as their ideal values are dependent on the listener. Although interaction may occur between the participants, it is the quality of the interaction that is critically important in terms of the efficacy of communication. A speaker may be mumbling or speaking quietly, for example, which would negatively affect the comprehension of the

listener. In other words, the values of the volume and clarity properties are not suitable. It is possible, through extended effort and concentration, for the listener to comprehend the speaker. However, if the listener is given the ability to adjust some of the values of the properties—by requesting that the speaker speak louder and more clearly—the quality of the interaction is affected, and the efficacy of the communication is increased. Thus the interaction stays the same, but the interactivity changes. By giving control to the listener she can adjust the values of the properties to suit her contextual needs and facilitate comprehension.

While using CASTs, there is also a dialogue that is taking place. As previously mentioned, the efficacy of tools in supporting cognitive activities depends in part on the quality of this dialogue. In the context of this paper, this dialogue takes place through visual, rather than auditory, representations of information. This paper identifies ten properties of VRs that affect the performance of complex cognitive activities: appearance, complexity, configuration, density, dynamism, fidelity, fragmentation, interiority, scope, and type. Each of these properties has a value: the value of complexity may be high, low, or in between; the value of dynamism may be high, low, or in between; the value of type may be a tree diagram, a plot, or some other representational form; and so on. Just as the context in the situation described above is important—whether the conversation is taking place in a noisy environment, for example—and has an effect on the ideal values of the properties, so too the context in which complex cognitive activities take place is important.

4.3 Human-Information Interaction in Complex Cognitive Activities

Researchers interested in HII investigate the relationships between humans and information, rather than those between humans and technology. HII is a broad area of research, and scholars are interested in many different aspects of HII, including those related to information retrieval, foraging, sharing, and seeking; information visualization; personal information management; medical, health, and bio informatics; human-computer

interaction; and information systems. Therefore, the focus of HII research varies according to the dominant discipline in which researchers are situated, and their pertinent research challenges, domains of application, methodologies, and underlying theoretical frameworks.

4.3.1 Complex Cognitive Activities as Emergent Phenomena

One of the challenges for HII researchers is to develop models and frameworks that characterize and explicate complex cognitive activities and how they are performed through the mediation of CASTs. Considering the complexity of the human cognitive system, the complexity of the activities, as well as the sophistication of modern computational tools, addressing such a challenge is a formidable endeavor. Other components of the EDIFICE framework have begun to address aspects of this research challenge. For instance, Sedig and Parsons (2013) have identified and characterized a number of complex cognitive activities, developed a model of how such activities emerge over time through interaction that occurs at multiple levels of granularity, and have developed a model of the structure and process of HII during the performance of complex cognitive activities (see also Parsons & Sedig, 2013b). As was discussed in the previous section, Sedig et al., (2013) have further characterized the structure of HII and have identified a number of micro- and macro-level elements and factors that contribute to overall interactivity when using interactive tools to support complex cognitive activities. To situate EDIFICE-PVR, these other components of the EDIFICE framework can be briefly summarized as follows.

Complex cognitive activities are hierarchical, embedded, and emergent. Activities typically include sub-activities, which include tasks and sub-tasks, which include actions and micro-level physical events such as mouse clicks and gestures. Complex cognitive activities emerge over time from the performance of micro-level events, actions, tasks, and sub-activities. For example, consider the use of a CAST to support making sense of a large body of information regarding a terrorist attack. In order to make sense of the structure and features of the information, an actor may perform a number of tasks, such as scanning phone records for specific dates or locations; identifying prominent

individuals and their relationships; browsing a collection of photographs; and categorizing emails and phone calls. Each task may involve the performance of any number of lower-level actions. For instance, to identify prominent individuals and their relationships, the actor might filter names based on dates or other criteria, annotate photographs or emails to add meta-information, rearrange a list of names and dates, or translate information from a table to a node-link diagram. To complete any one of these actions, a number of micro-level events such as mouse clicks, finger swipes, or keystrokes may be required. Thus, a sequence of events, actions, sub-tasks, tasks, and sub-activities results in a trajectory through the cognitive activity space that eventually leads to the accomplishment of an overall activity. During the performance of such activities, actors deploy general, high-level strategies that include the performance of many tasks and low-level actions that help actors alter their information environment, and, as a result, transform and support their cognitive processes to gradually achieve the ultimate goals of an activity (Sedig & Parsons, 2013).

4.3.2 Structure and Process of Human-Information Interaction in Complex Cognitive Activities

In the context of using CASTs that mediate human-information discourse, there are many components that require consideration. These include, among others, the information, the internal workings of the CAST, the representation of information at the interface of the CAST, characteristics of the actor, and the reciprocal action that takes place between the actor and the represented information. Moreover, if a CAST is to fulfill its intended function, the relationships between each of these aforementioned components must be considered carefully. To facilitate conceptualization for research and design, we have, in previous work (see Sedig, Parsons, & Babanski, 2012), proposed a categorization of this discourse into five broad spaces: 1) information space, 2) computing space, 3) representation space, 4) interaction space, and 5) mental space.

Information space refers to the body of information with which an actor is interacting to perform an activity. The types of complex activities in which actors engage often require access to information from multiple domains. For example, an analyst may require

demographic, historic, financial, and geographic information to make decisions regarding the distribution of resources. As CASTs can maintain and provide access to all kinds of information, actors can interact with information that is combined and blended from multiple sources and environments. Thus, the term information space refers to a body of information that contains any combination of entities, properties, or relationships—whether concrete, abstract, large, small, visible, or invisible, and from any possible combination of domains—with which actors access and interact through the mediation of CASTs to perform cognitive activities. Henceforth, for the sake of simplicity, the term ‘information item’ will be used to refer to any constituent of an information space, such as an entity, component, structure, property, relationship, or process. Many researchers limit their scope to either concrete information sources (e.g., as in scientific visualization) or abstract information sources (e.g., as in information visualization). The high-level approach of EDIFICE-PVR, however, is applicable to all sources of information. Cognitive and perceptual processes that are influenced by the properties of VRs are consistent regardless of the source of information. Consequently, EDIFICE-PVR is applicable to a wide variety of domains, including business, medicine, mathematics, economics, biology, history, physics, sociology, and library science. *Computing space* refers to the internal portion of the CAST, where information items are digitally represented, stored, and operated upon. Data cleaning, filtering, normalization, and other pre-processing procedures take place in computing space. Moreover, data mining and knowledge discovery techniques allow CASTs to assume an active information-processing role and become active participants in information processing for complex cognitive activities (see Parsons & Sedig, 2013b for more on this issue). *Representation space* refers to the space in which information is represented in visual form at the interface of a CAST. This space is comprised of VRs of items from the information space, as well as representations of action possibilities, controls, labels, and other elements that are not part of the information space. As digital information is not directly visible to actors, it is only through the representation space that actors access, interact with, modify, or insert information into the underlying information space. Research and design of representation space is concerned with, among other things, how information can be organized and displayed in visual forms, how representation and encoding

techniques influence the performance of tasks and activities, and how VRs affect actors' perceptual and cognitive processing of information. *Interaction space* refers to the space in which actions are performed and subsequent reactions occur. This space is where there is a back-and-forth flow of information between an actor and a CAST. Research and design of interaction space is concerned with what actions can and should be made available to actors to operate upon VRs, the utility of such actions in the context of performing complex cognitive activities, and how actions and their reactions should be operationalized. *Mental space* refers to the space in which internal mental events and operations take place (e.g., apprehension, induction, deduction, memory encoding, memory storage, memory retrieval, judgment, classification, and categorization).

These spaces do not exist or operate in isolation. When an actor performs complex cognitive activities, the actor and CAST form a joint, coordinated cognitive system across which cognitive processing is distributed (see Clark, 2008; Kirsh, 2005; Sedig & Parsons, 2013). That is, some of the processing takes place in mental space, some is offloaded onto VRs and computational processes, and some takes place through interactions with VRs. A principled understanding of how to best distribute the load of information processing for different activities and actors is still an open research problem (see Parsons & Sedig, 2013b for further discussion of this issue). Figure 1 depicts the structure and process of CAST-mediated human-information interaction. Interaction is depicted as a cyclical process in which an actor perceives VRs, performs some mental operations, acts upon VRs, a reaction occurs (visibly in representation space and/or hidden within computing space), and then the cycle repeats itself.

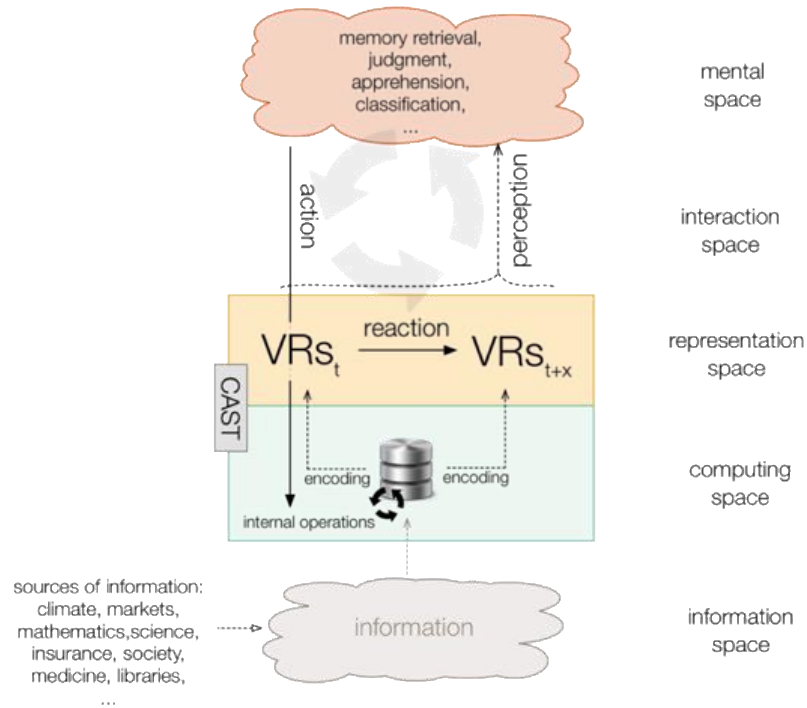


Figure 4-1 The structure and process of CAST-mediated human-information interaction

4.3.3 Role of Interactive VRs in Performing Complex Cognitive Activities

By organizing and giving form to information, VRs give perceptual access to an underlying information space in such a way that there is a unity of meaning between the VR and the information—in other words, *from the perspective of the actor, the VR is the information* (Cole & Derry, 2005; Peterson, 1996; Zhang & Norman, 1994).

Consequently, the design and use of VRs in CASTs requires careful consideration. When using VRs to assist with cognitive activities, an actor's external cognition is engaged (Scaife & Rogers, 1996). The partnership that is formed between internal mental processes and external representations provides a number of benefits for performing complex cognitive activities (see Kirsh, 2010; Sedig et al., 2013 for a discussion of some of these benefits). However, when VRs are static, actors may be forced to exert a great deal of mental effort in order to reason and think about the information. Complex cognitive activities take place over a span of time, where internal mental processes (e.g.,

categorizations, abstractions, memory encodings, and comparisons) are dynamic and involve constant assimilation and reorganization of information. Static representations do not readily share in and distribute this temporal and dynamic processing of information, and thus force more of the processing load onto internal mental processes. This lack of operational harmony creates a distance between the mental space of an actor and representation space. With the addition of interaction, however, this distance can potentially be bridged. If interaction is operationalized properly, a strong coupling can be formed between an actor and a CAST that provides better support for performing cognitive activities (see Brey, 2005; Clark, 1998; Hoc, 2005; Kirsh, 1997, 2005, 2010; Sedig et al., 2013).

When CASTs are designed in a human-centered fashion, actors can dynamically adapt VRs to fit their cognitive and contextual needs. As a VR typically encodes only a subset of items from an information space, static VRs can force actors to make extrapolations regarding the items that are latent. In addition, with static VRs, the values of their properties are not adjustable, which can lead to an unnecessary burden being placed on actors' perceptual and cognitive faculties. When VRs are interactive, on the other hand, actors can fluidly and repeatedly act upon VRs to adjust them to best integrate them into their cognitive processing of the information. Consider Figure 2, which depicts a portion of an activity. The VRs at time t encode some items from the information space. The actor perceives the encoded information and performs an action (A_n). The reaction (R_n) results in the new state of the VRs (at time $t+1$), which encodes new items from the information space. The actor perceives the result (i.e., VR_{t+1} , as well as the process of transformation from VR_{t+1} to VR_{t+1}). Based on updated goals and strategies, the actor performs another action (A_{n+1}), and a reaction (R_{n+1}) ensues. The VRs at time $t+2$ now encode more items from the information space. In addition to accessing and working with items from the information space, such actions can adjust the values of the properties of the VRs. For instance, the appearance and density values of the VRs at time $t+1$ may not be appropriate for a task that an actor is trying to perform. By acting upon the VRs, the actor may adjust them to a more appropriate value, resulting in the VRs at time $t+2$. If a CAST is designed properly, this process of reciprocal action creates an operational

harmony between mental space and the other spaces that increases interactivity and provides better support for the performance of complex cognitive activities.

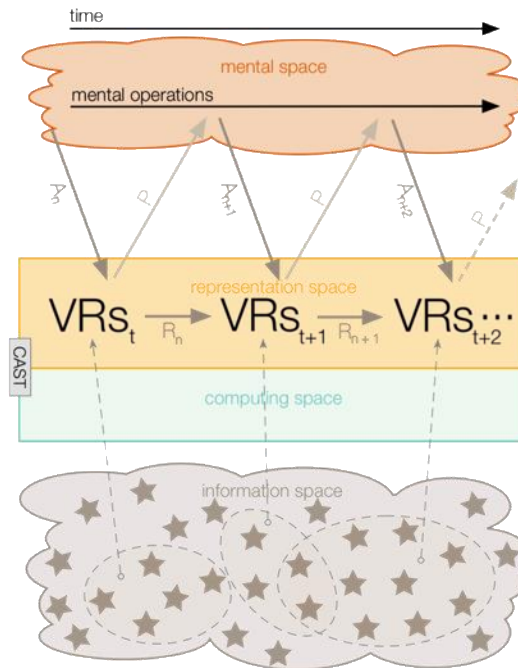


Figure 4-2 The performance of a cognitive activity through information discourse that is mediated by a CAST.

4.4 Related Work

Because of the inherently multidisciplinary nature of HII, researchers approach its study from different disciplines and areas of interest, such as those mentioned in the previous section. Only a small subset of such research, however, has taken a human-centered approach to HII at the intersection of complex cognition, human activities, and interactive technologies. Stasko and colleagues have been working on incorporating current theories and models from cognitive science research into information visualization research. For example, Liu, Nersessian, & Stasko (2008) have examined the use of distributed cognition as a theoretical framework for information visualization. Pike, Stasko, Chang,

and O'Connell (2009) have strongly emphasized the importance of interaction in human insight and in the development of information systems. In addition, Liu & Stasko (2010) have developed a framework that combines research on mental models and reasoning with interaction and visualization, and have emphasized the primacy of the interplay between internal and external representations in the emergence of cognitive processes—an important area of research that requires much further examination. Sedig and colleagues have been investigating the role of interaction with VRs in supporting cognitive tasks and activities in the context of concept learning and distributed cognition (Sedig et al., 2001; Liang & Sedig, 2010a), visual and spatial reasoning (Sedig, Rowhani, Morey, & Liang, 2003; Liang & Sedig, 2010b), formation of cognitive maps (Sedig, Rowhani, & Liang, 2005), and other considerations for HII in complex cognitive activities (e.g., Fast & Sedig, 2005, 2011; Liang et al., 2010; Sedig & Liang, 2008; Sedig & Parsons, 2013; Sedig et al., 2013). Arias-Hernandez, Green, and Fisher (2012) have recently contributed a useful critique of the use of models of cognition in visual analytic research, and provide a loose framework for thinking about the material basis of cognition in visual analytics. Other contributions that have some general application to this area include Fidel's (2012) recent work on human-information interaction and cognitive work analysis, Kaptelinin and Nardi's (2012) recent work on activity theory in HCI, and Marchionini's (2008, 2010) work on information concepts and human-information interaction.

While more attention in general has been given to HII in recent years, existing work does not focus strongly on the particulars of how interactive VRs affect higher-order cognitive processes and complex cognitive activities. Although some existing research has examined how features of VRs influence human cognition, it has mostly been in the context of low-level perceptual and cognitive effects (e.g., Bertin, 1967; Tukey, 1977; Cleveland & McGill, 1984; Mackinlay, 1986; MacEachren, 1995; Nowell, 1997; Ware, 2008, 2012). Research that has examined some higher-level cognitive effects of VRs (e.g., Baker, Jones, & Burkman, 2009; Cheng, Lowe, & Scaife, 2001; Huang, Eades, & Hong, 2009; Shimojima, 1996; Zhang & Norman, 1994) has not attempted to systematically identify and characterize the essential properties of interactive VRs and describe how or why their values depend on both actors and CASTs. The need for such a

research effort has been previously discussed and will not be repeated here. Following the next section, which presents the EDIFICE-PVR framework, there will be a more detailed comparison with some existing work in order to demonstrate the utility and unique contribution of EDIFICE-PVR.

4.5 The EDIFICE-PVR Framework

The presentation of EDIFICE-PVR in this section is divided into three subsections: 1) a discussion of the rationale for the development of EDIFICE-PVR; 2) a description of method of identification and development of the 10 properties; and 3) a detailed treatment of each property, including an examination of each one's cognitive and perceptual influences, and examples of CASTs that provide the ability to adjust the values of properties to support complex cognitive activities.

4.5.1 Rationale

In recent years, researchers have been emphasizing the need for more systematic development of theoretical frameworks (e.g., Chen, 2010; Fabrikant, 2011; Kaptelinin & Nardi, 2012; Keim, Kohlhammer, & Ellis, 2010). Kaptelinin and Nardi, for instance, state that “while understanding the structure and dynamics of purposeful human activities and identifying possibilities for their advanced technological support remain important issues, there is currently also *marked interest in frameworks that can provide an explanation of why and how certain subjective phenomena are taking place in situations surrounding the use of interactive technologies.*” (2012, p. 47, italics added). One of the goals of EDIFICE is to develop a comprehensive framework that is applicable to all interactive tools that support the performance of complex cognitive activities through rich HII. In other words, the goal is to develop a general and comprehensive framework that can motivate research and design for a broad range of tools, tasks, actors, activities, platforms, techniques, and domains. As EDIFICE-PVR is one component of the EDIFICE framework, it adopts the same goal. Therefore, the properties of VRs that are presented as part of EDIFICE-PVR are generally applicable—whether to information

visualization, visual analytics, or health informatics; whether using a laptop, desktop, tablet, or projection display; whether engaged in sense making, learning, problem solving, or decision making; whether in the context of biology, engineering, education, finance, or healthcare; whether the actor being young or old; and whether for a single actor or for multiple actors. Furthermore, as EDIFICE-PVR is concerned with human-information interaction, rather than human-technology interaction, it is not invalidated by technological change and is applicable across a wide variety of technologies and platforms.

Since EDIFICE-PVR is concerned with HII in the context of using CASTs, where cognitive activities are often complex and unstructured, to be most useful the properties must be embedded within a theoretical substrate that accounts for the complexities involved in the performance of such activities. In other words, simply identifying a number of properties—although potentially useful and welcome work—is of limited value if the properties are isolated from underlying theoretical frameworks and models that explain and describe how complex cognitive activities are performed. Thus, the initial task for developing EDIFICE-PVR was to situate it firmly within a broader theoretical framework, such that its conceptualization was consistent with other research concerned with HII, interactivity, and the performance of complex cognitive activities. Therefore, the theoretical foundations discussed above—which have been developed further in other components of the EDIFICE framework—were important in the conceptualization of the properties themselves, and in understanding how adjusting the values of properties fits into the overall performance of complex cognitive activities. Furthermore, the development of EDIFICE-PVR was guided by the conviction that syncretic and holistic research is much needed in this area, and by the assumption that there are indeed principles, features, processes, and relationships that are universal to all information spaces, domains, VRs, activities, and actors. As this domain is relatively young and underdeveloped, the explication and organization of fundamental concepts and their relationships that EDIFICE-PVR provides—e.g., VRs, information spaces, tasks, activities, and perceptual and cognitive influences of VRs—can stimulate further theoretical research and the development of frameworks that more fully describe, explain, and predict the performance of complex cognitive activities through CAST-mediated HII.

4.5.2 Identification and Development of Properties

Two processes shaped the identification and development of the properties of EDIFICE-PVR: 1) a broad survey of existing literature, and 2) a broad survey of existing CASTs. The survey of existing literature included research from the cognitive and learning sciences, perceptual psychology, information science, human-computer interaction, diagrammatic reasoning, interaction design, information design, and multiple visualization sciences. Based on numerous studies that have been done in these areas, it is well known that there are certain properties of VRs and visual information displays that affect perceptual processing of information, the speed with which decisions can be made, and other aspects of how humans process and think with information. Thus, in light of our goal to develop a general framework, our search was for properties of VRs that transcended particulars, and that, in the context of interactive VRs, could be adjusted to facilitate complex cognitive activities. We examined studies that had been conducted in the aforementioned areas to determine which of the findings were applicable to or could be generalized to interactive VRs. In addition to the aforementioned disciplines, we examined relevant literature from information graphics, communication design, information behavior, and other areas that are not necessarily concerned with interactive VRs and/or cognitive activities, but which could still provide valuable insights into the development of EDIFICE-PVR. During this process of literature review, we took note of the findings of studies that examined how features of VRs affected cognitive and perceptual processing, and examined existing established design and evaluation guidelines for VRs. We identified properties of VRs from literature that described the use, development, and evaluation of financial analytics tools, digital library interfaces, digital games, learning tools, visual analytic tools, and others.

The second process that shaped the identification and development of the properties was a systematic examination of 100 CASTs. To assure a wide sampling, we included tools from many domains. Although there is overlap, they can be roughly broken into 50 from visualization—information, data, geographic, scientific, medical and health visualization,

and visual analytics; 25 from cognitive, educational, and learning technologies and digital cognitive games; 25 from personal information management, information retrieval, knowledge management, library science, and general productivity tools. A sampling of these is listed in Appendix 10.1. While examining each tool, we identified the features of its VRs and kept a record of them. This process was similar to the process of pattern mining described by Dearden and Finlay (2006), in which invariant features of existing designs are identified and used to construct design patterns.

As these two mutually reinforcing processes were conducted in the context of developing a general framework, we categorized a number of features of VRs that were consistent across activities, domains, and actors. Eventually, these features were given a common label, and are now known by the properties that are presented in this paper. During the identification of properties of any phenomena, a desired level of abstraction must be determined. In the context of EDIFICE-PVR, the desired level of abstraction was based on three overlapping goals: 1) to provide a reasonable number of properties with which researchers and designers could work; 2) to ensure that the features of each property had a significant-enough effect on cognitive processes to warrant their own category; and 3) to maintain a consistent level of abstraction across all properties. Consider, for example, the *appearance* property (discussed in the following section). This property includes features such as hue, color, and opacity. Making each of these a separate property, however, would lead to a large, cumbersome list of properties that would likely be of limited value. In addition, these features alone do not seem to have a significant enough effect on cognitive processes to warrant a distinct property.

The two processes described above were intertwined and mutually beneficial. A continual identification of features, categorization of features, refinement of categorizations, and confirmation and testing between literature and CASTs eventually led to the properties that are now present. These are listed and briefly characterized below in Table 1. This systematic approach leads us to believe that the list of properties is fairly comprehensive; however, we do not claim that it is exhaustive, and, especially since this is an initial attempt at this particular area of research, it is possible that additions or refinements may occur in the future.

A Note on the Justification and Validity of Particular Properties. It may appear, at a first glance, that some properties are simply different labels for the same phenomenon; after closer investigation, however, it should become evident that each property is distinct in its fundamental nature. Indeed, an attempt has been made here to demonstrate the intrinsic and distinct nature of each property. This distinctiveness does not preclude, however, situations in which there is a positive correlation between the values of two or more properties—situations in which increasing or decreasing the value of a property also increases or decreases the value of one or more other properties. In fact, it is often the case that adjusting the values of a property adjusts the values of other properties. As mentioned earlier, interactivity is an emergent property that results in part from the interaction between an actor and VRs—where such VRs, in practice, manifest the values of properties in a coalesced manner. While the values of each property in isolation may have an effect on cognitive processes, *the ultimate utility of this framework rests on a balance between analysis and synthesis of properties with respect to their influence on the performance of complex cognitive activities.*

In what follows, each property is accompanied by examples of CASTs that demonstrate and validate the existence of that particular property. The fact that a VR is dense, for instance, ontologically validates the density property; there is no need for experimenting to see whether or not the property exists. What is in need of experimentation, however, is the effect of the properties on the performance of cognitive activities. We have attempted below to validate these by referring to numerous empirical studies dealing with the perceptual and cognitive effects of VRs across a wide variety of activities, tasks, and domains.

Table 4-1 Essential properties of interactive VRs, the values of which should be made adjustable to provide better support for the performance of complex cognitive activities.

Property	Characterization
Appearance	aesthetic features (e.g., color and texture) by which information items are encoded in a VR
Complexity	degree to which encoded information items exhibit elaborateness and intricacy in terms of their quantity and interrelationships in a VR
Configuration	manner of arrangement, organization, and ordering of information items that are encoded in a VR
Density	degree to which information items are encoded compactly in a VR
Dynamism	degree to which encoded information items exhibit movement in a VR
Fidelity	degree to which information items are accurately encoded in a VR
Fragmentation	degree to which information items are broken up and discretized and encoded into non-continuous areas in a VR
Interiority	degree to which information items are latent and remain hidden below the surface of a VR, but are potentially accessible and encodable
Scope	degree to which the growth and development of information items are encoded in a VR
Type	form of a VR in which information items are encoded

4.5.3 Properties

4.5.3.1 Appearance

Appearance refers to aesthetic features such as color, saturation, density, perspective, angle, orientation, and texture by which information items are encoded in a VR. Much research confirms that such features can significantly influence cognitive and perceptual

processes (e.g., see Cleveland & McGill, 1984; Nowell, 1997; Ware, 2008, 2012). While performing visual search tasks, for instance, a distinct size or color can effectively make VRs stand out and thus increase speed of identification (see Wolfe, 1998). Additionally, actors often have their own appearance-related preferences that can help them perform tasks (Yi et al., 2007). For instance, actors may associate a particular shape or color with a particular meaning (see Sedig, Rowhani, Morey, & Liang, 2003). In addition, color can have very different semantics from one culture to the next (Ware, 2008). Not only do the values of appearance affect cognitive and perceptual processes, but the process of change between different appearance values can also have a significant effect (Ware, 2004).

Consider a sense-making activity in which an actor is trying to develop a mental model of a citation network. The appearance of a VR of the network could be adjusted in different ways depending on the task being performed. For instance, to identify all papers that share a common keyword or subject area, the actor could adjust the values such that the appropriate components of the VR are encoded with a particular color. To encode the relative strength of the connections between authors, the connections between them could be encoded with relative degrees of saturation. The most effective feature to adjust in any situation is dependent on the task. If actors are interested in tasks involving categorical properties of the information space, for example, color and texture are effective; for tasks involving ordinal properties, saturation and density are effective. Designers and evaluators must be aware of which of these features are best suited to which tasks (see, e.g., Cleveland & McGill, 1984; Nowell, 1997; Spence, 1997; Ware, 2008). However, as actors do not follow an algorithmic approach during the performance of complex cognitive activities, and strategies and goals are constantly revised and updated (see Sedig & Parsons, 2013), actors should be given the ability to adjust such values to best suit their task and mental state at any point during an activity.

4.5.3.2 Complexity

Complexity refers to the degree to which encoded information items exhibit elaborateness and intricacy in terms of their quantity and interrelationships in a VR. Complexity ranges in value from low (e.g., a single item with no encoded relationships)

to high (e.g., thousands of items with many intricate pathways and connections among them). If complexity of VRs is not suitable for a task or an activity, a large burden can be placed on perceptual and cognitive faculties (Demetriadis & Cadoz, 2005; Moody, 2007). This burden can result in cognitive overload (Sweller, 2002) and has been shown to result in errors while performing tasks (e.g., see Huang, Eades, & Hong, 2009). Numerous studies have been performed confirming the negative effects of inappropriate values of complexity while performing tasks and activities. For example, Kumar & Benbasat (2004) found that as the complexity of graphs increased, the time taken to comprehend information also increased. Cruz-Lemus, Maes, Genero, Poels, & Piattini (2007) also found that as the complexity of a diagram increased, the length of time it took to understand the information also increased; in addition, they found that the efficiency with which the information was understood decreased. Huang et al. (2009) tested the effect of VR complexity on cognitive load. Their results similarly demonstrated that complexity had a significant effect on response time and on efficiency while performing tasks. However, they also measured the effect of complexity on the amount of mental effort required to complete a task, and found that more complex VRs required a significantly higher amount of mental effort to understand.

It may sometimes be the case that the increased perceptual and cognitive burden that high values of complexity place on actors is desirable. For instance, there is some evidence that high values of complexity can lead to increased planning (see Ainsworth and Peevers, 2003). It is possible that information is more likely to be committed to memory when VRs are more complex, whereas lower values of complexity allow actors to rely on visual search without engaging in deep mental processing of information. This type of forced deep engagement with information may be desirable for some types of CASTs, such as educational tools, but not others, such as tools for intelligence analysis (see also Parsons & Sedig, 2013b for more discussion of this topic).

Figure 3 shows a CAST, *VisANT* (<http://visant.bu.edu>), that supports visual data mining of multi-scale biological networks and pathways. One sub-activity that would be a likely component of any complex cognitive activity performed with this tool is sense making—an activity involving the development of a mental model of an information space about

which one has insufficient knowledge (Klein, Moon, & Hoffman, 2006). Such an activity involves tasks such as identifying important items or pathways within the space, categorizing items based on similar features, and determining the hierarchical structure of the space. The complexity of the VR in Figure 3 (L), however, can make such tasks challenging. For instance, the number of items and the number of pathways among them can make the identification of important pathways very difficult due to cognitive and perceptual load. Figure 3 (R) shows how the actor can, through interaction, collapse a number of nodes into their metabolic modules to facilitate identification of high-level pathways within the network. As the actor progresses in the sense making activity, she can repeatedly collapse and expand VRs to dynamically adjust and develop her mental model of the information space.

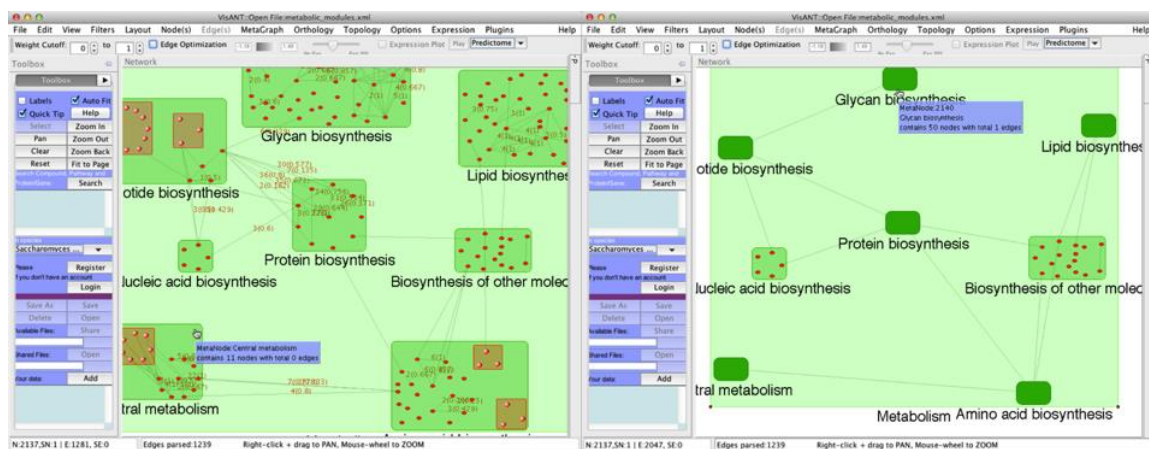


Figure 4-3 Adjusting the value of complexity of a VR.

4.5.3.3 Configuration

Configuration refers to the manner of arrangement, organization, and ordering of information items that are encoded in a VR. Encoded items may be arranged according to certain data attributes (e.g., categorical, ordinal) or they may have a random arrangement. Different arrangements and orderings of encoded information items can affect cognitive activities in fundamentally different ways (Peng, Ward, Rundensteiner, 2004). For example, the ordering of encoded information items affects how easily actors detect

underlying patterns, dependencies, trends, correlations, and relationships (Spence, 2007; Pirolli & Rao, 1996; Siirtola, 1999). Many CASTs are designed without much consideration for how encoded information items are arranged, and often do not provide mechanisms for adjusting the value of configuration (Peng et al. 2004). However, as mental space and representation space become coupled into a coordinated cognitive system through interaction, adjusting the ordering of information items in representation space can directly impact the ordering of information items in mental space (Kirsh, 1995a). Research in cognitive science has shown that it is easier to adjust the configuration of external representations of information while performing cognitive activities than to adjust one's internal mental representations without external support (Kirsh, 1995a). Indeed, studies have shown that adjusting the configuration of information representations has a significant positive effect on the performance of cognitive activities (e.g., see Kirsh, 1995b; Maglio, Matlock, Raphaely, Chernicky, & Kirsh, 1999). Providing mechanisms whereby actors can adjust the configuration of representations can facilitate cognitive activities by triggering mental associations that result from viewing new perspectives of information, and by simplifying the representation space from the perspective of the actor (Kirsh, 1995a).

Figure 13 shows a CAST, *Regional eXplorer* (stats.oecd.org/OECDregionalstatistics), that supports numerous activities involving regional statistics related to economic cooperation and development. The manner in which information items are organized in Figure 4 (L) does not make it easy to identify correlations within the encoded information. However, the actor can adjust the configuration value by sorting one column of the table (Figure 4R). Although no new information has been encoded, adjusting the value of configuration in this manner makes it very easy for the actor to identify a strong correlation between two columns.

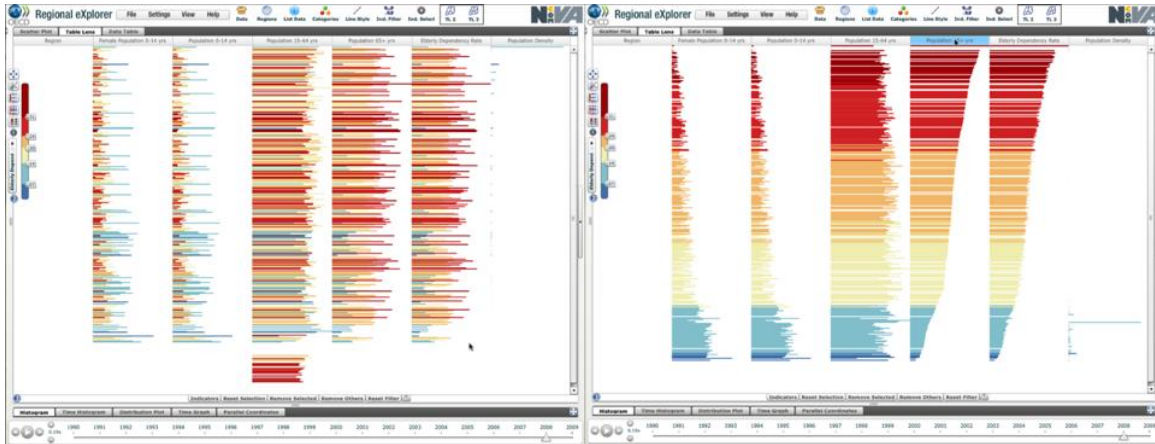


Figure 4-4 Adjusting the value of configuration of a VR.

4.5.3.4 Density

Density refers to the degree to which information items are encoded compactly in a VR. Density ranges in value from low (e.g., one or two dots that are spread out in a large display area) to high (e.g., thousands of information items encoded compactly in a small area). If the value of density of VRs is too high, perceptual tasks, such as locating and extracting relevant information, can be negatively affected (Pirolli, Card, & van Der Wege, 2001). In addition, such VRs can burden actors' mental faculties by placing a large informational load on working memory (Green & Petre, 1996). When engaged in decision making, for example, VRs that are too dense hinder quick extraction of information that is required to make decisions (Rosenholtz, Li, & Nakano, 2007). Indeed, numerous studies have shown decreased task performance when VRs have density values that are not appropriate for a task. For instance, Phillips and Noyes (1982) demonstrated that maps with low density values were associated with better performance on a number of visual tasks. Similarly, Springer (1987) showed quicker locating of targets when VRs were less dense. The results of these studies suggest that tasks—especially those requiring quick performance—are hindered if the value of density is too high. However, more compactness of information encoding can sometimes be desirable. For example, representations that encode many information items and are very compact can provide a high-level overview of very large information spaces and can facilitate high-level comparisons (Tufte, 2001).

Many VRs are designed with the intention of encoding a large amount of information in an attempt to increase the cognitive information processing capabilities of actors (Pirolli et al., 2001). Long-standing prescriptions, however, often do not consider VRs with their interactive features at the forefront of consideration. For instance, according to Tufte (1990), “enriching the density of data displays [is one of] the essential tasks of information design” (p. 33), and, “visual displays rich with data are...frequently optimal...the more relevant information within eyespan, the better.” (ibid., 50). This may be true for many non-interactive, static representations. However, such propositions are not necessarily applicable to CASTs. Consider Figure 5, which shows a CAST, *Global Council Interlinkage* (janwillemtulp.com/worldeconomicforum/), that supports exploration of data derived from a survey of experts from 72 Global Agenda Councils of the World Economic Forum. The value of density of the VR shown on the left makes it difficult to perform tasks such as identifying connections between councils. Through interaction, an actor can select a particular council to show connections only to it and hide other connections, thereby facilitating such a task. Note that it is not the complexity of the VR that hinders such a task—that is, the hindrance is not due to the elaborate and intricate nature of the encoded items and their connections—but rather, it is due to the compactness with which the connections are encoded.

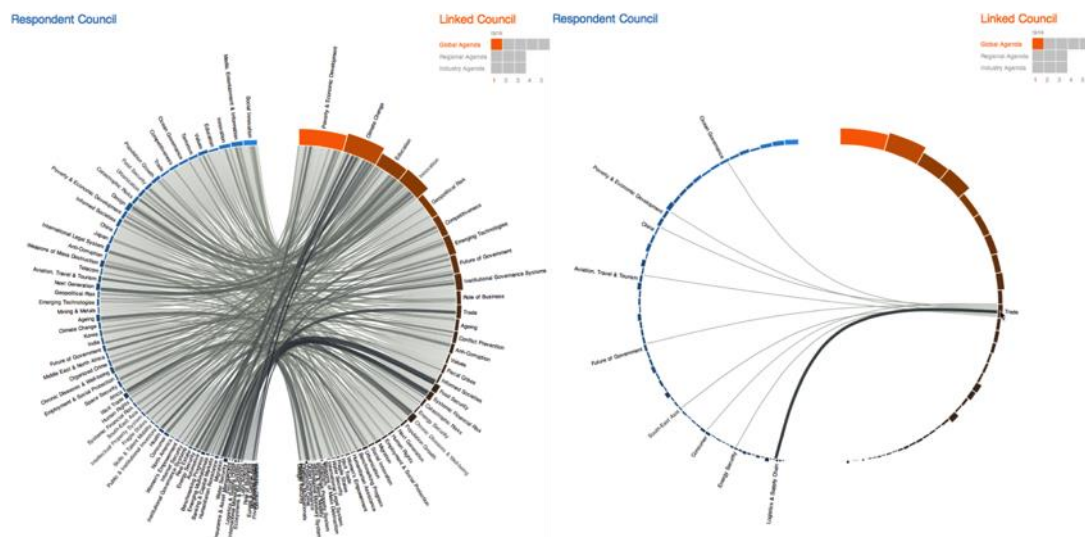


Figure 4-5 Adjusting the value of density of a VR.

4.5.3.5 Dynamism

Dynamism refers to the degree of movement of encoded information items in a VR. Dynamism ranges in value from zero (i.e., all encoded information items are static) to high (i.e., all encoded information items are in motion). Actors can adjust the value of this property to increase or decrease the value of dynamism while performing cognitive activities. VRs that exhibit movement can effectively illustrate structural, functional, and procedural relationships among encoded information items (Jones & Scaife, 2000). Additionally, movement within a VR can make spatial information and depth order salient, reduce spatial ambiguities, and help overcome perceptual and cognitive biases that can be acquired from static VRs (Kaiser & Proffitt, 1987). It is often the case that cognitive activities involve information spaces that have a temporal nature, and motion in VRs can be an effective way to communicate temporal processes. However, although dynamism can facilitate cognitive activities, information items may be encoded in a transient fashion that does not facilitate sustained visual inspection (Tversky, Morrison, & Betrancourt, 2002). In other words, when a VR has no motion it is available for inspection without temporal constraints. This gives actors time to explore a VR at their own pace, which potentially avoids perceptual and cognitive overload (Cook, 2006). Schwan and Riempp (2004) compared performance of subjects who could adjust the dynamism values of VRs to those who could not. The results showed a significant decrease in time required to master the task in those who could adjust the values to suit their contextual and cognitive needs. As actors have different needs according to different tasks that are performed during an activity, no exact value of dynamism can be considered ideal for all contexts, and mechanisms should be provided to allow actors to adjust the value of dynamism to suit their particular tasks.

4.5.3.6 Fidelity

Fidelity refers to the degree to which information items are accurately encoded in a VR. Fidelity is a multi-faceted property and can be with respect to structure, time, geometry, process, or function. Actors can adjust the value of one facet only or of multiple facets simultaneously. Fidelity ranges in value from low (i.e., very inaccurate) to high (i.e.,

completely accurate). The ideal value of fidelity for any given VR is very much context-dependent. Waller, Knapp, & Hunt (2001) suggest that tasks involving perceptual and motor training about particular information spaces benefit from high values of fidelity (see also Hunt & Waller, 1999). With tasks involving higher-level, conscious cognitive processing and the development of flexible mental models, however, a high value of fidelity is not necessarily best. In their study, Waller et al. found that differences in individual characteristics, such as gender, level of expertise, and cognitive ability, accounted for a significant variance in performance of the subjects, suggesting that even with a common task the ideal value of fidelity is actor-dependent. The ideal value of fidelity is also dependent on the tasks being performed during an activity. However, it may not always be obvious which aspects of an information space should be encoded with a high value of fidelity. For example, with the famous problem of the Seven Bridges of Königsberg, it was long thought that the geometry of the information space was important to represent with a high value of fidelity. By realizing that the geometry was irrelevant to the problem, however, Euler could represent the information space with a set of vertices and edges that were independent of the geometry of the information space, which allowed him to solve the problem. For the purpose of his problem solving activity, it was the network topology of the bridges that required a high value of fidelity. Another well-known example involves the famous London Underground map. When introduced, although the map had a low value of geometric fidelity, it encoded the topology of the subway network in a manner that facilitated pertinent tasks. It is reported that people found the map much more useful than the previous map that had a higher value of geometric fidelity, as they did not require a high value of geometric accuracy for the types of activities they were performing—namely, planning how to navigate from one location to another. Giving actors the ability to dynamically adjust fidelity values of a VR of the London Underground could potentially provide even stronger support for such planning and decision making activities. Consider the CAST, *Time Travel Tube Map* (www.tom-carden.co.uk/p5/tube_map_travel_times/applet/), shown in Figure 6 that supports planning and making decisions about travelling the London Underground. Actors are initially presented with a VR that encodes the geometry of the information space with a high value of fidelity (Figure 6 L). However, because their task is to identify

travel times in order to plan and make decisions, such geometric fidelity is not helpful. This CAST allows actors to decrease the geometric fidelity to help identify travel times between stations (Figure 6 M and R). Although the resulting VRs have a lower value of geometric fidelity, allowing the actor to adjust this value can contribute to the overall planning activity. If the actor needs to perform another task, such as identifying the precise location of a station and its proximity to a particular part of the city, she could adjust the value of geometric fidelity to make it high again.

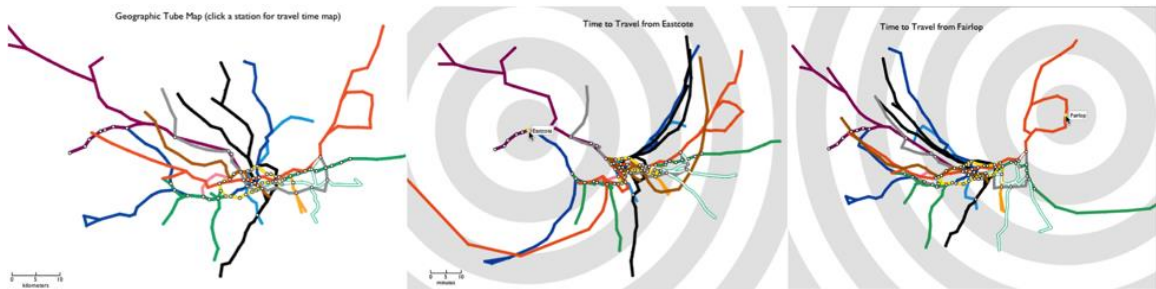


Figure 4-6 Adjusting the value of geometric fidelity of a VR.

4.5.3.7 Fragmentation

Fragmentation refers to the degree to which information items are broken up and discretized when encoded in a VR. Information items may be encoded in a whole and continuous manner; alternatively, they may be encoded in a divided and discrete manner. Fragmentation ranges in value from zero (i.e., completely whole and continuous) to high (i.e., completely divided and discrete). Developing a mental model of an information space that includes an accurate model of discreteness and continuity and whole-part relationships is important in many complex cognitive activities. In the context of mathematical thinking and problem solving, for example, research suggests that to understand mathematical concepts (e.g., proportions, fractions, ratios) it is important to deeply understand discreteness and wholeness of an information space and the relations between wholes and parts (see Lesh & Harel, 2003). Olive (2000) suggests that allowing actors to interact with VRs of such concepts to adjust their values of fragmentation can facilitate such an understanding. Dörner & Wearing (1995) note that one of the essential elements of effective problem solving, planning, and decision making in complex situations is proper whole-part analysis during actors' goal formation. As goals are

constantly revised and updated during the performance of complex cognitive activities while one explores and works with an information space, adjusting the value of fragmentation of VRs can help with whole-part analysis and the development of more sophisticated goals. Such thinking—often referred to as thinking both globally and locally—is important for reasoning, problem solving, and decision making in health professions (Higgs & Jones, 2008) and in business and management contexts (Proctor, 2010). Aside from understanding whole-part relationships, VRs with a low value of fragmentation can alleviate potential burden placed on working memory while carrying out tasks (Munyofu, Swain, Ausman, Lin, Kidwai, & Dwyer, 2007).

Figure 7 shows a CAST, *Panopticon* (www.panopticon.com), that supports analytical reasoning, decision making, and other activities concerned with financial information spaces. To perform such complex cognitive activities, an actor would likely need to develop an elaborate mental model of the information space, which would certainly involve tasks such as identifying whole-part relationships among industries and sectors, categorizing stocks according to their industries and sectors, and assessing the relative value of stocks. Figure 7 shows how the actor can adjust the value of fragmentation of the VR to show the relationships among and values of industries, and their division into supersectors and individual stocks.



Figure 4-7 Adjusting the value of fragmentation of a VR.

4.5.3.8 Interiority

Interiority refers to the degree to which information items are latent and remain hidden below the surface of a VR, but are potentially accessible and encodable. Interiority ranges in value from zero (i.e., all information items are encoded at the visually perceptible surface of a VR) to high (i.e., most information items are latent and unencoded, but can be brought to the visually perceptible surface of a VR). Actors can act upon a VR (e.g., by drilling into it) to access deeper layers of information and bring latent information items to the surface. Historically, with static representations designers have had to make sacrifices and decide on trade-offs. As a result, information items that actors require for tasks may not be encoded and actors may be forced to make extrapolations, which may place a large burden on mental space. VRs that provide options for actors to adjust their value of interiority allow latent information to be probed and investigated when needed (Jern, 1997; Spence, 2007; Stone, Fishkin, & Brier, 1994). This can help to mitigate perceptual and cognitive overload and can also help create balance between overview and detail (Yi et al., 2007). When such interactive features are included in CASTs, actors can perceive the macrostructure of the encoded information, pose questions about it, and answer them by subsequently drilling them for latent information (Eick, 2000). Huang et al. (2009) compared the effect of VRs that encoded only the information items required for a task to VRs that encoded extra items from the information space. They found that extraneous encodings had a significant negative effect on cognitive load and on task performance. Such studies suggest that actors should be given the ability to adjust the value of interiority to work with only the information that is needed for a particular task.

Figure 8 shows a CAST, *EdgeMaps* (mariandoerk.de/edgemaps/), that integrates the representation of explicit and implicit relations among items within an information space to support sense making and knowledge discovery. The VR in Figure 8 is depicting a timeline of well-known philosophers. To perform tasks such as identifying influences between philosophers and assessing the relative effect of their influences, actors can drill into the VR of each individual philosopher to bring such information to the surface and facilitate the performance of such tasks. As it would be unwieldy to encode such

information all at once, control is given to actors to adjust the value of interiority and bring such information to the surface as needed.

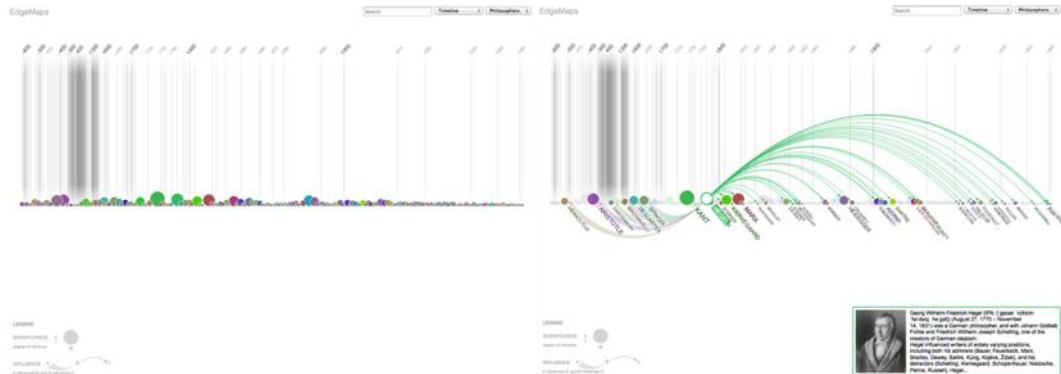


Figure 4-8 Adjusting the value of interiority of a VR.

4.5.3.9 Scope

Scope refers to the degree to which the growth and development of information items are encoded in a VR. Actors can adjust the value of this property so that a VR encodes more or less of the growth of information items in a successive and sequential manner. Many information spaces contain information items that exhibit successive stages of growth through time and/or space. Being able to understand the prevalence of certain structures within such information spaces often depends upon tasks such as identifying the temporal order in which relationships are established (Moody, McFarland, & Bender-deMoll, 2005). Doing so can facilitate activities such as forecasting research trends and the life span of scientific communities (An, Jansen, & Milios, 2001). Gradually encoding the growth or development of an information space can be particularly useful for information spaces encompassing mathematical patterns, physical structures, as well as social, computer, disease, political, scientific, and co-citation networks (see Chen, 2004; Chen & Morris, 2003; Moody et al., 2005; Toyoda & Kitsuregawa, 2005), and can facilitate the detection of patterns and the understanding of how clusters are merged and split over time (Card, Suh, Pendleton, Heer, & Bodnar, 2006; Toyoda & Kitsuregawa, 2005). As actors develop mental models of such information spaces, static VRs can lead to erroneous interpretations, whereas interactive and/or dynamic VRs that show the growth

of the information space can lead to more accurate interpretations (Moody et al., 2005). The ability to adjust the scope of VRs can play an important role in the performance of many complex cognitive activities, as the ability to analyze ideas by reasoning forward and backward and make sense of how information items are chained together is important in analytical thinking (Shrinivasan & Wijk, 2008).

Figure 9 shows a CAST, *NetLogo* (Wilensky, 1999, 2005), that supports numerous activities involving multi-agent modeling. In this particular example, an actor is making sense of the dynamics of preferential attachment networks. In this instance, the scope of the VR is being adjusted to increase it and encode more of the growth of the information space (Figure 9 from L to R). The CAST allows only for adjusting the scope value in this one direction. Often times, however, actors will want to adjust the scope in both directions. Designers should consider the nature of tasks and activities that will be performed to determine how the value of this property should be made adjustable.

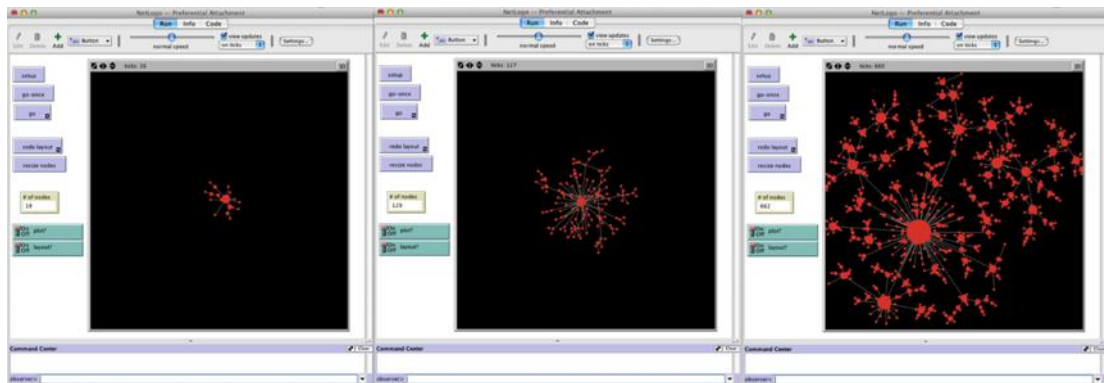


Figure 4-9 Adjusting the value of scope of a VR.

4.5.3.10 Type

Type refers to the form of a VR in which information items are encoded. Different forms of VRs, such as plots, diagrams, images, symbols, and linguistic representations, have different benefits and trade-offs for communicating information (see Larkin & Simon, 1987; Novick, 2006; Stenning & Oberlander, 1995; Suwa & Tversky, 1995). Not only do different representational forms facilitate different tasks, but also the act of translating a

representation from one type to another has been shown to facilitate the performance of complex cognitive activities (Tabachneck-Schijf & Simon, 1996). For example, when trying to solve a problem, changing the representational form of the information space can sometimes trigger apprehension of a solution (Robertson, 2001). Bodner and Domin (2000) investigated problem solving in the context of organic chemistry and concluded that “a significant difference between students who are successful in organic chemistry and those who are not is the students’ ability to switch from one representation system [type] to another” (ibid., p.27).

To think about this property systematically, taxonomies and catalogs of types of VRs and their characterizations are needed. Although some work has been done in this area, there is no widely agreed upon typology of VRs. In the context of CAST-mediated HII, most designers and evaluators likely need a catalog of types that is manageable, accounts for common visualization techniques, and also identifies their utility in supporting complex cognitive activities. To contribute to this need, Parsons and Sedig (2013a) have recently categorized common VRs into six high-level types: 1) visual encodings and marks; 2) glyphs and multidimensional icons; 3) plots and charts; 4) maps; 5) graphs, trees, and networks; and 6) enclosure diagrams. In addition, they discuss the utility of each type for performing complex cognitive activities. They also identify a number of common techniques (e.g., treemaps, radial convergence diagrams, heatmaps, parallel coordinate plots) that fall under each category. With a manageable set of types, an examination of which types best suit particular tasks and activities, and a categorization of many common visualization techniques, such work can support methodical design and evaluation of this particular property of VRs. This work is far from complete, however, and future research is needed to develop more comprehensive categorizations of VRs at different levels of granularity.

Figure 33 show a CAST, *Tulip* (<http://tulip.labri.fr>), that supports numerous activities dealing with complex networks, such as scientific, social, or biological networks. Figure 10 (L) shows a VR of the relations among authors and papers within the information visualization community. This node-link VR type encodes relationships and facilitates tasks such as identifying highly connected nodes and major pathways. Other tasks, such

as determining exact values and precise rankings, however, are not easily accomplished with such a VR. Figure 10 (R) shows the result of an actor translating or converting the node-link VR into a tabular form to facilitate such tasks.

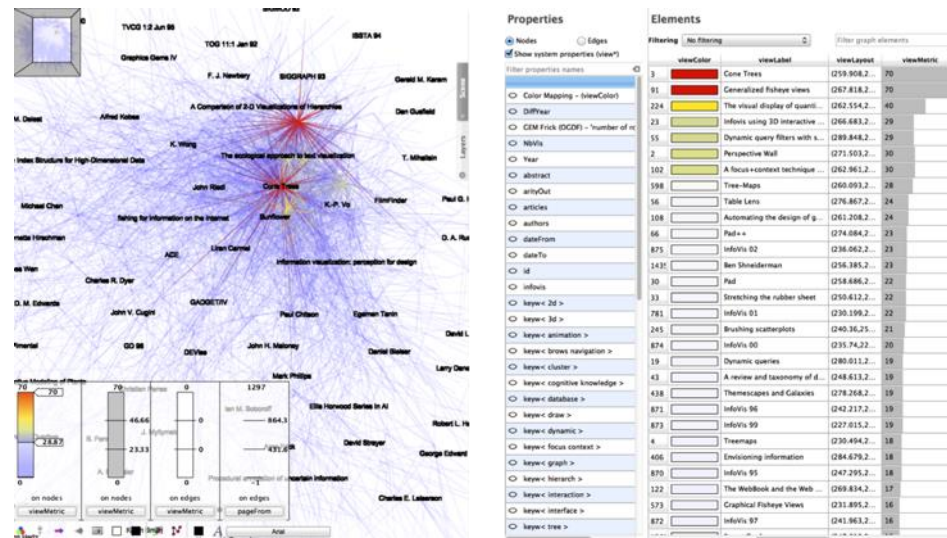


Figure 4-10 Adjusting the value of type of a VR.

4.5.4 Integrated Scenario: Epidemiological Analysis

In the previous section, CASTs from different domains that supported different complex cognitive activities were used to demonstrate the universality and general applicability of EDIFICE-PVR. In contrast, this section demonstrates how EDIFICE-PVR can be used in an integrated manner for systematic design and evaluation of a single CAST for a particular activity. This is demonstrated using a scenario in which an epidemiologist is engaged in an analytical reasoning activity regarding a disease outbreak. As the focus is on the interaction between the actor and VRs, for the sake of the scenario it is assumed that other considerations for proper design and use of CASTs are in place (e.g., data is accurate, complete, and consistent; the tool has built-in algorithmic behaviors; and so on).

To perform such an activity, the epidemiologist would need to perform other complex cognitive activities (i.e., sub-activities) such as problem solving, sense making, and forecasting. Furthermore, as described previously, such activities involve the

performance of goal-directed tasks and sub-tasks, as well as actions and low-level interface events. For example, to make sense of the current state and progression of the disease outbreak, the epidemiologist would likely need to perform tasks such as locating the origin of the disease, determining the rate and/or direction of its spread, navigating the disease network to discover pathways, and identifying individuals of importance. EDIFICE-PVR can support systematic thinking about design and evaluation of VRs from a human-centered perspective that accounts for the tasks and activities an actor will likely perform. Consider the VR shown in Figure 11 (L), which encodes the existence and location of disease occurrences and known relationships among the infected individuals (e.g., friend, coworker, or relative). In the context of performing specific tasks, such as locating the origin of the disease and determining the rate and/or direction of its spread, a designer could infer which properties of the VR would likely need to have their values adjusted to help carry out the tasks. One strategy is to go through the properties methodically as follows. In terms of appearance, actors may wish to adjust colors to facilitate certain sub-tasks (e.g., to categorize diseases according to status, to identify and mark items of interest) while reasoning about how the disease is spreading and which areas are more seriously affected. Adjusting the value of density would not likely have a significant benefit for these particular tasks, as more diffuseness would not bring the actor any closer to locating the origin of the disease or determining its spread. Adjusting the value of complexity would not help to locate the origin of the disease, as it is not a matter of adjusting the elaborateness or intricacy of the VR. Adjusting the configuration value could help with similar tasks in other contexts; however, with this VR it would be detrimental, as the geographical locations of disease occurrences must be maintained to adequately complete the tasks. Adjusting the dynamism value would not likely be beneficial—increasing the value of motion would not facilitate such tasks. In terms of fidelity, in this case a high degree of structural and geometric fidelity must be maintained, as the tasks are fundamentally linked with geospatial accuracy. In terms of fragmentation, neither increasing or decreasing its value would help, as the epidemiologist needs to see the disease occurrences in a discrete manner to identify their geographical locations and connections between them. In terms of interiority, drilling into the VR to encode latent information may potentially be of some benefit, as it can provide information such as the

date of infection. However, the most benefit would likely come from adjusting the value of the scope property of the VR. By adjusting the value of this property, the epidemiologist could increase and decrease the degree to which the growth and development of information items are encoded in the VR (see Figure 11 R). Doing so can help the epidemiologist perform other tasks, such as determining how certain areas grow and merge over time, where and when certain clusters are formed, and tasks concerned with the growth of the disease network and the connections among disease occurrences. Finally, adjusting the type value could help with these tasks, except that abandoning the map-based VR would hinder tasks in which geospatial accuracy is important.

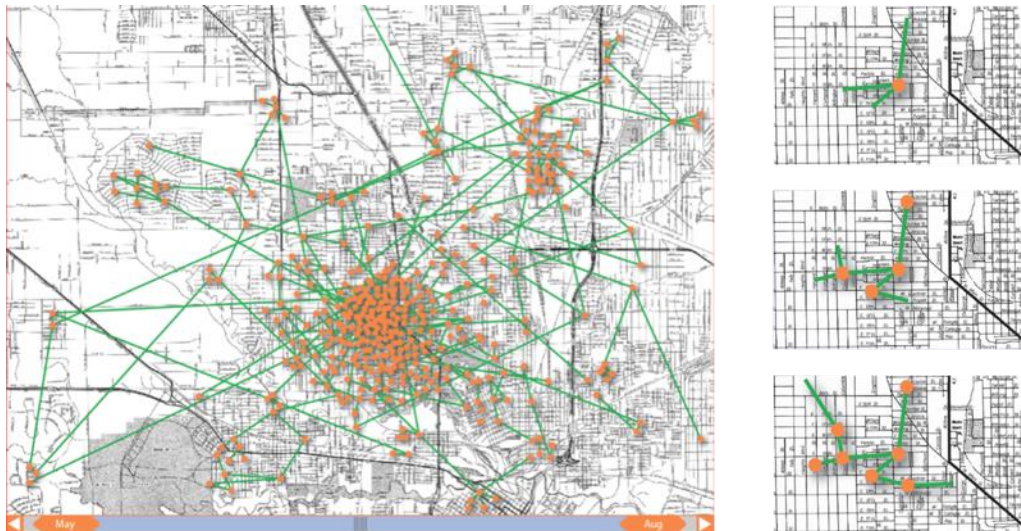


Figure 4-11 VR of disease occurrences and relationships (L). Adjusting the scope of the VR to locate the origin of the disease and determine its direction of spread (R).

As an alternative to the strategy examined above, designers and evaluators can first go through each property systematically to predict which tasks and activities would be facilitated by providing the ability to adjust its values. Such an endeavor could help to project what actions should be made available to adjust values of a VR's properties. For example, as the information space in this scenario is very large and complex, many of the information items are not encoded in the representation space and remain latent. It would be very likely that at some point during an activity, actors would need to access deeper layers of information from the information space. The epidemiologist may wish to

browse or compare the relationships between individual disease occurrences and other known disease factors that may have causal links to the disease being investigated. Therefore, providing opportunities for actors to drill into the VR to bring latent information to the surface can be helpful. Designers can then use their creativity and design expertise to determine how to implement such a feature. For instance, Figure 12 shows the result of an actor drilling into a VR to access latent information items (i.e., individual disease occurrences and their relationships to known disease factors) and bring them to the surface. The prior state of the representation space encoded disease occurrences and their locations (as orange dots), but known information about each occurrence was latent. With the newly encoded information, disease occurrences are encoded (as orange lines) and their relations to known disease factors (i.e., genetic, nutritional, lifestyle, and psychological factors) are also encoded and brought to the surface of the VR. Designers can then determine which tasks would likely be performed, and provide options for adjusting values of different properties as they deem fit.

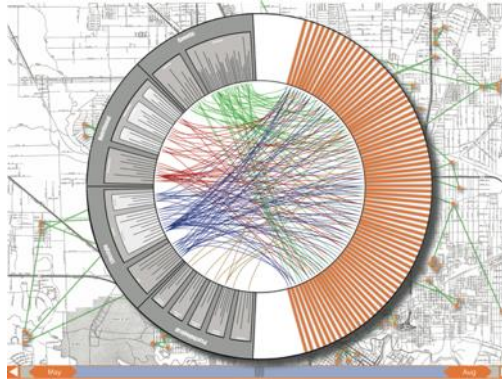


Figure 4-12 Adjusting interiority value to encode latent information.

Although analyzing a CAST according to individual properties is useful, as mentioned previously, the ultimate utility of EDIFICE-PVR rests on a balance between analysis and synthesis of properties with respect to their influence on the performance of complex cognitive activities. This necessitates thinking about adjusting the values of a VR's properties in the context of the overall structure and process of HII in complex cognitive activities (see Figures 1 and 2). To do so, one must think about the hierarchical nature of complex cognitive activities, and how such activities emerge over time through the

performance of multiple actions, tasks, and sub-activities. Figure 13 demonstrates how continually adjusting values of properties from the CAST above can be conceptualized within the context of an action, reaction, perception cycle that occurs over time while performing a complex cognitive activity. Figure 13 depicts the process of an actor decreasing the density of a VR to identify connections to one particular disease factor (e.g., obesity), perceiving the reaction, acting upon the new state of the VR to then increase the value of density and simultaneously decrease the value of fragmentation, perceive the reaction, and so on. As this process takes place, the actor performs numerous mental operations (e.g. induction, deduction, memory retrieval) as she attempts to develop an accurate mental model of the information space in order to plan and make decisions. Figure 14 suggests that designers and evaluators can ask themselves, with many different VRs and at different states during the performance of a complex cognitive activity, whether or not it is useful and possible for actors to adjust the values of certain properties to facilitate tasks.

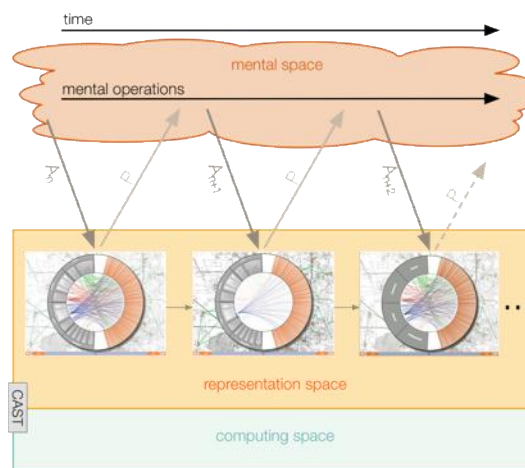


Figure 4-13 Adjusting values of properties during the performance of an analytical reasoning activity.

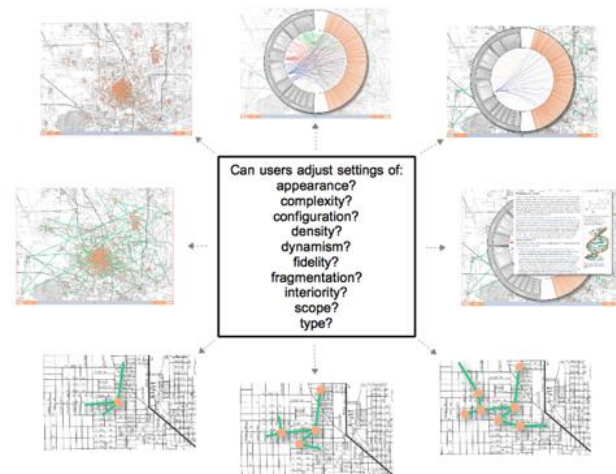


Figure 4-14 Considering the properties of EDIFICE-PVR in an integrated manner for design and evaluation.

4.6 Discussion

EDIFICE-PVR provides a high-level support structure for thinking about the quality of human-information interaction during the performance of complex cognitive activities. However, as this a young area of research, there is further work to be done to more fully understand the role of VRs in such activities. By laying some groundwork in this area, EDIFICE-PVR can contextualize and orient future research. Indeed, conceptual frameworks, such as EDIFICE-PVR, fundamentally influence research processes by determining what to look for, how phenomena are conceptualized, what their presumed relationships are, and how to make sense of observations and data (Becker, 1993). For instance, in the context of conducting empirical research, “the conceptual framework is both a guide and a ballast...” (Ravitch & Riggan, 2011, p. xiii). Researchers have suggested that such frameworks are needed for empirical studies. While discussing the state of research in the information visualization community, for example, Chen has noted that “the lack of theories becomes particularly prominent...when designing empirical and evaluative studies” (2010, p. 396). EDIFICE-PVR can provide a theoretical framework that facilitates the design of empirical studies, and determines what to look for and how results should be interpreted.

Not only does EDIFICE-PVR have utility for researchers, but it can also serve as a useful guide for designers and evaluators. One of the major hurdles confronting the effective design and evaluation of CASTs is a lack of comprehensive frameworks (see Chen, 2010; Sedig et al., 2013). While discussing the role and importance of theory in HCI, Kaptelinin and Nardi (2012) observe that both user studies and the design and evaluation of tools are rarely framed within a theoretical framework. Without such frameworks, design and evaluation of CASTs must be largely ad hoc and based on personal intuition. Bederson and Shneiderman (2003) note that theories can help not only to describe and explain, but also to predict performance, prescribe guidelines and best practices, and generate novel ideas to improve research and practice. Such frameworks can help designers and evaluators also by simply “stabilizing terminology and helping designers carry on meaningful discussions.” (Bederson & Shneiderman, 2003, p. 350). Currently, there is no agreed upon terminology that designers can use to discuss VRs in a general manner.

EDIFICE-PVR provides a set of terms and concepts that can be used consistently by designers in numerous different contexts.

In terms of evaluation, researchers have previously mentioned the need to move beyond traditional usability metrics and evaluation techniques to accurately analyze the interactivity of CASTs (e.g., Scholtz, 2006). Part of the problem with traditional approaches to evaluation is an overemphasis on quantification, which can place too much focus on quick and easy measurements, but may not give much indication as to the overall utility of a tool in supporting complex activities (Meyer et al., 2010; Albers, 2011). The EDIFICE-PVR framework provides a flexible and high-level support structure for thinking about the quality of human-information discourse, which is based on a manageable set of criteria (i.e., 10 properties). The EDIFICE-PVR framework can help evaluators think deeply and systematically about how the properties of VRs influence the performance of cognitive activities. Although outside the scope of this paper, future work may build on EDIFICE-PVR to construct evaluation heuristics and guidelines similar to others (e.g., Nielsen's heuristics) that have been devised from earlier theoretical and empirical research.

As a final note on the utility of EDIFICE-PVR for design and evaluation, it must be emphasized that EDIFICE-PVR is not simply a list of properties. Rather, it provides a holistic framework that enables systematic conceptualization of the performance of complex cognitive activities—especially when combined with other components of the EDIFICE framework. Such research is much needed, and is not the same as isolated design principles or guidelines. As Fidel has appositely noted, what is required for the design of tools that support HII is research that is “conducive to the theoretical developments and relevant to the design of systems that support information interaction”, and that “realizing this potential also necessitates a *conceptual basis that is continuous—rather than a fragmented puzzle of conceptual constructs*—and research strands that touch one another—rather than strands in isolation.” (2012, p. 255, italics added). In other words, the design of CASTs cannot be optimally effective if based on fragmented—or nonexistent—underlying theoretical models and/or frameworks.

4.6.1 Comparison to Existing Work

As mentioned previously, much of the existing research has been concerned with static VRs and/or with only low-level perceptual and cognitive effects of VRs, and not explicitly with implications for complex cognitive activities (see related work section above). For instance, work by researchers such as Bertin (1967), Tukey (1977), Cleveland and McGill (1984), Mackinlay (1986), MacEachren (1995), Nowell (1997), and Ware (2008, 2012) has provided us with valuable insights into how VRs affect simple cognition—i.e., low-level perceptual and cognitive processes. Such research is certainly important and is necessary to consider for design and evaluation of any CAST. However, such work does not necessarily describe or explain the effects of VRs on high-level cognitive processes or even situate the low-level effects within the context of more complex activities, and thus cannot provide much guidance for design and evaluation of CASTs for complex cognitive activities. Although many of the references provided in the section above that presents the properties are concerned with only low-level effects, unlike much of the aforementioned work, such is not the extent of concern in this article. Rather, we contend that such effects must be contextualized within larger models and frameworks pertaining to HII in complex cognitive activities. Consequently, it is the emergent effects that result from the combination of such low-level effects that must be analyzed and studied in the context of human-information discourse during the performance of goal-directed tasks and overall complex cognitive activities.

One research endeavor worth comparing with EDIFICE-PVR is the Cognitive Dimensions of Notations framework (Green & Petre, 1996; Blackwell et al., 2001), which has examined some cognitive effects of notation systems and information artifacts. The framework is intended to help designers make choices where there are usability tradeoffs (Blackwell et al., 2001), and has been used for usability analysis for visual programming environments, calculators, spreadsheets, calendars, and other information artifacts (see Blackwell et al., 2001; Green & Blackwell, 1998; Green & Petre, 1996). While this framework is useful in certain contexts, it was not intended for design or evaluation of interactive VRs in the context of supporting complex cognitive activities. It does not include any model of human-information discourse, of the emergent nature of

cognitive activities, of the complex structure and functioning of CASTs, or of the dynamic coupling that is formed between internal and external representations during the performance of cognitive activities. Certain of the cognitive dimensions identified in the framework (e.g., *premature-commitment*, *progressive evaluation*, *provisionality*, *consistency*, *secondary notation*, *error-proneness*, and *viscosity*) obviously deal with general usability rather than with complex cognitive activities. Other dimensions (e.g., *visibility*, *abstraction*, *closeness of mapping*, *diffuseness*, and *hard mental operations*) that may seem, on initial observation, to overlap the properties proposed by EDIFICE-PVR, are seen to be distinct after a quick examination. For instance, *diffuseness* may seem similar to our identified property of *density*. *Diffuseness* is characterized as “verbosity of language” (Blackwell et al., 2001, p. 328) and “how much or little can be said in a few word or symbols.” (Blackwell, Green, & Nunn, 2000, p. 328). The property of *density* proposed by EDIFICE-PVR refers to how compactly a VR encodes information—this applies to interactive animations, plots, treemaps, and any other type of VR. As such, its concern is different from verbosity. A similar investigation of other dimensions will reveal the fundamental difference between the Cognitive Dimensions of Notations framework and EDIFICE-PVR. Furthermore, an understanding of how and why the values of properties should be adjusted, and how such interaction fits into an overall process of human-information discourse and cognitive processing, is not under the purview of the Cognitive Dimensions of Notations framework.

Although not constituting comprehensive models or frameworks, it is useful to briefly comment on two oft-cited mantras, the first being the Information Seeking Mantra: “overview first, zoom and filter, details-on-demand” (Shneiderman, 1996), and the second being the Visual Analytics Mantra: “analyze first, show the important, zoom, filter and analyze further, details on demand” (Keim, Mansmann, Schneidewind, & Ziegler, 2006). While these provide useful high-level guidance, and may be sufficient in some contexts, they are not entirely sufficient to guide design and evaluation of tools that provide all kinds of interactive possibilities and facilitate complex information-intensive tasks during the performance of complex cognitive activities (see Sedig & Parsons, 2013). Additionally, while they indirectly touch upon some of the properties identified in EDIFICE-PVR (e.g., complexity, density) they do not explicitly identify or characterize

them, nor describe their cognitive and perceptual effects. Other properties (e.g., appearance, configuration, dynamism, fidelity, type), which have been shown above to have implications for the performance of complex cognitive activities, are not identified directly or indirectly by the mantras.

Researchers have recognized the lack of systematic and comprehensive research on VRs and their cognitive effects in general, and have suggested that much work is still required. For instance, in the context of geovisualization and visual analytics, Fabrikant has recently stated that “we still know little about the effectiveness of graphic displays for space-time problem solving and behavior, exploratory data analysis, knowledge exploration, learning, and decision-making” (2011, p. 2009). Green and Fisher (2011) have also recently observed that “there is still a lack of precedent on how to conduct research into visually enabled reasoning. It is not at all clear how one might evaluate interfaces with respect to their ability to scaffold higher-order cognitive tasks.” In other words, we still know little about designing interactive VRs that effectively support complex cognitive activities. Research has hitherto provided us with a good idea of how features of VRs such as color and texture affect perceptual tasks and low-level cognitive processes; how humans perform simple, structured tasks; and how the usability of artifacts is affected by certain aspects of their design. What is not as clear, however, is how humans process and work with interactive VRs to solve complex problems, make sense of complex information spaces, and to perform other complex activities, and how the interactive features of VRs can and should be designed to best support such activities in the context of an overall human-information discourse. The EDIFICE-PVR framework attempts to provide more clarity to this matter by enabling a systematic approach to research, design, and evaluation of CASTs.

4.7 Summary and Future Work

This paper is concerned with interactive computational tools that mediate human-information interaction to support complex cognitive activities. Such tools have been referred to in this paper as cognitive activity support tools (CASTs). One of the important

components of CASTs is their information interface, which is composed of visual representations (VRs). Actors perceive and work with VRs to facilitate their cognitive processes while engaged in sense making, problem solving, knowledge discovery, and other complex cognitive activities. In order to engage in systematic research, design, and/or evaluation of CASTs, and to facilitate consistent and accurate communication among researchers and designers, the essential properties of interactive VRs that influence the performance of complex cognitive activities must be identified and explicated. This paper has presented a framework that identifies and characterizes ten such properties, and discusses how their values influence cognitive and perceptual processes during the performance of complex cognitive activities. These properties are: appearance, complexity, configuration, density, dynamism, fidelity, fragmentation, interiority, scope, and type. Not only are these properties essential (i.e., present in every instance of a VR); they are also relational (i.e., depend on both actors and CASTs). The ideal values of these properties are dependent upon the characteristics of actors—their strategies, goals, needs, preferences, and prior knowledge and expertise—as well as the characteristics of CASTs and the context in which complex cognitive activities take place. The framework presented here provides a support structure to facilitate systematic thinking about how actors can and should be provided with options to adjust the values of these properties to provide better support for the performance of complex cognitive activities. This paper is part of a larger research plan aimed at establishing a comprehensive framework for human-information interaction in complex cognitive activities, named EDIFICE (Epistemology and Design of human-InFormation Interaction in complex Cognitive activitiEs), and has been referred to as EDIFICE-PVR, where PVR stands for Properties of Visual Representations.

EDIFICE-PVR provides opportunities for much future research. As discussed previously, such a high-level framework can encourage further theoretical research that more fully describes, explains, and predicts the performance of complex cognitive activities through CAST-mediated HII. For instance, the relationship among actions, tasks, and activities in the emergence of an overall complex cognitive activity requires further explication. In addition, the role of adjusting the values of properties in achieving goal-directed tasks through the performance of low-level actions is not completely understood. On another

note, we still have a limited understanding of precisely how, when, and in what fashion adjustability options should be made available for particular activities, actors, and contexts.

EDIFICE-PVR can also stimulate empirical research, and can function as a lens through which studies are designed and interpreted. Although there is evidence to suggest how the values of properties affect some activities (e.g., problem solving), others are not as well understood (e.g., analytical reasoning). In addition, some properties have been more closely investigated than others, and by identifying these 10 essential properties of interactive VRs, EDIFICE-PVR can hopefully encourage research that results in a more balanced understanding. Moreover, many of the studies cited here were not conducted in the context of today's highly interactive computational tools. Thus, while their findings are relevant and applicable to the use of CASTs, further studies must be done to develop a better understanding of the role of these properties and their values in the context of performing complex cognitive activities with highly interactive tools. Furthermore, studies must be done to determine how the values of properties affect cognitive activities with particular types and characteristics of data and information, particular categories and techniques of VRs, particular actions and tasks, and actors with particular ages, skills, and levels of expertise. A future extension of such aforementioned research is the development of comprehensive *prescriptive* frameworks and design principles and guidelines that enable a systematic approach to the design of CASTs.

4.8 Acknowledgments

This research has been financially supported by the Natural Sciences and Engineering Research Council of Canada. We would like to thank the anonymous reviewers for their constructive comments which have helped this paper reach its current form.

4.9 References

- Afzal S., Maciejewski R., & Ebert D. S. (2011). Visual analytics decision support environment for epidemic modeling and response evaluation. In Proceedings of the IEEE Conference on Visual Analytics Science and Technology (VAST), 191–200.
- Ahlberg, C. (1996). Spotfire: an information exploration environment. *SIGMOD Record*, 25, 25-29.
- Ahlberg, C. & Shneiderman, B. (1994). Visual information seeking using the filmfinder. In Conference Companion on Human Factors in Computing Systems, 433-434.
- Aigner, W. (2011). Understanding the role and value of interaction: First steps. In Proceedings of the International Workshop on Visual Analytics (EuroVA 2011) (pp. 17–20).
- Ainsworth, S.E., & Peevers, G.J. (2003). The Interaction between informational and computational properties of external representations on problem-solving and learning. In R. Altmann & D. Kirsh (Eds.), Proceedings of 25th Annual Conference of the Cognitive Science Society.
- Ainsworth, S. & van Labeke, N. (2002). Using a multi-representational design framework to develop and evaluate a dynamic simulation environment. In *International Workshop on Dynamic Visualizations and Learning*, Tubingen, Germany.
- Albers, M.J. (2011). Human-information interactions with complex software. In A. Marcus (Ed.) Design, User Experience, and Usability, Pt II, HCII 2011, LNCS 6770, pp. 245–254, Springer-Verlag Berlin.
- An, Y., Janssen, J., and Milios, E. (2001). Characterizing and mining the citation graph of the computer science literature, *Knowledge and Information Systems*, 6(6), pp. 664-678.
- Andrews, K., Gütl, C., Moser, J., Sabol, V., & Lackner, W. (2001). Search result visualization with xFIND. In Proceedings of the 2nd International Workshop on User Interfaces to Data Intensive Systems (UIDIS '01), 9pp.
- Andrews, K., Kienreich, W., Sabol, V., Becker, J., Droschl, G., Kappe, F., Granitzer, M., Auer, P. & Tochtermann, K. (2002). The InfoSky visual explorer: exploiting hierarchical structure and document similarities. *Information Visualization*, 1(3/4), 166-181.
- Anselin, L., Syabri, I., & Kho, Y. (2004). GeoDa: An introduction to spatial data analysis. *Geographical Analysis*, 38(1), 5-22.
- Arias-Hernandez, R., Green, T., Fisher, B. (2012). From cognitive amplifiers to cognitive prostheses: Understandings of the material basis of cognition in visual analytics. *Interdisciplinary Science Reviews* 37(1), 4-18.
- Avouris, N., Margaritis, M. & Komis, C. (2003). Real-time collaborative problem solving: A study on alternative coordination mechanisms. In Proceedings of the

- 3rd IEEE International Conference on Advanced Learning Technologies (ICALT'03), 86-90.
- Baddeley, A.D. (2007). *Working Memory, Thought, and Action*. NY: Oxford University Press.
- Baker, J., Jones, D., & Burkman, J. (2009). Using visual representations of data to enhance sensemaking in data exploration tasks. *Journal of the Association for Information Systems*, 10(7), 533-559.
- Bastian M., Heymann S., & Jacomy M. (2009). Gephi: an open source software for exploring and manipulating networks. *International AAAI Conference on Weblogs and Social Media*.
- Becker, H. S. (1993). Theory: the necessary evil. In D. J. Flinders and G. E. Mills (Eds.), *Theory and concepts in qualitative research: Perspectives from the field*, pp. 218-229. NY: Teachers College Press.
- Bederson, B. B. and Shneiderman, B. (2003, Eds.). Theories for understanding information visualization. In *The Craft of Information Visualization: Readings and Reflections*, pp. 349–351. San Francisco: Morgan Kaufmann.
- Bertin, J. (1967). *Sémiologie Graphique. Les diagrammes, les réseaux, les cartes*. With Marc Barbut [et al.]. Paris: Gauthier-Villars. (Translation 1983. *Semiology of Graphics* by William J. Berg.)
- Blackwell, A.F., Britton, C., Cox, A., Green, T.R.G., Gurr, C., Kadoda, G., Kutar, M.S., Loomes, M., Nehaniv, C.L., Petre, M., Roast, C., Roes, C., Wong, A., & Young, R.M. (2001). Cognitive Dimensions of Notations: Design Tools for Cognitive Technology. In M. Beynon, C.L. Nehaniv, and K. Dautenhahn (Eds.) *Cognitive Technology 2001 (LNAI 2117)*. Springer-Verlag, pp. 325-341
- Blackwell, A.F. & Green, T. (2003). Notational systems—The cognitive dimensions of notations framework. In J.M. Carroll (Ed.), *HCI models, theories, and frameworks: Toward a multidisciplinary science* (pp. 103-134). San Francisco: Morgan Kauffman.
- Blackwell, A.F., Green, R., & Nunn, D.J. (2000). Cognitive dimensions and musical notation systems. *ICMC 2000, Berlin: Workshop on Notation and Music Information Retrieval in the Computer Age*.
- Bodner G. M. & Domin D. S. (2000). Mental Models: The Role of Representations in Problem Solving in Chemistry, *University Chemistry Education*, 4, pp. 24-30.
- Brey (2005). The epistemology and ontology of human-computer interaction. *Minds and Machines*, 15, 383-398.
- Brodbeck, D. & Girardin, L. (2003). Design Study: Using multiple coordinated views to analyze geo-referenced high-dimensional datasets. In *Proceedings of International Conference on Coordinated & Multiple Views in Exploratory Visualization (CMV2003)*, 8pp.

- Buchel, O. & K. Sedig (2011). Using map-based visual interfaces to facilitate knowledge discovery in digital libraries. In *Proceedings of the American Society for Information Science and Technology*, (48)1, 1-5.
- Card, S., Suh, B., Pendleton, B. A., Heer, J., and Bodnar, J. W. (2006). Time Tree: Exploring time changing hierarchies, *IEEE Symposium On Visual Analytics Science And Technology*, pp. 3-10.
- Carey, M., Heesch, D., & Rger, S. (2003). Info Navigator: A visualization tool for document searching and browsing. In *Proceedings of the 9th International Conference on Distributed Multimedia Systems (DMS)*, 24-36.
- Chen, C. (2004). Searching for intellectual turning points: Progressive knowledge domain visualization, in *Proceedings of the National Academy of Sciences*, 101(1), pp. 5303-5310.
- Chen, C. (2010). Information visualization. *Wiley Interdisciplinary Reviews: Computational Statistics*, 2(4), 387-403.
- Chen, C., and Morris, S. (2003). Visualizing evolving networks: Minimum spanning trees versus Pathfinder networks, in *Proceedings of IEEE Symposium on Information Vizualization*, pp. 67-74.
- Cheng, P. C-H., Lowe, R. K., & Scaife, M. (2001). Cognitive science approaches to understanding diagrammatic representations. *Artificial Intelligence Reviews*, 15, 79-94.
- Clark, A. (1998). Time and mind. *Journal of Philosophy*, 95(7), 354-376.
- Clark, A. (2008). *Supersizing the mind: Embodiment, action, and cognitive extension*. Oxford: Oxford University Press.
- Cleveland, W. S. & McGill, R. (1984). Graphical perception: Theory, experimentation, and application to the development of graphical methods. *Journal of the American Statistical Association*, 79(387), 531-554.
- Cole, M. & Derry, J. (2005). We have met technology and it is us. In R. J. Sternberg & D. D. Preiss (Eds.), *Intelligence and Technology: The impact of tools on the nature and development of human abilities*, 210–227. Mahwah, NJ: Lawrence Erlbaum.
- Collins, C., Carpendale, S., Penn, G. (2009). DocuBurst: Visualizing document content using language structure. In *Proceedings of Eurographics/IEEE- VGTC Symposium on Visualization (EuroVis '09)*, 28(3), 1039-1046.
- Cook, M. P. (2006). Visual representations in science education: The influence of prior knowledge and cognitive load theory on instructional design principles. *Science Education*, 90(6), 1073–1091.
- Cruz-Lemus, J. A., Maes, A., Genero, M., Poels, G., & Piattini, M. (2010). The impact of structural complexity on the understandability of UML statechart diagrams. *Information Sciences*, 180(11), 2209-2220.

- Cutrell, E., Robbins, D., Dumais, S., & Sarin, R. (2006). Fast, flexible filtering with Phlat. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 261-270.
- Dearden, A.M. and Finlay, J. (2006). Pattern languages in HCI: A critical review. *Human Computer Interaction*, 21(1), 49-102.
- Demetriadis, S., & Cadoz, C. (2005). A conceptual framework for the integrative design of adaptable representations for learning. In A. Méndez-Vilas, B. González-Pereira, J. Mesa González, J. A. Mesa González (Eds.), *Recent research developments in learning technologies* (pp. 1250-1255). Badajoz, Spain: Formatex.
- Dörk, M., Carpendale, S., & Williamson, C. (2011). EdgeMaps: Visualizing explicit and implicit relations. In *Proceedings of VDA 2011: Conference on Visualization and Data Analysis, IS&T/SPIE*, 12 pp.
- Dörk, M., Williamson, C., & Carpendale, S. (2009). Towards visual web search: Interactive Query formulation and search result visualization. In *WSSP 2009: WWW Workshop on Web Search Result Summarization and Presentation*, 4 pp.
- Dörner, D. & Wearing, A.J. (1995). Complex problem solving: Toward a (computersimulated) theory. In P.A. Frensch & J. Funke (Eds.), *Complex Problem Solving: The European Perspective*. Hillsdale, NJ: Lawrence Erlbaum.
- Dumais, S., Cutrell, E., Cadiz, J. J., Jnacke, G., Sarin, R., & Robbins, D. C. (2003). Stuff I've Seen: A system for personal information retrieval and re-use. In *Proceedings of ACM Special Interest Group on Information Retrieval (SIGIR '03)*, 8 pp.
- Eccles, R., Kapler, T. K., Harper, R., & Wright, W. (2008). Stories in GeoTime. *Information Visualization*, 7(3), 3-17.
- Eick, S. G. (2000). Visual discovery and analysis. *IEEE transactions on visualization and computer graphics*, 6(1), 44-58.
- Eick, S. G., Steffen, J. L., & Sumner, E. E. (1992). Seesoft—A tool for visualizing line oriented software statistics. *IEEE Transactions on Software Engineering*, 18(11), 957-968.
- Elsweiler, D., Ruthven, I., & Jones, W. (2005). Dealing with fragmented recollection of context in information management. In *Proceedings of the 5th International and Interdisciplinary conference on Modeling and Using Context (CONTEXT-05)*.
- Elsweiler, D., Ruthven, I., & Ma, L. (2006). Considering human memory in PIM. In *ACM SIGIR 2006 Workshop on Personal Information Management*, 10-11.
- Fabrikant, S.I. (2011). Persistent problem in geographic visualization: Evidence of geovis(ual analytics) utility and usefulness. In *ICA Geovis Commission ICC2011 Workshop*, Paris, France.
- Fast, K. & Sedig, K. (2005). The INVENT framework: Examining the role of information visualization in the reconceptualization of digital libraries. *Journal of Digital Information*, 6(3).

- Fast, K. & Sedig, K. (2011). Interaction and the epistemic potential of digital libraries. *International Journal on Digital Libraries*, 11(3), 169-207.
- Fidel, R. (2012). *Human-Information Interaction: An Ecological Approach to Information Behavior*. Cambridge, MA: MIT Press.
- Ford D. A., Kaufman J. H., & Eiron, I. (2006). An extensible spatial and temporal epidemiological modelling system. *International Journal of Health Geographics*, 5(1).
- Fox, E. A., Hix, D., Nowell, L. T., Brueni, D. J. Wake, W. C. Heath, L. S. & Rao, D. (1993). Users, user interfaces, and objects: Envision, a digital library. *Journal of the American Society for Information Science*, 44, 480-491.
- Funke, J. (2010). Complex problem solving: A case for complex cognition? *Cognitive Processing*, 11, 133-42.
- Gemmell, J., Bell, F., Lueder, R., Drucker, S., & Wong, C. (2002). MyLifeBits: Fulfilling the Memex vision. In *Proceedings of the 10th ACM International Conference on Multimedia*, 235-238.
- Goodall, J. R. (2011). An evaluation of visual and textual network analysis tools. *Information Visualization*, 10(2), 145-157.
- Green, T. M. & Fisher, B. (2011). The personal equation of complex individual cognition during visual interface interaction. In A. Ebert, A. Dix, N. Gershon, & M. Pohl (Eds.), *Human Aspects of Visualization*, LNCS 6431, 38- 57.
- Green, T. R. G., & Blackwell, A. (1998). Cognitive Dimensions of information artefacts: A tutorial. Presented at the BCS HCI Conference '98.
- Green, T. R. G., & Petre, M. (1996). Usability analysis of visual programming environments: A 'cognitive dimensions' framework. *Journal of Visual Languages and Computing*, 7, 131-174.
- Gotz, D., When, Z., Lu, J., Kissa, P., Cao, N., Qian, W. H., Liu, S. X., and Zhou, M. X. (2010) HARVEST: An intelligent visual analytic tool for the masses. In *Proceedings of ACM IUI 2010 International Workshop on Intelligent Visual Interfaces for Text Analysis*, 4 pp.
- Gove, R., Dunne, C., Shneiderman, B., Klavans, J., & Dorr, B. (2011). Evaluating visual and statistical exploration of scientific literature networks. *IEEE Symposium on Visual Languages and Human-Centric Computing*, 217-224.
- Guarino, N. (1995). Formal ontology, conceptual analysis and knowledge representation. *International Journal of Human-Computer Studies*, 43, 625-640.
- Hearst, M. A. & Karadi, C. (1997). Cat-a-Cone: An interactive interface for specifying searching and viewing retrieval results sing a large category hierarchy. In *Proceedings of the 20th Annual International ACM/SIGIR Conference*, 246-255.
- Heer, J. & Boyd, D. (2005). Vizster: Visualizing online social networks. In *IEEE Symposium on Information Visualization (InfoVis '05)*, 33-40.

- Hemmje, M., Kunkel, C., & Willett, A. (1994). LyberWorld—A visualization user interface supporting full text retrieval. In Proceedings of the 17th Annual International ACM/SIGIR Conference on Research and Development in Information Retrieval, 249-259.
- Hert, C.A., Denn, S.O., Gillman, D.W., Oh, J.S., Pattuelli, M.C., Hernández, N. (2007). Investigating and Modeling Metadata Use to Support Information Architecture Development in the Statistical Knowledge Network. *Journal of the American Society for Information Science and Technology*, 58(9), 1267-1284.
- Higgs, J. & Jones, M.A. (2008). Clinical decision making and multiple problem space. In J. Higgs, M.A. Jones, S. Loftus, & N. Christensen (Eds.), *Clinical Reasoning in the Health Professions* (3rd Ed.). NY: Elsevier.
- Hoc, J-M. (2005). Cooperation between human cognition and technology in dynamic situations. In R. J. Sternberg & D. D. Preiss (Eds.), *Intelligence and Technology: The impact of tools on the nature and development of human abilities*. Mahwah, NJ: Lawrence Erlbaum.
- Hoerber, O., & Yang, X. D. (2006). The visual exploration of web search results using HotMap. In Proceedings of the 10th International Conference on Information Visualization (IV 2006), 157-165.
- Hollan, J., Hutchins, E., & Kirsh, D. (2000). Distributed cognition: toward a new foundation for human-computer interaction research. In *ACM Transactions on Computer-Human Interaction (TOCHI)*, 7(2), 174-196.
- Hu, Z., Hung, J. H., Wang, Y., Chang, Y. C., Huang, C. L., Huyck, M., & DeLisi, C. (2009). VisANT 3.5: Multiscale network visualization, analysis and inference based on the gene ontology. *Nucleic Acids Res* (37), W115-W121.
- Huang, W., Eades, P., & Hong, S.-K. (2009). Measuring effectiveness of graph visualizations: A cognitive load perspective. *Information Visualization*, 8(3) 139-152.
- Hunt, E. & Waller, D. (1999). Orientation and wayfinding: A review (ONR Technical Report N00014-96-0380). Arlington, VA: Office of Naval Research.
- Jern, M. (1997). Information drill-down using web tools. In Proceedings of visualization in scientific computing (pp. 118-125).
- Jones, S., & Scaife, M. (2000). Animated diagrams: An investigation into the cognitive effects of using animation to illustrate dynamic processes. In M. Anderson & P. Cheng (Eds.), *Theory & applications of diagrams*, LNAI 1889 (pp. 231-244). Berlin: Springer-Verlag.
- Jonker, D., Wright, W., Schroh, D., Proulx, P., & Cort, B. (2005). Information triage with TRIST. Presented at the 2005 Intelligence Analysis Conference, Washington, DC, 6 pp.
- Kaiser, M., & Proffitt, D. (1987) Human-display interactions: Context-specific biases. NASA Technical Memorandum 89430.

- Kang, H., Plaisant, C., & Oard, D. (2010). Making sense of archived e-mail: Exploring the Enron collection with NetLens. *Journal of the American Society for Information Science and Technology*, 61(4), 723-744.
- Kaptelinin, V. & Nardi, B. (2012). *Activity Theory in HCI*. Bonita Springs, FL: Morgan & Claypool.
- Keim, D.A., Kohlhammer, J, Ellis, G., & Mansmann, F. (2010). Mastering the information age: Solving problems with visual analytics. Goslar, Germany: Eurographics.
- Keim, D.A. Mansmann, F., Schneidewind, J., & Ziegler, H. (2006). Challenges in visual data analysis. In *Proceedings of the Tenth International Conference on Information Visualization (IV 2006)*, 9-16.
- Kirsh, D. (1995a). The intelligent use of space, *Artificial Intelligence*, 73, pp. 31-68.
- Kirsh, D. (1995b). Complementary Strategies: Why we use our hands when we think. In *Proceedings of the Seventeenth Annual Conference of the Cognitive Science Society*.
- Kirsh, D. (1997). Interactivity and multimedia interfaces. *Instructional Science*, 25(2), 79-96.
- Kirsh, D. (2005). Metacognition, distributed cognition and visual design. *Cognition, Education, and Communication Technology*, 1-22.
- Kirsh, D. (2010). Thinking with external representations. *AI & Society*, 25, 441-454.
- Klein, G., Moon, B., & Hoffman, R.R. (2006). Making sense of sensemaking 2: A macrocognitive model. *IEEE Intelligent Systems*, 21(5), 88-92.
- Knauff, M. & Wolf, A.G. (2010). Complex cognition: The science of human reasoning, problem-solving, and decision-making. *Cognitive Processing*, 11, 99-102.
- Kulik, O., Kosara, R., Urquiza, J., & Wassink, I. (2007). Human-centered aspects. In A. Kerren, A. Ebert, & J. Meyer (Eds.), *Human-Centered Visualization Environments*. Berlin: Springer.
- Kumar, N., & Benbasat, I. (2004). The effect of relationship encoding, task type, and complexity on information representation: an empirical evaluation of 2D and 3D line graphs. *MIS Quarterly* 28(2), 255-281.
- Larkin, J. H. & Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science*, 11, 65-99.
- Lesh, R. & Harel, G. (2003). Problem solving, modeling, and local conceptual development. *Mathematical Thinking and Learning*, 5(2/3), 157-189.
- Liang, H.-N., Parsons, P., Wu, H.-C., & Sedig (2010). An exploratory study of interactivity in visualization tools: 'Flow' of interaction. *Journal of Interactive Learning Research*, 21(1), 5-45.
- Liang, H-N. & Sedig, K. (2010a). Can interactive visualization tools engage and support pre-university students in exploring non-trivial mathematical concepts? *Computers & Education*, 54(4), 972-991.

- Liang, H-N. & Sedig, K. (2010b). Role of interaction in enhancing the epistemic utility of 3D mathematical visualizations. *International Journal of Computers for Mathematical Learning*, 15(3), 191-224.
- Liu, Z., Nersessian, N. J., Stasko, J. T. (2008). Distributed Cognition as a Theoretical Framework for Information Visualization. *IEEE Transactions on Visualization and Computer Graphics*, 14(6), 1173-1180
- Liu, Z. & Stasko, J. T. (2010). Mental models, visual reasoning and interaction in information visualization: A top-down perspective. *IEEE transactions on visualization and computer graphics*, 16(6), 999-1008.
- Livnat Y., Gesteland P., Benuzillo J., Pettey W., Bolton D., Drews F., et al. Epinome-a novel workbench for epidemic investigation and analysis of search strategies in public health practice. *AMIA Annual Symposium Proceedings*. 2010. p. 647.
- Ma, J., Liao, I., Ma, K-L., & Frazier, J. (2012). Living Liquid: Design and evaluation of an exploratory visualization tool for museum visitors. *IEEE Transactions on Visualization and Computer Graphics*, 18(12), 2799-2808.
- MacEachren, A. M. (1995). *How Maps Work: Representation, Visualization, and Design*. NY: Guilford Press.
- Mackinlay, J. (1986). Automating the design of graphical presentations of relational information. *ACM Transactions on Graphics*, 5(2), 110-141
- Mackinlay, J., Rao, R., & Card, S. K. (1995). An organic user interface for searching citation links. In *Proceedings of the ACM Conference on Human Factors in Computing Systems (ACM CHI '91)*, 67-73.
- Maglio, P., Matlock, T., Raphaely, D., Chernicky, B., & Kirsh, D. (1999). Interactive skill in scrabble. In *Proceedings of the Twenty-first Annual Conference of the Cognitive Science Society*, 326-330.
- Mansmann, F., Fischer, F., North, S. C., Keim, D. A. (2009). Visual support for analyzing network traffic and intrusion detection events using treemap and graph representations. In *Proceedings of the Symposium on Computer Human Interaction for the Management of Information Technology (CHiMiT '09)*, 19-28.
- Marchionini, G. (2008). Human-information interaction research and development. *Library and information science research*, 30, 165-174.
- Marchionini, G. (2010). *Information Concepts: From Books to Cyberspace Identities*. Bonita Springs, FL: Morgan & Claypool.
- Marks, L., Hussell, J. A. T., McMahan, T. M. & Luce, R. E. (2005). ActiveGraph: A digital library visualization tool. *International Journal on Digital Libraries*, 5, 57-69.
- Meyer, J., Thomas, J., Diehl, S., & Fisher, B., Keim, D.A., Laidlaw, D.H., Miksch, S., Mueller, K., Ribarsky, W., Preim, B., & Ynnerman, A. (2010). From visualization to visually enabled reasoning. In H. Hagen (Ed.), *Scientific Visualization: Advanced Concepts*, Chapter 15, (pp. 227-245). Dagshtul Publishing.

- Moody, D. (2007). What makes a good diagram? Improving the cognitive effectiveness of diagrams in IS development. In W. Wojtkowski, W. G. Wojtkowski, J. Zupancic, G. Magyar, & G. Knapp (Eds.), *Advances in Information Systems Development* (pp. 481-192). New York: Springer.
- Moody, J., McFarland, D., and Bender-deMoll, S. (2005). Dynamic network visualization, *American Journal of Sociology*, 110(4), pp. 1206-1241.
- Morey, J. & Sedig, K. (2004a). Archimedean Kaleidoscope: A cognitive tool to support thinking and reasoning about geometric solids. In M. Sarfraz (Ed.), *Geometric modeling: Techniques, applications, systems and tools*. (pp. 376- 393). MA, Norwell: Kluwer Academic Publisher.
- Morey, J. & Sedig, K. (2004b). Using index-sequential geometric glyphs to explore visual patterns. *Computational Science—ICCS 2004, LNCS Vol. 3038*, 996-1003.
- Munyofu, M., Swain, W., Ausman, B., Lin, H., Kidwai, K., & Dwyer, F. (2007). The effect of different chunking strategies in complementing animated instruction. *Learning, Media and Technology*, 32(4), 407-419.
- Novick, L. (2006). The importance of both diagrammatic conventions and domain-specific knowledge for diagram literacy in science: The hierarchy as an illustrative case. In D. Barker-Plummer, R. Cox, & N. Swoboda (Eds.), *Diagrammatic Representation and Inference, LNCS 4045* (pp. 1-11). Berlin: Springer.
- Nowell, L. (1997). *Graphical encoding for information visualization: Using icon color, shape, and size to convey nominal and quantitative data*. Unpublished PhD dissertation. Virginia Polytechnic Institute and State University.
- Oelke, D., Spretke, D., Stoffel, A., & Keim, D. A. (2012). Visual readability analysis: How to make your writings easier to read. *IEEE Transactions on Visualization and Computer Graphics*, 18(5), 662-674.
- Olive, J. (2000). Computer tools for interactive mathematical activity in the elementary school. *International Journal of Computers for Mathematical Learning*, 5, 241–262.
- Parsons, P. & Sedig, K. (2013a, to appear). Common visualizations: Their cognitive utility. In T. Huang (Ed.), *Handbook of Human Centric Visualization*. Springer.
- Parsons, P. & Sedig, K. (2013b, to appear). Distribution of information processing while performing complex cognitive activities with visualization tools. In T. Huang (Ed.), *Handbook of Human Centric Visualization*. Springer.
- Peng, W., Ward, M., & Rundensteiner, E. (2004). Clutter Reduction in Multi-Dimensional Data Visualization Using Dimension Reordering. *IEEE Symposium on Information Visualization, (INFOVIS 2004)*, 89-96.
- Perer, A. & Shneiderman, B. (2006). Balancing systematic and flexible exploration of social networks. *IEEE Transactions on Visualization and Computer Graphics (InfoVis 2006)*, 12(5), 693-700.
- Peterson, D. (1996). *Forms of Representation*. Exeter, UK: Intellect Books.

- Petersson, H., Sinkvist, D., Wang, C., & Smedby, Ö. (2009). Web-based interactive 3D visualization as a tool for improved anatomy learning. *Anatomical Sciences Education*, 2, 61-68.
- Phillips, R. J., & Noyes, L., (1982). An investigation of visual clutter in the topographic base of a geological map, *The Cartographic Journal*, 19(2), 122-131.
- Pike, W. A., Stasko, J. T., Chang, R. & O'Connell, T. A. (2009). The Science of Interaction. *Information Visualization*, 8(4), pp. 263-274.
- Pioch, N. J. & Everett, J. O. (2006). POLESTAR: collaborative knowledge management and sensemaking tools for intelligence analysts. In *Proceedings of the 35th ACM International Conference on Information and Knowledge Management (CIKM '06)*, 513-521.
- Pirolli, P. Card, S.K., & Van Der Wege, S.M. (2001). Visual Information Foraging in a Focus + Context Visualization. In *Proceedings of the SIGCHI conference on Human factors in computing systems*. ACM: NY. doi 10.1145/365024.365337
- Pirolli, P. & Rao, R. (1996). Table lens as a tool for making sense of data. In *Proceedings of the workshop on Advanced visual interfaces*, pp. 67-80.
- Proctor, T. (2010). *Creative Problem Solving for Managers: Developing Skills for Decision Making and Innovation* (3rd Ed.). NY: Routledge.
- Rao, R. & Card, S. K. (1994). The Table Lens: Merging Graphical and Symbolic Representations in an Interactive Focus+Context Visualization for Tabular Information. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems*, pp. 1-7.
- Ravtich, S.M. & Riggan, M. (2011). *Reason & Rigor: How Conceptual Frameworks Guide Research*. LA: Sage.
- Reinhardt M., Elias J., Albert J., Frosch M., Harmsen D., & Vogel U. EpiScanGIS: an online geographic surveillance system for meningococcal disease. *International Journal of Health Geographics*. 7(1).
- Ritter, F. Berendt, B. Fischer, B. Richter, R. & Preim, B. (2002). Virtual 3D jigsaw puzzles: Studying the effect of exploring spatial relations with implicit guidance. In *Proceedings of Mensch & Computer*, 363-372.
- Robertson, S. I. (2001) *Problem Solving*. Philadelphia, PA: Psychology Press.
- Rosenholtz, R., Li, Y., & Nakano, L. (2007). Measuring visual clutter. *Journal of Vision*, 7(2), 1-22.
- Scaife, M. & Rogers, Y. (1996). External cognition: How do graphical representations work? *International Journal of Human-Computer Studies*, 45, 185-213.
- Schmid, U., Ragni, M., Gonzalez, C., & Funke, J. (2011). The challenge of complexity for cognitive systems. *Cognitive Systems Research*, 12, 211-218.
- Scholtz, J. (2006). Metrics for evaluating human information interaction systems. *Interacting with computers*, 18, 507-527.

- Schraefel, M. C., Modjeska, D., Wigdor, D., & Zhu, Y. (2002) Hunter Gatherer: Within-web-page collection making. In CHI '02 Extended Abstracts on Human Factors in Computing Systems (CHI EA '02), 498-499.
- Schwan, S., & Riempp, R. (2004). The cognitive benefits of interactive videos: Learning to tie nautical knots. *Learning and Instruction*, 14, 293–305.
- Sedig, K. & Klawe, M. M. (1996). Super Tangrams: A child-centered approach to designing a computer supported mathematics learning environment. In *Proceedings of the International Conference on the Learning Sciences*, Association for the Advancement of Computing in Education, 490-495.
- Sedig, K., Klawe, M., and Westrom, M. (2001). Role of interface manipulation style and scaffolding on cognition and concept learning in learnware, *ACM transactions on computer-human interaction*, 1(8), 34-59.
- Sedig, K. & Liang, H-N. (2008). Learner-information interaction: A macro-level framework characterizing visual cognitive tools. *Journal of Interactive Learning Research*, 19(1), 147-173.
- Sedig, K., Morey, J., & Chu, B. (2002). TileLand: A microworld for creating mathematical art. In *proceedings of EDMEDIA World Conference on Educational Multimedia, Hypermedia and Telecommunications*, 1778-1783.
- Sedig, K. & Parsons, P. (2013, to appear). Interaction design for complex cognitive activities with visual representations: A pattern-based approach. *AIS Transactions on Human-Computer Interaction*.
- Sedig, K., Parsons, P., & Babanksi, A. (2012). Towards a characterization of interactivity in visual analytics. *Journal of Multimedia Processing and Technologies: Special Issue on Theory and Application of Visual Analytics*, 3(1), 12-28.
- Sedig, K., Parsons, P., Dittmer, M., & Haworth, R. (2013, to appear). Human-centered interactivity of visualization tools: Micro- and macro-level considerations. In T. Huang (Ed.), *Handbook of Human Centric Visualization*. Springer.
- Sedig, K., Rowhani, S., & Liang, H-N. (2005). Designing interfaces that support formation of cognitive maps of transitional processes: An empirical study. *Interacting with Computers*, 17(4), 419-452.
- Sedig, K., Rowhani, S., Morey, J., & Liang, H-N. (2003). Application of information visualization techniques to the design of a mathematical mindtool: A usability study. *Journal of Information Visualization* 2(3), 142-160.
- Seo, J. & Shneiderman, B. (2005). A knowledge integration framework for information visualization, *LNCS Vol. 3379*, 207-220.
- Shannon, P., Markiel, A., Ozier, O., Baliga, N. S., Wang, J. T., Ramage, D., Amin, N., Schwikowski, B., & Ideker, T. (2003). Cytoscape: a software environment for integrated models of biomolecular interaction networks. *Genome Research*, (13)11, 2498- 2504.
- Shimojima, A. (1996). On the efficacy of representation. Doctoral Dissertation. Indiana University.

- Shipman, F., Hsieh, H., Moore, J. M., & Zacchi, A. (2004). Supporting personal collections across digital libraries in spatial hypertext. In Proceedings of the ACM and IEEE Joint Conference on Digital Libraries, 358-367.
- Shneiderman, B. (1996). The eyes have it: A task by data type taxonomy for information visualizations. In Proceedings of 1996 IEEE Conference Visual Languages, 336-343.
- Shrinivasan, Y. and Wijk, J. (2008). Supporting the analytical reasoning process in information visualization, in Proceeding of the twenty-sixth annual SIGCHI conference on Human factors in computing systems (pp. 1237-1246).
- Siirtola, H. (1999). Interaction and the reorderable matrix. In Proceedings of the IEEE International Conference on Information Visualization (pp. 272-277).
- Spence, R. (2007). Information visualization: design for interaction. (2nd Ed.). Essex, England: Pearson Education Limited.
- Springer, C. (1987). Retrieval of information from complex alphanumeric displays: Screen formatting variables' effects on target identification time. In Proceedings of the 2nd International Conference on Human-Computer Interaction (pp. 375-382).
- Stasko, J., Görg, C., & Liu, Z. (2008). Jigsaw: supporting investigative analysis through interactive visualization. *Information Visualization*, 7(2), 118-132.
- Stenning, K. & Oberlander, J. (1995). A cognitive theory of graphical and linguistic reasoning: Logic and implementation. *Cognitive Science*, 19(1), 97-140.
- Sternberg, R.J. & Ben-Zeev, T. (2001). *Complex Cognition: The Psychology of Human Thought*. NY: Oxford University Press.
- Stolte, C., Tang, D., & Hanrahan, P. (2002). Polaris: A system for query, analysis, and visualization of multidimensional relational databases. *IEEE Transactions on Visualization and Computer Graphics*, 8(1), 52-65.
- Stone, M., Fishkin, K., & Bier, E. (1994). The movable filter as a user interface tool, In Proceedings CHI '94 (pp. 306-312).
- Suwa, M., & Tversky, B. (2002). External representations contribute to the dynamic construction of ideas. In M. Hegarty, B. Meyer, & N. Narayanan (Eds.), *Diagrammatic representation and inference*, LNCS 2317 (pp. 149-160). Berlin: Springer.
- Sweller, J. (2002). Visualization and instructional design. In Proceedings of the International Workshop on Dynamic Visualizations and Learning, 1501-1510.
- Tabachneck-Schijf, H. J. M. & Simon, H. A. (1996). Alternative representations of instructional material. In D. Peterson (Ed.), *Forms of Representation*. Exeter, UK: Intellect Books.
- Theus, M. (2002). Interactive data visualization using Mondrian. *Journal of Statistical Software*, 7(11), 1-9.

- Thomas, J.J. & Cook, K.A. (2005). *Illuminating the path: The research and development agenda for visual analytics*. Washington, DC: IEEE Press.
- Tominksi, C., Abello, J., & Schumann, H. (2009). CGV—An interactive graph visualization system. *Computers and Graphics* (33), 660-678.
- Toyoda, M. and Kitsuregawa, M. (2005) A System for Visualizing and Analyzing the Evolution of the Web with a Time Series of Graphs. In *Proceedings of the sixteenth ACM conference on Hypertext and hypermedia*, 151-160.
- Tufte, E. R. (1990). *Envisioning information*. Cheshire, CT: Graphics Press.
- Tufte, E. R. (2001). *The visual display of quantitative information* (2nd Ed.). Cheshire, CT: Graphics Press.
- Tukey, J. W. (1977). *Exploratory Data Analysis*. Addison-Wesley.
- Tversky, B., Morrison, J. B., Betrancourt, M. (2002). Animation: Can it facilitate? *Journal of Human-Computer Studies*, 57(4), 247–262.
- Van Wijk, J.J. (2006). Views on visualization. *IEEE Transactions on Visualization and Computer Graphics*, 12(4), 421-432.
- Waller, D., Knapp, D., & Hunt, E. (2001). Spatial representations of virtual mazes: The role of visual fidelity and individual differences. *Human Factors*, 43(1), 147-158.
- Wand, Y. & Weber, R. (1990). An ontological model of an information system. *IEEE Transactions on Software Engineering*, 1282-1292.
- Ware, C. (2004). *Information visualization: Perception for design* (2nd Ed.). San Francisco, CA: Elsevier.
- Ware, C. (2008). *Visual thinking for design*. Burlington, MA: Morgan Kauffman.
- Ware, C. (2012). *Information visualization: Perception for design* (3rd Ed.). San Francisco, CA: Elsevier.
- Wilensky, U. (2005). NetLogo Preferential Attachment model.
<http://ccl.northwestern.edu/netlogo/models/PreferentialAttachment>. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.
- Wilensky, U. (1999). NetLogo. <http://ccl.northwestern.edu/netlogo/>. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.
- Willis, C., Greenberg, J., & White, H. (2012). Analysis and synthesis of metadata goals for scientific data. *Journal of the American Society for Information Science and Technology*, 63(8), 1505-1520.
- Winn, W. (1993). Perception Principles. In M. Fleming, & H. Levie (Eds.), *Instructional message design: Principles from the behavioral and cognitive sciences* (pp. 55-123). Englewood Cliffs, NJ: Educational Technology.
- Wolfe, J.M. (1998). Visual search. In H. Pashler (Ed.), *Attention* (pp. 13-74). University College London Press, London: UK.

- Wu, H-C., Liang, H-N. & Sedig, K. (2006). Exploring correlations in multivariate datasets using integrated interactive visualizations. In Proceedings of the International British HCI, Combining Visualisation and Interaction to Facilitate Scientific Exploration and Discovery Workshop.
- Yi, J. S., Kang, Y. A., Stasko, J., & Jacko, J. (2007). Toward a deeper understanding of the role of interaction in information visualization. *IEEE Transactions on Visualization and Computer Graphics*, 13, 1224–1231.
- Yi, J. S., Melton, R. Stasko, J., & Jacko, J. (2005). Dust and Magnet: multivariate information visualization using a magnet metaphor. *Information Visualization*, 4(4), 239-256.
- Zhang, J. & Norman, D. A. (1994). Representations in distributed cognitive tasks. *Cognitive Science*, 18, 87-122.
- Zhang, J. & Patel, V.L. (2006). Distributed cognition, representation, and affordance. *Pragmatics & Cognition* 14(2), 333–341.
- Zhang, J., Patel, V.L., Johnson, K.A., Smith, J.W., & Malin, J. (2002). Designing human-centered distributed information systems. *IEEE Intelligent Systems*, 17(5), 42-47.

Chapter 5 Human-centered interactivity of visualization tools: Micro- and macro-level considerations

This chapter has been published as Sedig, K., Parsons, P., Dittmer, M., & Haworth, R. (2013). Human-centered interactivity of visualization tools: Micro- and macro-level considerations. In W. Huang (Ed.), *Handbook of Human-Centric Visualization* (pp. 717-743). Springer, New York.

Due to copyright restrictions the content of this chapter has been removed. It can be accessed at the following location: http://link.springer.com/chapter/10.1007/978-1-4614-7485-2_29

5.1 Abstract

Visualization tools can support and enhance the performance of complex cognitive activities such as sense making, problem solving, and analytical reasoning. To do so effectively, however, a human-centered approach to their design and evaluation is required. One way to make visualization tools human-centered is to make them interactive. Although interaction allows a user to adjust the features of the tool to suit his or her cognitive and contextual needs, it is the quality of interaction that largely determines how well complex cognitive activities are supported. In this chapter, interactivity is conceptualized as the quality of interaction. As interactivity is a broad and complex construct, we categorize it into two levels: micro and macro. Interactivity at the

micro level emerges from the structural elements of individual interactions. Interactivity at the macro level emerges from the combination, sequencing, and aggregate properties and relationships of interactions as a user performs an activity. Twelve micro-level interactivity elements and five macro-level interactivity factors are identified and characterized. The framework presented in this chapter can provide some structure and facilitate a systematic approach to design and evaluation of interactivity in human-centered visualization tools.

Chapter 6 Distribution of information processing while performing complex cognitive activities with visualization tools

This chapter has been published as Parsons, P. & Sedig, K. (2013). Distribution of information processing while performing complex cognitive activities with visualization tools. In W. Huang (Ed.), *Handbook of Human-Centric Visualization* (pp. 671-691). Springer, New York.

Due to copyright restrictions the content of this chapter has been removed. It can be accessed at the following location: http://link.springer.com/chapter/10.1007/978-1-4614-7485-2_28

6.1 Abstract

When using visualization tools to perform complex cognitive activities, such as sense-making, analytical reasoning, and learning, human users and visualization tools form a joint cognitive system. Through processing and transfer of information within and among the components of this system, complex problems are solved, complex decisions are made, and complex cognitive processes emerge—all in a manner that would not be easily performable by the human or the visualization tool alone. Although researchers have recognized this, no systematic treatment of how to best distribute the information-processing load during the performance of complex cognitive activities is available in the existing literature. While previous research has identified some relevant principles that

shed light on this issue, the pertinent research findings are not integrated into coherent models and frameworks, and are scattered across many disciplines, such as cognitive psychology, educational psychology, information visualization, data analytics, and computer science. This chapter provides an initial examination of this issue by identifying and discussing some key concerns, integrating some fundamental concepts, and highlighting some current research gaps that require future study. The issues examined in this chapter are of importance to many domains, including visual analytics, data and information visualization, human-information interaction, educational and cognitive technologies, and human-computer interaction design. The approach taken in this chapter is human-centered, focusing on the distribution of information processing with the ultimate purpose of supporting the complex cognitive activities of human users of visualization tools.

Chapter 7 Common Visualizations: Their Cognitive Utility

This chapter has been published as Parsons, P. & Sedig, K. (2013). Common visualizations: Their cognitive utility. In W. Huang (Ed.), *Handbook of Human-Centric Visualization* (pp. 671-691). Springer, New York.

Due to copyright restrictions the content of this chapter has been removed. It can be accessed at the following location: http://link.springer.com/chapter/10.1007/978-1-4614-7485-2_27

7.1 Abstract

Visualizations have numerous benefits for problem solving, sense making, decision making, learning, analytical reasoning, and other high-level cognitive activities. Research in cognitive science has demonstrated that visualizations fundamentally influence cognitive processing and the overall performance of such aforementioned activities. However, although researchers often suggest that visualizations support, enhance, and/or amplify cognition, little research has examined the cognitive utility of different visualizations in a systematic and comprehensive manner. Rather, visualization research is often focused only on low-level cognitive and perceptual issues. To design visualizations that effectively support high-level cognitive activities, a strong understanding of the cognitive effects of different visual forms is required. To examine this issue, this chapter draws on research from a number of relevant domains, including information and data visualization, visual analytics, cognitive and perceptual psychology,

and diagrammatic reasoning. This chapter identifies and clarifies some important terms and discusses the current state of research and practice. In addition, a number of common visualizations are identified, their cognitive and perceptual influences are examined, and some implications for the performance of high-level cognitive activities are discussed. Readers from various fields in which a human-centered approach to visualization is necessary, such as health informatics, data and information visualization, visual analytics, journalism, education, and human-information interaction, will likely find this chapter a useful reference for research, design, and/or evaluation purposes.

Chapter 8 Research Application: Design of a Cognitive Activity Support Tool

8.1 Introduction and Motivation

This chapter will describe the design of a CAST that was guided by the research presented in this dissertation. The function of this chapter is to demonstrate the utility of this research in enabling systematic design of tools that support complex cognitive activities. As was mentioned earlier, our research is not intended to guide design at a low level, nor does it provide explicit prescriptive guidance. Rather, prescriptive guidance is implicit and operates at a high level of the design process. In his review on the nature of design practice, Stolterman (2008) suggests 4 forms of design support that designers of interactive tools have been found to actually use and find helpful: (1) precise and simple tools or techniques (e.g., sketching and prototypes); (2) frameworks that do not prescribe but that support reflection and decision-making; (3) individual concepts that are intriguing and open for interpretation and reflection on how they can be used; and (4) high-level theoretical and/or philosophical ideas and approaches that expand design thinking. The research presented in this dissertation supports design in 3 of the 4 ways (forms 2, 3, and 4). First, by providing a large and coherent theoretical foundation, our research supports reflection on the design situation (e.g., what are the main tasks and activities in which users may engage? What are the drawbacks of distributing more of the information-processing load onto the user?), and also facilitates principled decision making (e.g., which actions should my tool support? when should the user be able to adjust the properties of VRs?). Second, our research provides a number of individual (although not isolated) concepts that are not commonly discussed by designers. For

example, epistemic actions, interactivity, interaction levels, and emergent activities are all amenable to interpretation and use within a contextual design setting. Fourth, our research supports design by offering high-level, unified theoretical and philosophical ideas for design. As described in multiple places throughout the dissertation (e.g., Sections 3.3.1, 3.3.2, 4.1, and 4.3), our research unifies a number of seemingly disparate concepts and research findings into a coherent theoretical framework. This novel framework can act as a conceptual support structure to facilitate the development of mental models that expand design thinking, opening up new avenues of design and stimulating creativity in the mind of the designer. Thus, our research is intended to both inform designers and promote meta-cognitive awareness of the design process. Effective design depends on designers being “fully aware of internal thinking processes and mental models, for they influence communication ideas and content as ideas take shape” (Hansen, 2000, p. 195).

The result of any design process is influenced by multiple factors: the preferences, skills, and other characteristics of the designer; the needs and desires of the client and/or users; the characteristics of the information space; and the possibilities and limitations of the technological platform on which the tool is based. Consequently, every result (i.e., product or tool) in which any of these factors changes will likely be unique. Therefore, even with the same design framework and information space, two designers will likely produce tools with unique features. Moreover, it is possible that neither tool could be considered ‘better’ than the other. Indeed, unlike system-centered design, when it comes to human-centered design, it is not possible to have a single ‘best design’ (Cooley, 2000). As the rest of this chapter will demonstrate, the research presented here is not intended to enable replicable design products or to micro-manage the design process. Rather, the primary intention is on enabling the designer to have coherent design thinking where design decisions are principled yet still influenced by the designer’s intuition, experience, and creative impulse.

8.2 Background and Context

This section gives some background to the project before describing the design process. The primary function of the tool is to support sense making of collaborations within a university faculty. The next three subsections give some context before the design of the tool is discussed. Three main issues will be covered: 1) an overview of the information space; 2) a brief description of the tasks and activities users are likely to perform; and 3) some technical implementation details of the tool.

8.2.1 Information Space

There are four main sources of information that comprise the information space:

1. Publication data downloaded from SciVerse Scopus³ and Thomson Reuters Web of Science⁴. Contains information about publication title, venue, authors, affiliations, and other typical publication information.
2. Grant application data from university researchers. Contains names, dates, departments, application titles, programs, request status, and other typical grant characteristics.
3. Co-supervision data. Contains supervisor names and indicates co-supervisions of graduate students.
4. Faculty members. Contains names of faculty members and the departments to which they belong.

Important note: because of the sensitivity and confidentiality of the data, screenshots in this section have been made to show randomly generated data and should not be considered as accurately conveying aspects of the information space.

³ <http://www.scopus.com/>

⁴ <http://thomsonreuters.com/web-of-science/>

8.2.2 Tasks and Activities

Through a participatory design approach, a number of goals of the client⁵ were identified.

These can be formulated in the form of the following tasks:

- Identify research clusters based on grant collaborations and/or co-publications and/or co-supervision of graduate students
- Determine points of contact between research clusters
- Browse and explore collaboration networks
- Assess the relationship between administrative plans and emergence of research clusters over time
- Categorize grant applications according to status
- Identify roughly the proportion of inter- vs. intra-departmental collaborations

The main activity that this tool is intended to support is sense making. In addition to the tasks listed above, as was discussed in Sections 3.2.4 and 6.4.1.1, a typical sense making activity involves a number of general tasks: scanning the information space, assessing the relevance of items within the space, selecting items for further attention, examining them in more detail and integrating them into mental models, establishing questions to be asked, determining how to organize the answers, searching for pieces of information, filtering aspects of information, and categorizing items of information. Section 8.3 will describe the process of supporting these general and particular tasks based on the research described in the previous chapters.

8.2.3 Implementation Details

The choice of technological platform was dictated by the desire of the client for a web-based tool. Briefly, we are running a Node.js web server and an Apache CouchDB database. Most of the data processing is done on the server, stored in the database, and

⁵ In this case, the client is a user of the tool, but not all eventual users of the tool will be clients.

sent to the client when requested. On the client side, aside from HTML5 and CSS3, two main JavaScript libraries are used for visual representation and interaction. The first is D3.js, a library for visually encoding data as SVG elements in the representation space. This is done by binding data to elements within the Document Object Model (DOM). The other is jQuery, a library that facilitates client-side scripting. Both libraries offer a level of abstraction for incorporating interaction into the tool, mostly in the form of determining responses to user actions.

8.3 Design Process

This section will describe the design process based on the needs of the client and the characteristics of the information space according to the research presented in the previous chapters of this dissertation. The description will not be exhaustive, but will attempt to highlight some unique features.

8.3.1 Choice of Visual Representations

This tool uses four different VRs, each of which is shown in Figure 8-1. Each one communicates and emphasizes different aspects of the information space and offers its own unique interaction possibilities. A brief description of each can be given as follows (from L to R, T to B): an instance of a network or graph VR, explicitly encoding collaborations between individuals; an instance of a network or graph VR that uses a Sankey technique, encoding the ‘flow’ and status of grant proposals; an instance of an enclosure VR that uses an adjacency matrix technique, encoding collaborations between individuals; and an instance of an enclosure VR that uses a Treemap technique, encoding hierarchical information about grant proposals.

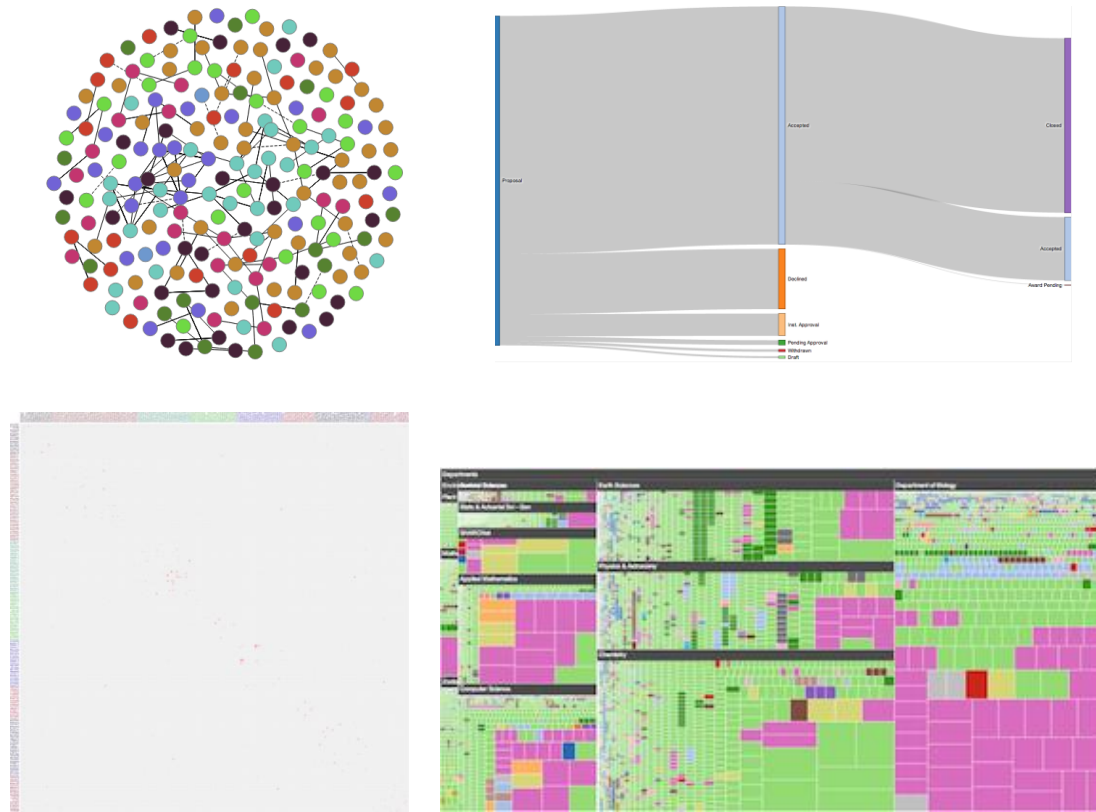


Figure 8-1 The four VRs used in this tool to support the overall sense making activity.

8.3.2 Interaction and Interactivity Design

It should first be noted that in this case the designers of the tool were also the authors of the research. Therefore, design support in the form of promoting reflection on important concepts, developing mental models, and providing a high-level framework for conceptualization (as discussed in Section 8.1) was already well integrated into the thinking of the designers. Three broad approaches were used during the interaction design process. The first was guided by EDIFICE-AP. This approach involved consulting the action taxonomy to determine which action patterns would be useful. The second involved using EDIFICE-PVR to determine when it would be useful to allow users to adjust the properties of VRs. The third approach was concerned with interactivity, and was based on the EDIFICE-IVT framework. Although these three approaches can be identified, they were not separate, nor were they sequential components of the design

process. Rather, they were interwoven and visited continuously throughout the overall process. In the subsections below, we attempt to describe some aspects of these three approaches. It should be kept in mind that these sections do not describe the complete design process, nor do they accurately convey the sequence of design.

8.3.2.1 Epistemic Action Patterns

During the design process, we continually consulted the action taxonomy to determine which action patterns should be implemented to provide support for the types of tasks that the users would be performing. This section will describe the context around a few of the design decisions that were made using the action taxonomy. Although a number of action patterns were deemed useful, only 4 will be described here: arranging, scoping, searching, and translating. Consider the network-like VR in the top left of Figure 8-1. Given the tasks identified by the client above, we tried to assess whether it would facilitate the desired tasks if the user could see a different ordering or configuration of the VR. In this case, considering one of the goals was to identify intra-departmental collaborations, arranging the VR according to individuals' respective departments could indeed be helpful. Figure 8-2 shows the result of a user performing such an action. Certain characteristics of the information space become immediately clear. For instance, there are no collaborations between Department F and Department E or between Department B and Department C. As the actions from EDIFICE-AP are abstract patterns, each one can be implemented in any number of ways. Often, it may be provide better support to have multiple implementations of the same pattern. For example, while the action shown in Figure 8-2 certainly has utility in supporting the aforementioned task, a user may find it beneficial to arrange the VR according to his/her own personal preferences to support the development of a rich mental model of the information space. Figure 8-3 shows an example of the user performing multiple instances of an arranging action to adjust the configuration of the VR by moving individual information items. In this case, the user can develop a more fine-grained mental model of the information space by identifying and reasoning about individual information items and their connections.

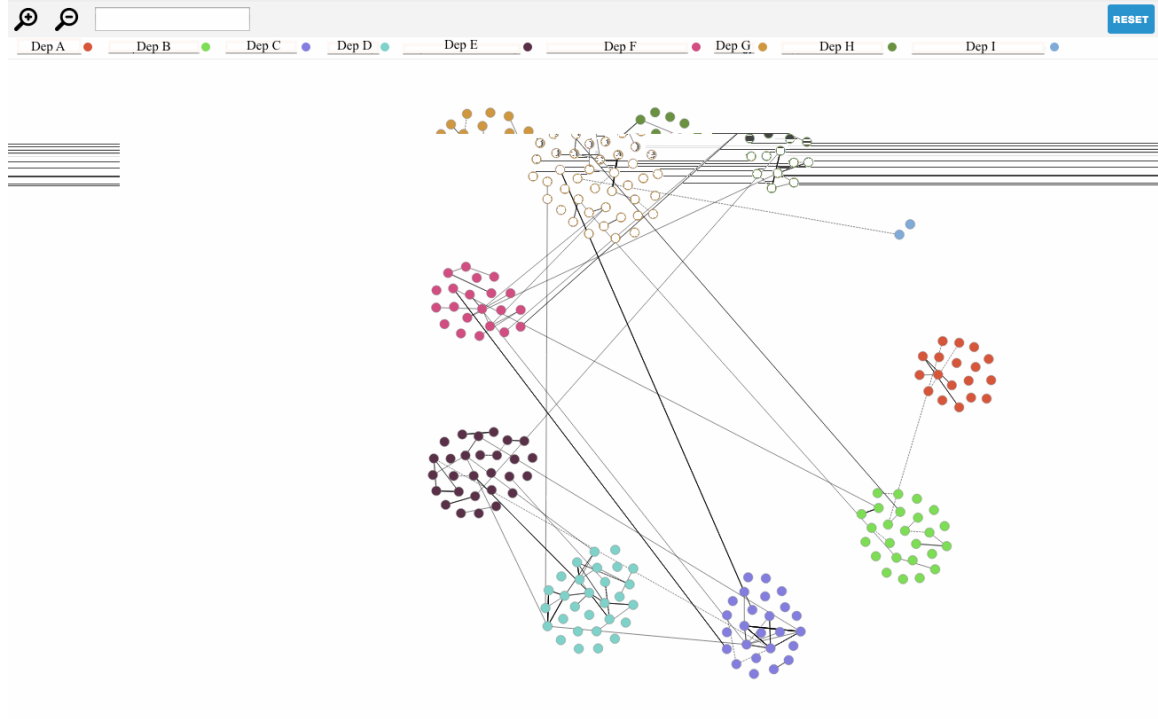


Figure 8-2 The result of arranging the VR according to departments to which individuals belong.

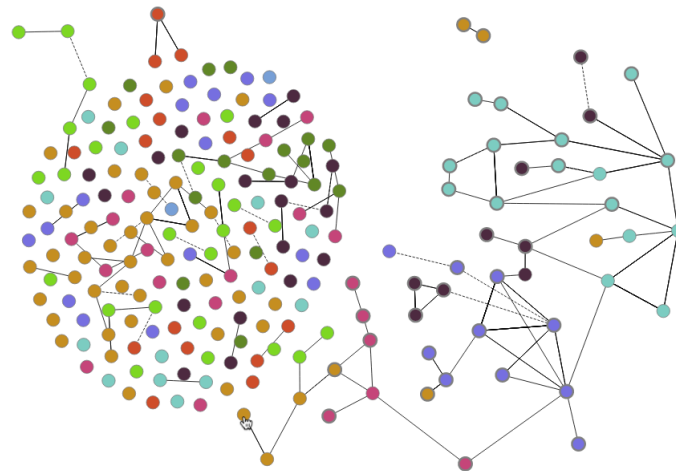


Figure 8-3 The result of multiple instances of an arranging action where the position of individual items is changed.

With regard to the scoping pattern, considering that an explicit goal of the client was to be able to identify changes in the information space over time, and to reason about temporal patterns, scoping has clear utility for achieving the goal of the task. The screen

captures in Figure 8-4 depict successive stages of a scoping action, showing growth of the network from 2008-2009 (L), 2008-2010 (TR), and 2008-2011 (BR). By performing this action, the user can identify important connections within the network. For instance, in Figure 8-4 (L), a number of small clusters are evident, four of which have been circled and labeled. As the user performs the scoping action to show growth in the VR until 2010, three of the clusters (A, B, and C) merge into one due to some collaborations that took place in that year. The user can clearly identify the collaborations that connect the three clusters. In a similar fashion, when scoping the growth further to the year 2011, a collaboration can easily be identified that incorporated the ‘D’ cluster into the larger cluster. Being able to identify such connections helps the user to make sense of the growth of the network, and to reason further about other aspects of the information space.

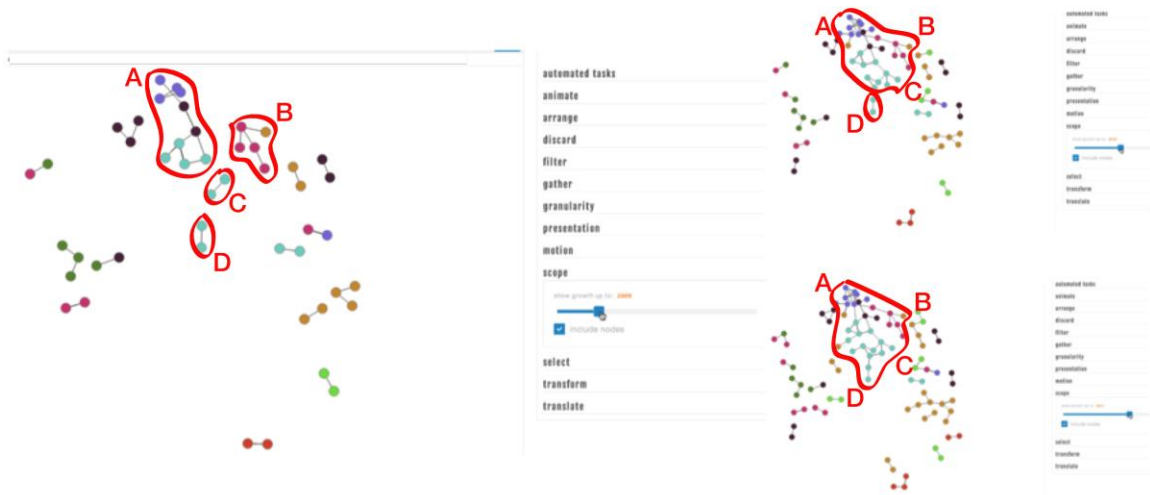


Figure 8-4 Successive stages of a scoping action, showing growth of the network until 2009 (L), 2010 (TR), and 2011 (BR).

The third action pattern that we are describing here is searching. Implementing such an action is likely useful in supporting any sense making activity. During the performance of a sense making activity with our tool, it is likely that a user would wish to seek out the existence of a particular individual to determine his/her collaborations. Figure 8-5 shows the result of acting upon the VR to seek out the existence and location of a particular person—for this demonstration, the name has been changed to “John Doe”. The response to the action could be implemented in any number of ways. In this case, to facilitate the

identification of direct collaborations, the CAST highlights the individual with a red outline and increases the transparency of all information items except the direct connections to the searched individual.

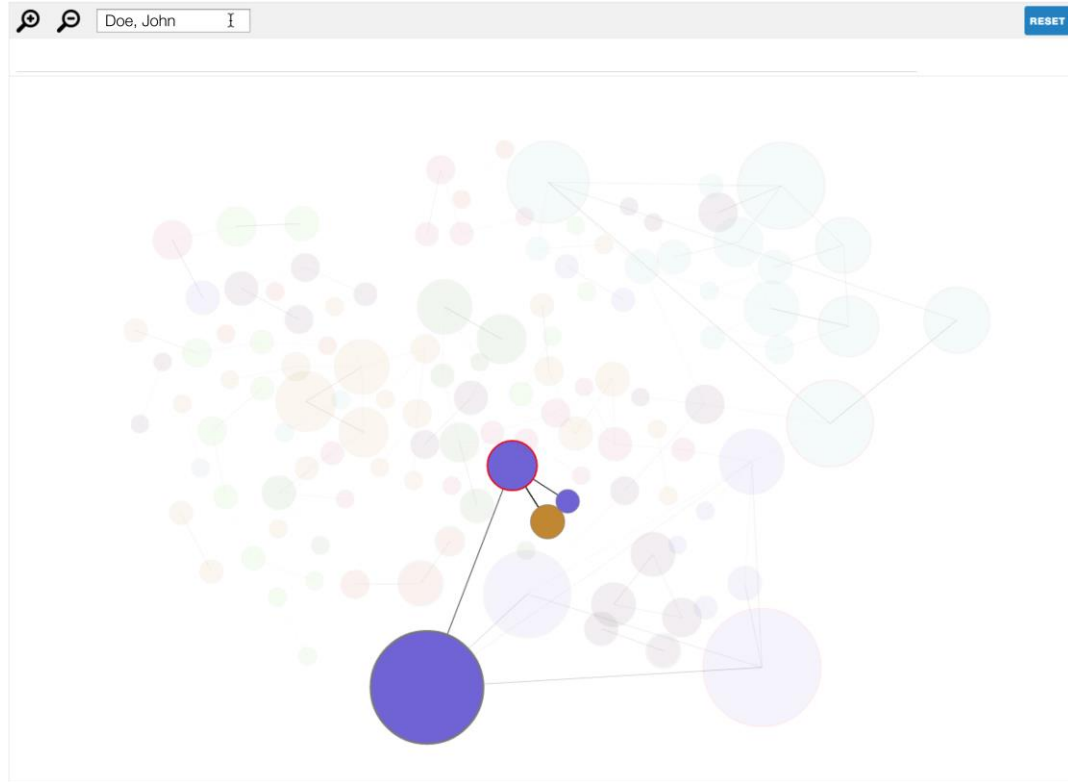


Figure 8-5 An implementation of the searching pattern.

The fourth action pattern being described in this section is translating. While the network-style VR shown above has certain identifiable benefits for communicating aspects of the information space and supporting particular tasks, other tasks are not so readily supported. For instance, the user cannot easily identify the ordering of individuals according to number of collaborations, nor easily develop an impression of the distribution of inter- and intra-departmental collaborations. As described in Section 7.6, VRs that are instantiations of enclosure diagrams can readily communicate precise and indexical information, even within a large set of information. In addition, such VRs can direct attention to certain enclosed areas (e.g., empty cells). As a result, we decided to provide the user with the ability to translate the VR into the form shown in Figure 8-6. In this case, the figure is showing the result of the user translating the VR. This VR can be

compared to the one shown in Figure 8-2. These two VRs are almost entirely informationally equivalent, and thus demonstrate very nicely the utility of the translating action in supporting different tasks. In this VR, individuals are listed horizontally along the top and vertically along the left. Squares that are colored red encode the existence of collaboration, where the opacity of the square encodes the number of collaborations. In Figure 8-6, the fact that most collaborations occur within departments (as evidenced by most red squares falling within the diagonal white-dotted-squares from top-left to bottom-right) is very easily determined. Using the VR in Figure 8-2, however, this characteristic of the information space is not so readily apparent.

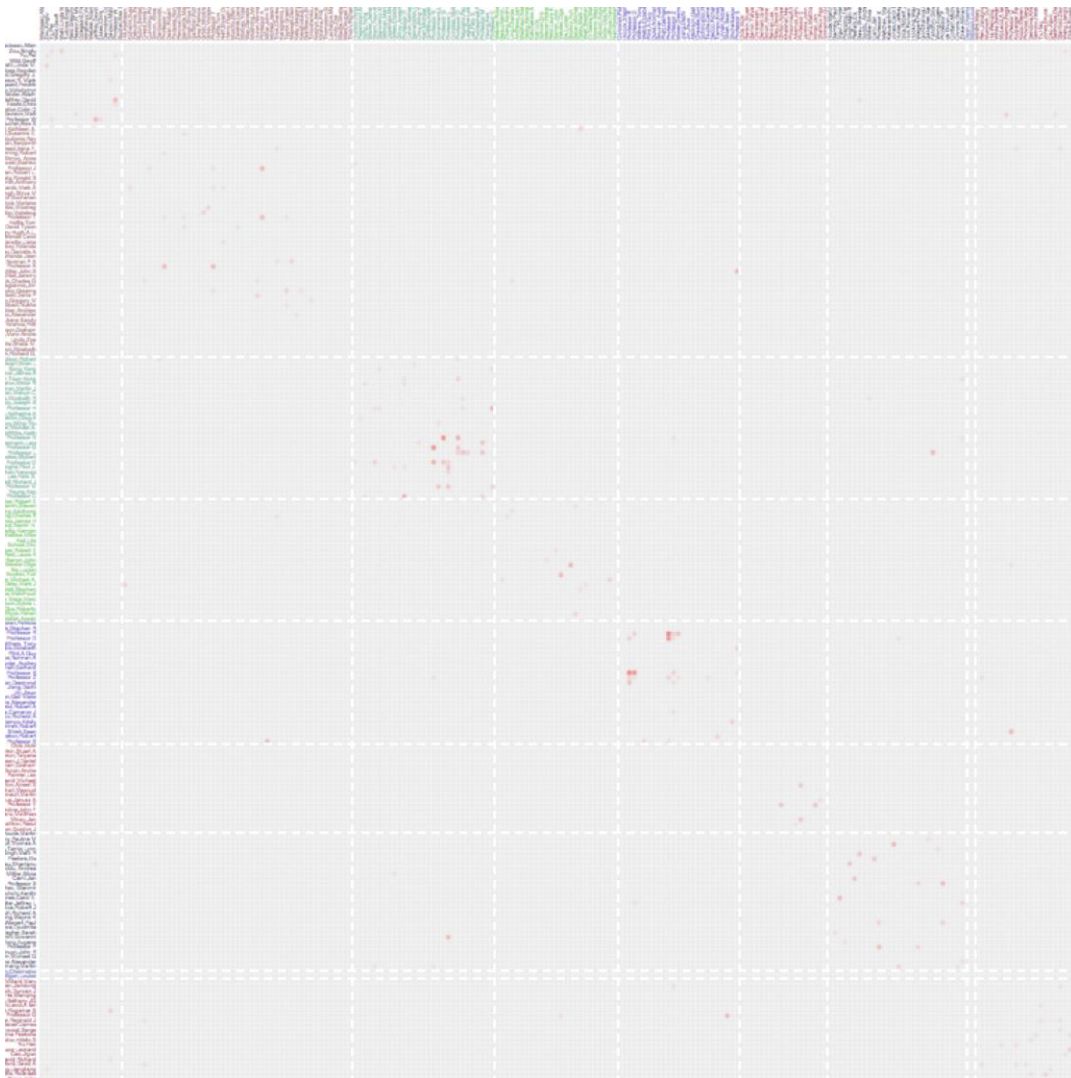


Figure 8-6 The result of the user translating the VR.

8.3.2.2 Adjustable Properties of VRs

In addition to the epistemic action patterns, we used EDIFICE-PVR to shape the design of the tool throughout the design process. By using the EDIFICE-PVR framework, we decided to add interactions whose utility may not have become apparent by consulting the action taxonomy alone. For instance, if we revisit the original network-style VR, first shown in Figure 8-1, our reflection on its density led us to implement the action that is depicted in Figure 8-7. Considering that one of the desired goals of the client is to be able to identify clusters of collaboration, the density of the VR shown in Figure 8-7 (L) can make perceptual identification tasks difficult, and can also place an unnecessary demand on working memory while trying to reason with the VR. Thus, we chose to implement an option for adjusting the density, which is an implementation of the transforming action pattern. After adjusting the density setting of the VR by decreasing it (Figure 8-7 R), it is much easier to identify clusters of collaboration. Note that there is exact information equivalence in both states of the VR, but the density setting of one provides much better support for certain tasks than the other.

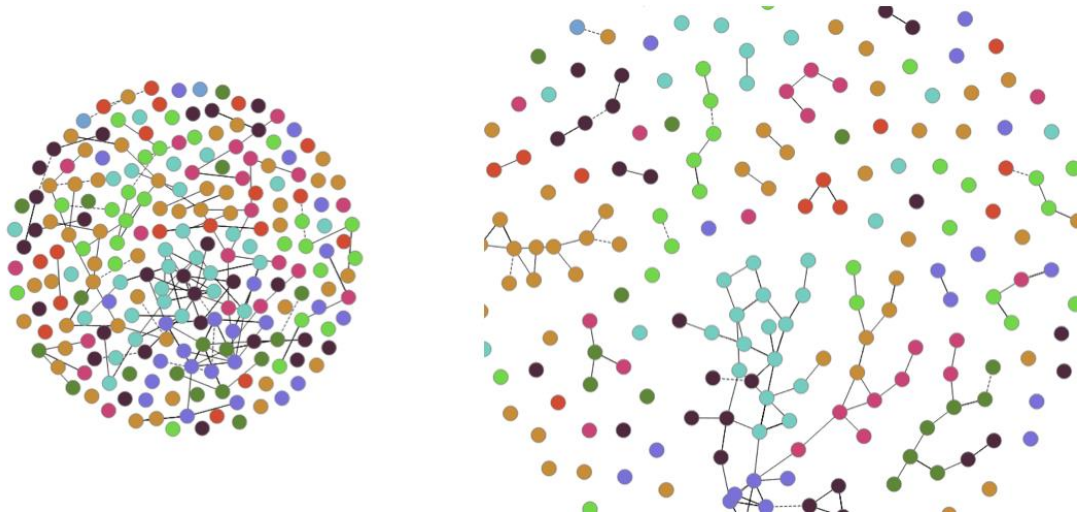


Figure 8-7 Adjusting the density setting of the VR to assist with identifying clusters of collaboration.

In consulting EDIFICE-PVR, another property of the network-style VR that we determined should be made adjustable is the appearance property. The user can adjust the

size of the individual circles as shown in Figure 8-8. In this instance, the user has performed a transforming action with the intention of changing the geometric properties of the nodes such that their sizes correspond to the respective number of collaborations. Because making perceptual judgments based on surface area is done poorly by the human visual system, such a choice is not good if the intention is to facilitate precise judgments. However, if the intention is to facilitate imprecise judgments (as in determining that one circle is clearly larger than another without having any interest in quantifying the difference), such geometric differences can be quickly and easily detected by pre-attentive perceptual processing of the VR. Thus, by devoting little cognitive attention, the user can quickly identify nodes that have a high number of collaborations. With the addition of a few more actions, the user can easily determine the major connection points between departmental clusters.

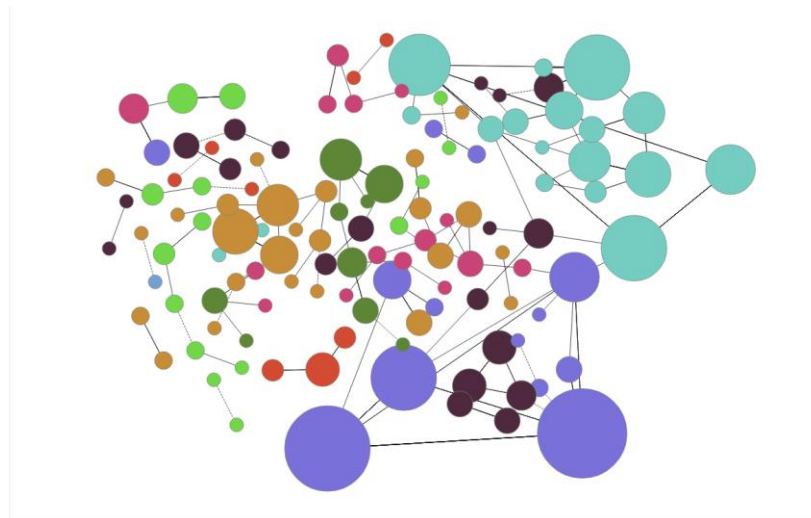


Figure 8-8 An implementation of the transforming pattern to adjust the appearance of the VR.

If we revisit the VR in the top right of Figure 8-1, one property that should be made adjustable is the fragmentation of the VR. Based on the nature of the information space and on the goals of the user, providing the ability to adjust this property could help support the overall sense making activity. For example, while it may be useful for the user to get a sense of the proportion of successful to unsuccessful grant applications at a general level, the user may need finer-grained detail. Figure 8-9 shows the user adjusting

the settings of the VR to increase the degree of fragmentation (from L to R). As the ideal setting depends on the task being performed, users should be given the ability to adjust this property in either direction. For instance, while the VR in Figure 8-9 (R) gives detail at a finer level of granularity, the higher degree of fragmentation can increase perceptual load and impede the performance of tasks that do not require that amount of fragmentation.



Figure 8-9 Adjusting the settings of the VR to increase the fragmentation (L to R).

8.3.2.3 Interactivity

Here we will give an example of a single interaction to demonstrate how the micro-level interactivity analysis described in Section 5.4.2 influenced design thinking. One task that the client expressed a desire in performing was to be able to identify yearly changes in collaboration clusters. To support this task, the tool offers a special filtering action, in which the reaction shows and hides changes to the clusters according to year. This particular interaction was implemented with deliberate attention to its action *granularity* and its reaction *flow*. As described in Section 5.4.2, action granularity is concerned with the constituent steps of an action, and has two main forms: atomic and composite. Both forms of action granularity are offered to the user for this interaction. In the composite form, the user performs a number of steps to set the parameters of operation (e.g., set the time period between 2009 and 2012, set the speed of the yearly change), and then presses a ‘start’ button such that the reaction occurs according to the determined parameters. Alternatively, in the atomic form, the user can simply click a button that has default parameters and the reaction ensues. In the first case, the steps of the action may engage

the user more deeply in the sense making activity. As described in Section 5.4.2, reaction flow is concerned with how a reaction is parsed in time, and has two main forms: discrete and continuous. For this interaction, only continuous flow was implemented. As the year changed from one to the next, the new clusters slowly appeared over a period of a few seconds, while the old clusters disappeared over the same time interval. This continuity provides support for perceptual tasks, allowing easy identification of changes in the information space over time. In an earlier version of the tool, the reaction flow was discrete, which led to greater cognitive burden in trying to reason about year-to-year changes in the information space.

In EDIFICE-IVT, the analysis of macro-level interactivity was a preliminary attempt to give some high-level structure to interactivity at this level. Therefore, at this point in the research, we are far from having a comprehensive understanding of macro-level interactivity that could lead to any sort of principled prescriptive guidance. However, the macro-level analysis of EDIFICE-IVT can still support design thinking at a high level. Here we list very briefly how each factor influenced design thinking. With respect to *diversity* of actions, we made a conscious attempt to give the user many different action possibilities in order to give rich support for the emergence of the overall activity. Other action possibilities that could have been implemented, but had little perceived cognitive utility, were left out to avoid overwhelming the user. With respect to *complementarity*, although it is impossible to demonstrate the multiple ways of combining and sequencing actions to meet the goals of certain tasks, one example will be given. Based on the goals of the client as described above, we determined that it would be beneficial to have the scoping and filtering actions complement one another. Thus, a specific filtering ability was implemented such that the two actions could easily work in tandem (see Figure 8-10).

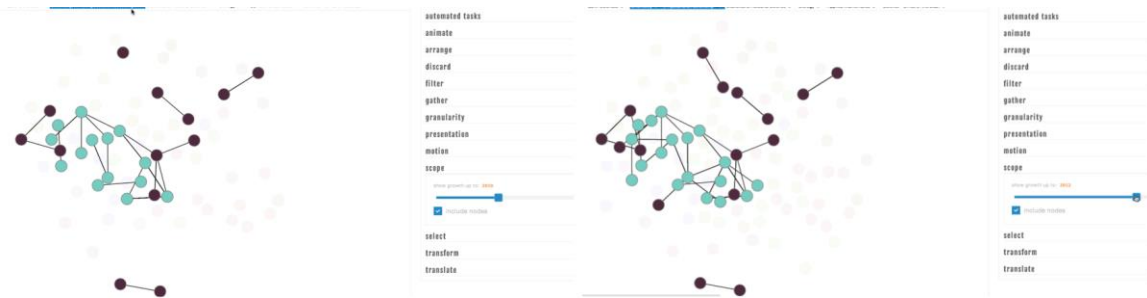


Figure 8-10 Combining filtering and scoping to show co-publications between two departments until 2010 (L) and 2012 (R).

With respect to the factor of *fitness*, we consulted EDIFICE-IVT to support reflective thinking about the appropriateness of the interactions offered by the tool. As should be apparent in the sections above, we thought very carefully about the task fitness of the implemented interactions. Indeed, the desired tasks were identified at the outset and used to make design decisions throughout the design process. Design decisions with respect to semantic fitness have also been described throughout the previous sections. As both the intended user group and the contextual settings for tool use are very homogeneous, user and context fitness were not difficult to address in design. In other words, interactions were geared to the skills and cognitive needs of the users (i.e., primarily university administrators) and the environmental requirements (i.e., a web-based tool for supporting sense-making activities). With respect to *flexibility*, the main adjustability options provided with this tool are with regard the properties described above in Section 8.3.2.2, as this is the aspect of flexibility that has been most clearly analyzed and explicated in the research thus far. Additionally, to support exploratory tasks, little rigidity has been put in place with respect to the possible sequencing of actions. Furthermore, certain tasks have been supported by deliberately offering different action trajectories to meet the same goal. For example, a user can perform a single action to have the tool spatially isolate the individual collaboration clusters and hide individuals that do not belong to any cluster. Alternatively, the same goal can be reached through the performance of multiple filtering, arranging, and transforming actions. With respect to the factor of *genre*, the transaction styles are a combination of access, annotation, and modification—that is, the user can perform actions that give access to existing, tool-created VRs, that allow adding personal

meta-information to the existing VRs, and that allows altering the properties of the existing VRs. Currently, no available actions support construction-based transactions. In a future version of the tool, such actions may be made available to support decision making and forecasting through simulations and hypothetical scenarios.

8.4 Summary

This chapter has described the design of a tool using the research presented throughout the previous chapters of the dissertation. Although it is not possible to depict the organic nature of the design process, we have tried to demonstrate how our research leads to systematic and principled design. By combining the different approaches described in this chapter, our research provides a robust, high-level design framework. In other words, designers can think about the design of a tool from multiple angles that often overlap one another. For instance, although a designer may have used the action taxonomy from EDIFICE-AP during design, by consulting EDIFICE-PVR, the designer may identify the need for an additional action based on some property that should be adjustable. Furthermore, by consulting EDIFICE-IVT, the designer may realize that one of the action components should be operationalized differently to support a task that users will likely perform. Such an interwoven process should be continual throughout all stages of design. In addition, the designer must think about the benefits and tradeoffs of using certain categories of VRs to communicate aspects of an information space, and how the information-processing load should be distributed across the user and the tool. Although this chapter has only described a small portion of the whole design process, it should demonstrate how using this research as a design framework for conceptual support can lead to more systematic and principled design of tools that support for the performance of complex cognitive activities.

8.5 References

Cooley, M. (2000). Human-Centered Design. In R. Jacobson (Ed.), *Information Design*, pp. 59-81. Cambridge, MA: MIT Press.

- Hansen, Y. M. (2000). Visualization for thinking, planning, and problem solving. In R. Jacobson (Ed.), *Information Design*, pp. 193-220. Cambridge, MA: MIT Press.
- Stolterman, E. (2008). The nature of design practice and implications for interaction design research. *International Journal of Design* 2(1), 55-65.

Chapter 9 Summary, Contributions, and Future Work

This dissertation has touched upon a number of themes related to human-information interaction in complex cognitive activities and the design of tools that support such activities. This chapter is divided into 3 main sections: (1) a summary of each chapter and some of its contributions; (2) general conclusions about the utility of this research for science and for design; and (3) suggestions for future work.

9.1 Chapter Summaries and Contributions

This section provides a summary of the main research presented in this dissertation (Chapters 3 to 7), and identifies some of their particular contributions to the existing literature.

Interaction design. In Chapter 3, we present one component of the EDIFICE framework, EDIFICE-AP. This component syncretizes a number of foundational concepts related to interaction and complex cognitive activities. These include information space, visual representations, epistemic actions, interactive coupling and complex cognitive activities, levels of interaction, and emergence of complex cognitive activities. Included in the framework is a catalog of 32 fundamental epistemic action patterns. Each action pattern is characterized and examined in terms of its utility in supporting different complex cognitive activities, and potential usage scenarios are identified to provide examples for designers and to stimulate creativity. This framework can greatly support interaction

designers by helping them to become familiar with the process of complex cognitive activities and the role of individual action patterns in performing them.

Adjustable properties of VRs. In Chapter 4, we present a second component of EDIFICE, EDIFICE-PVR. This component presents an ontological analysis of interactive VRs as they are used to support the performance of complex cognitive activities. This constitutes a major contribution to the existing research literature, as such an analysis does not currently exist. As a result of this analysis, 10 essential, relational properties whose values can be adjusted through interaction are identified. Each one is characterized and effects on perceptual and cognitive processing are discussed. Studies that shed light on the effects of a particular property are also discussed. In addition, we demonstrate how, through adjusting the values of these properties, better coordination between humans and tools can be effected, leading to higher-quality performance of complex cognitive activities.

Interactivity. In Chapter 5, we present a third component of EDIFICE, EDIFICE-IVT. While EDIFICE-AP deals with interaction, EDIFICE-IVT deals with interactivity. The distinction between the two is critical for systematic research and design. Thus, aside from the framework itself, an important contribution of this chapter is an explication of the concept of interactivity. As interactivity is a broad and complex construct, it is categorized it into two levels: micro and macro. Interactivity at the micro level emerges from the structural elements of individual interactions. Interactivity at the macro level emerges from the combination, sequencing, and aggregate properties and relationships of interactions as a user performs an activity. Twelve micro-level interactivity elements and five macro- level interactivity factors are identified and characterized.

Distribution of information processing. In Chapter 6, we present an analysis of the distribution of information processing in human-VT cognitive systems. The chapter identifies and elaborates upon some key concerns, integrates some fundamental concepts, and highlights some current research gaps that require future study. In addition, it builds on earlier conceptualizations of the structure and process of human-information discourse, primarily from EDIFICE-AP and EDIFICE-PVR. Although this chapter is a

preliminary explication of the issue, and does not constitute an exhaustive analysis, it is still expected that it will be perceived as a valuable research contribution. The existing literature does not contain anything similar, and this chapter integrates a number of existing concerns in a logical and consistent manner. In doing so, it can promote further research in this area and support high-level design thinking.

Cognitive utility of common visualizations. In Chapter 7, we present 6 categories of VRs, and categorize a number of common techniques according to their structure, function, and cognitive utility. Although this chapter does not present a comprehensive categorization of all existing techniques, it is expected that it will be welcomed as a valuable contribution to the existing literature. Since at least 2005, researchers have been suggesting this is a much-needed area of research, as comprehensive taxonomies and frameworks in this area can bring order and structure to the growing landscape of visualization techniques. Moreover, such taxonomies and frameworks can help designers deal with an overwhelming number of visualization techniques by choosing VRs that fit the context. In this chapter we discuss the perceptual and cognitive influences of VRs in each category, with a concerted effort to identify utility for complex cognitive activities.

Figure 9-1 below situates these contributions within the general model of human-information interaction that was presented in Chapter 3. Although the coherent nature of these contributions has been discussed throughout this dissertation, Figure 9-1 serves to depict their structural and logical relationships in a diagrammatic fashion. This figure should suggest to the reader at least the internal consistency and unity of the contributions, and should demonstrate how these individual contributions are not isolated research endeavors. It is ultimately in this respect—i.e., the manner in which the individual components of the dissertation finally come together in a seamless and complementary fashion—that this dissertation makes its most consequential contribution to the existing design landscape. Designers can engage in a *systematic process of design* of the different components of CASTs using this integrated and coherent framework. For example, a designer can use Chapter 7 to make principled decisions about how to visually represent their datasets and information spaces (orange in Figure 9-1); Chapter 6 to make

principled decisions about how to distribute the load of information processing in their desired user-tool system (purple in Figure 9-1); Chapter 4 to make principled decisions about adjustability options for their chosen VRs based on the requisite contextual factors (blue in Figure 9-1); Chapter 3 to make principled decisions about which epistemic action patterns to implement to support the intended users' cognitive activities and to support adjusting the properties of the previously chosen VRs (red in Figure 9-1); and Chapter 5 to make principled decisions about how such interactions (actions and reactions) should be operationalized (green in Figure 9-1).

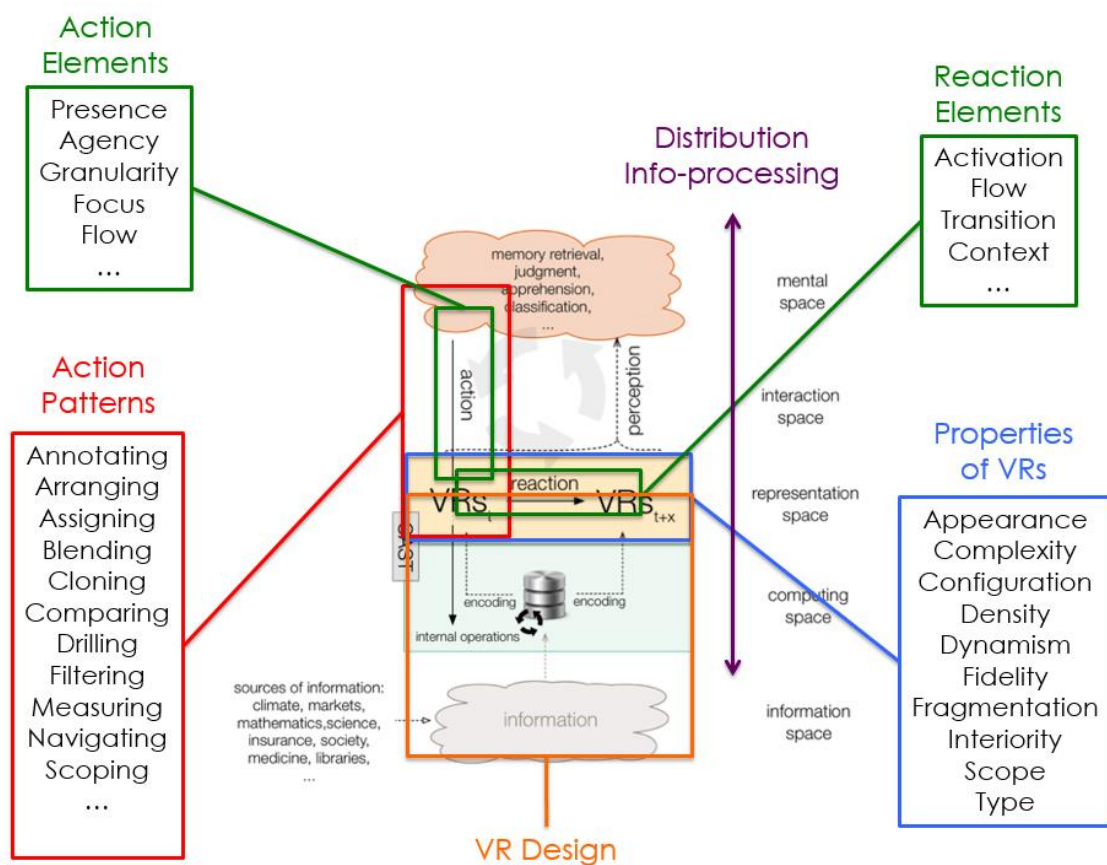


Figure 9-1 Major aspects of the dissertation as components of a coherent framework.

9.2 General Contributions and Conclusions

While Section 9.1 summarizes and describes some of the particular contributions of each chapter, this section briefly draws some general conclusions about the utility of this research for science and for design. Unlike the discussion of particular contributions above, the general conclusions drawn here are based primarily on the philosophical approach, conceptual novelty, and theoretical integration of the dissertation at a foundational level.

9.2.1 Scientific and Research Contribution

As described in Chapter 1, the broad concern of this research lies at the intersection of interactive computational technology, informatics, and human cognition. Various labels are given to research that falls into this area of concern, including information visualization, human-computer interaction, human-information interaction, cognitive tools and technologies, informatics tools, decision sciences and decision support, educational technology, and others. As a relatively young area, research has typically been scattered and fragmented according to the primary discipline in which researchers reside. Further fragmentation has arisen from researchers bringing assumptions, methodologies, and terminology from their own backgrounds into this area of research. Throughout this dissertation, we have highlighted the need to move beyond the phase of narrow specialization and excitement about impressive tools, to a phase in which commonalities are abstracted, and the deeper, general features of this area of research are explicated and integrated into coherent, unifying theories, models, and frameworks. It is in response to this aforementioned need that this dissertation makes its main general contribution to the research community at a foundational, theoretical level. That is, the main overall contribution of this dissertation is a general, unifying, comprehensive, theoretical framework. Aside from the particular contributions of this dissertation, its manner of syncretic conceptualization and theoretical integration can provide a unified foundation for true interdisciplinary research. This framework goes to the very heart of cognitive support for human-information interaction with computational technologies. Researchers in many domains can use the research presented herein to support

conceptualization, interdisciplinary communication, the development of more special models, theories, taxonomies, and frameworks, and to help frame empirical studies and interpret their results.

9.2.2 Design Contribution

The second overall contribution of this dissertation has to do with the support it provides for the design of cognitive activity support tools. As described throughout this dissertation, much of the existing design support is concerned with static VRs and/or with only low-level perceptual and cognitive effects of VRs, and not explicitly with design for complex cognitive activities. As a result, designers are left largely on their own when it comes to interaction and interactivity design for supporting complex activities with interactive VRs. As Chapter 8 has described in detail, this dissertation provides 3 main forms of design support: (1) coherent support for reflection and decision-making; (2) individual concepts that are intriguing and open for interpretation and reflection on how they can be used; and (3) high-level theoretical and/or philosophical ideas and approaches that expand design thinking. Using this dissertation, designers can approach the creation of a tool with a robust mental model of how humans interact with information to perform complex cognitive activities. Chapter 8 has given a detailed account of how this research can support principled design in a systematic manner. Designers in the following areas will likely find this dissertation useful: data and information visualization, medical and health informatics, journalism, statistics, data science, visual analytics, digital games, and educational and learning technologies.

9.3 Future Work

Future extensions of this research can be divided into the following three categories: descriptive and explanatory models, taxonomies, and frameworks; prescriptive design support; and empirical studies. Readers can also consult the future work sections of individual chapters to get a more specific discussion of future work with regard to a particular aspect of the dissertation.

9.3.1 Descriptive and Explanatory Models, Taxonomies, and Frameworks

9.3.1.1 Interaction

Although this dissertation has carefully explicated certain areas of the research space, others still remain. For instance, the level of abstraction between action patterns and activities—namely, tasks—has been treated in only a cursory manner thus far. Research needs to develop a clearer understanding of this level of interaction, and address existing research questions such as: What are the main tasks that exist, and what are their respective characteristics? Which actions most effectively lead to the completion of which tasks? Which tasks are most commonly used to perform which activities? At a lower level than action patterns, taxonomies that organize and categorize interaction techniques, if devised, can be integrated with the action taxonomy of EDIFICE-AP. There are currently hundreds of existing techniques that are presented and discussed in the literature with no existing comprehensive categorization. Research in this area could greatly organize and simplify the interaction design space. Another closely related line of research is in devising new sets of interaction techniques and implementations that fall under the same action pattern to compare, contrast, and study their trade-offs. As it is now, we have little principled understanding of the relative benefits of interaction techniques for achieving a particular action-based goal. Further research needs to be conducted to explicate the cognitive processes that make certain tasks and actions useful at a more fine-grained level. Although some of this research exists, much of it has been conducted in contexts other than cognitive support with interactive visual representations.

9.3.1.2 Interactivity

While the framework presented in Chapter 5 gives a very broad coverage of interactivity, and is comprehensive in identifying the elements and factors of micro- and macro-level interactivity, future work is needed to bring more depth to our understanding. For example, although we have identified factors that affect interactivity at the macro-level, such as diversity of actions, we still have little understanding of which particular actions

should be made available to users in any given context. We know that providing too few or too many actions can incur a cognitive cost, yet do not have any existing model to determine the cost or ideal number in particular settings. To give another example, we know that complementarity of actions affects interactivity at the macro level. However, similar to the situation with diversity, we do not have a comprehensive understanding of which actions complement each other. Conducting further research in these areas to develop models, taxonomies, and frameworks would be a very welcome contribution to the existing research. Although more work has been done on interactivity at the micro level than at the macro level, there is still a great deal of research that can be done. In addition, although the general framework presented in Chapter 5 is important, special frameworks also need to be developed to enhance our understanding. For instance, in the context of digital games, frameworks could be developed that describe how micro-level operational forms of interactions during gameplay affect cognitive processes of the player. As another example, frameworks could be developed that describe such effects for analytical reasoning of genome sequences in bioinformatics tools. Such frameworks can reduce the conceptual distance between the general framework presented in Chapter 5 and a particular domain of application for the design of empirical studies and the development of prescriptive design guidance.

9.3.1.3 Visual representations

Although Chapter 7 has categorized techniques of visual representation and discussed some effects on cognitive and perceptual processes, there still remains much research to be done in this area. Future research should develop more comprehensive and elaborate taxonomies and catalogs of VRs. One potentially useful area of research is to develop frameworks that systematically describe the communicative utility of different categories of VRs. For example, while it is known that certain VRs readily communicate certain aspects of an information space, we are far from having coherent explanatory models and comprehensive descriptive frameworks and taxonomies in this regard. Another potential line of future research is in developing a more principled understanding of the relationship between perception and cognition in the performance of complex cognitive activities. While we know that the perceptual effects of certain visualizations may

naturally facilitate certain cognitive activities, there it is still based on a large degree of speculation and somewhat nebulous principles. Finally, a grand challenge of such research must be to develop comprehensive descriptive frameworks that integrate the aforementioned lines of research. Descriptive frameworks can capture a broad range of considerations to help thinking about the utility of all kinds of visualizations for many different cognitive activities. Carrying out these aforementioned lines of research can help develop a more comprehensive understanding of how visual representations can and should be used to support complex cognitive activities.

9.3.2 Prescriptive Design Support

With regard to prescriptive design support, a number of different avenues of research can be pursued. One is the development of prescriptive frameworks that give clear design guidance for domain-specific users and contexts. For instance, prescriptive frameworks can be devised to support design in the context of decision support for intelligence analysis. Such a framework would include design guidance for supporting specific tasks, including which action patterns are particularly useful, techniques for their implementation, and benefits of different operational forms. Such frameworks could also be developed for other contexts such as education, personal information management, or clinical decision support. Prescriptive frameworks can also be devised to guide the design of visual representations in particular contexts. Although some support already exists in this regard, it is not well organized and is far from comprehensive. One useful but challenging line of future research is in developing a pattern language for the design of visual representations. Such a pattern language could assist design at multiple stages and levels of abstraction. For example, designers could be given assistance in determining the characteristics of an information space and, with the needs of the user in mind, determining how to best represent certain aspects of the information space. Such a framework could also help the designer move down to the level of concrete implementation, giving guidance for encoding information with colors, textures, and other visual variables. As more ‘non-expert’ designers (e.g., journalists, data scientists) are becoming interested in designing interactive visualizations, such prescriptive

frameworks can help designers avoid common mistakes and provide invaluable support for principled design.

9.3.3 Empirical Studies

Numerous lines of future empirical investigation are opened up by this dissertation. One of the main issues that this dissertation highlights is that previous research has been fragmented, focusing on only a small subset of actions, properties of VRs, and interactivity elements and factors. Thus we do not have a balanced landscape of empirical findings from which to draw. For example, although there is evidence to suggest how the values of properties of VRs affect some activities (e.g., problem solving), others are not as well understood (e.g., analytical reasoning); while the effects of some action patterns on cognitive processes have been well established through empirical means (e.g., studies on arranging tiles while playing Tetris), others (e.g., blending) have not received much attention; while we have a general understanding of how to distribute the information-processing load during the performance of complex cognitive activities, research is lacking when it comes to particulars; and, while some micro-level interactivity elements have been carefully studied (e.g., action and reaction flow) others have received little attention. By identifying many different aspects of human-information interaction and articulating them coherently in a comprehensive framework, it is hoped that our research will invite a more balanced empirical investigation of all the factors that require further study.

In addition to stimulating the type of empirical research described above, the novel contributions of this dissertation can facilitate the framing of studies and the interpretation of results. For example, a particular category of VR can be studied to determine its effect on cognitive processes and its utility for supporting a particular set of tasks (e.g., detecting anomalies in gene sequences with radial convergence diagrams). While a result may be discovered, the researcher knows from consulting this dissertation that the VR has a number of essential properties that influence cognitive processes. If the VR was not originally designed with proper adjustability options in mind, the result of the study may not provide decisive information about the utility of the VR in that

particular context. If the study is run with users being given adjustability options to support the requisite tasks, a different result may be found. Alternatively, the researcher may consult this dissertation and determine that the complementarity of actions was not appropriate under the given circumstances, or that too much of the information-processing load was placed on the mental space of the user. Although this is a contrived example, it should indicate the robust nature of this dissertation with respect to promoting and supporting future empirical research.

Chapter 10 Appendices

10.1 Additional Action Patterns⁶

The following provides a detailed characterization of the remaining 28 action patterns, along with their epistemic utilities, usage scenarios, and example CASTs in which they have been used. Although under each pattern we suggest certain activities that the action facilitates, because complex cognitive activities are emergent phenomena that result from the interaction of numerous actions and tasks, each action pattern can have utility in all activities. We have simply provided references to research in which an action has been shown to support some particular activity. Additionally, research with regard to the usage and effect of the different actions in the context of different activities is not evenly distributed. Despite the fact that we have tried to devote the same amount of space to each pattern, because some actions have been previously investigated more than others, we provide more references for some actions than others. However, EDIFICE-AP may encourage more systematic and balanced research to investigate the presented actions in the context of different information spaces, VRs, CASTs, and complex cognitive activities.

10.1.1 Unipolar Actions

10.1.1.1 Annotating

Characterization: Acting upon VRs to augment them with additional visual marks and coding schemes. This action creates a layer of personal meta-information on top of existing VRs. Here, “meta” signifies personalized editorial marks and commentary. Annotating does not inject information into the original information space.

⁶ Full references are listed in section 3.6

Utility: Among others, this action facilitates learning, sense making, problem solving, and reasoning (Hwang and Shadiev, 2008; Schilit et al., 1998; Harris, 1990; Sedig et al., 2002; Wolfe and Neuwirth, 2001; Fast and Sedig, 2011; Marshall, 1997). In reasoning, problem solving, and sense making, augmenting VRs with additional information can facilitate reflective, inductive, and elaborative thinking (Ormrod, 1995; Kahney, 2003; Peper and Mayer 1986). It supports and encourages users to build and strengthen connections between the represented information and their previous knowledge (Peper and Mayer, 1986; Foos et al., 1994). This in turn can facilitate critical thinking, which is fundamental to understanding and acquisition of further knowledge (Phelps and Wilensky, 1997; Schilit, et al., 1998). Annotating can facilitate recall and reflection on past action, thereby supporting search for solutions to problems (Pimm, 1995; Preece et al., 2002; Sedig et al., 2002). Annotating can also help with text comprehension and reading. It can promote users' meta-cognitive skills and aid understanding, memorization, and later retrieval (Slotte and Lonka, 1999; Hwang and Wang, 2004; Kiewra, 1989). Annotating, even in the form of simply underlining text, can be as effective as or equivalent to other learning strategies such as re-reading, answering periodic study questions, or summarizing (Anderson et al., 1984). The ability to spontaneously annotate information can facilitate sense making, even if users are not given a chance to review their annotations (Lonka et al., 1994; Lahtinen et al., 1997). Past research has shown that test performance and writing ability can improve as a result of annotating (Harris, 1990; Hynd et al., 1990; Strode, 1991). For instance, in a study by Liu (2006), it was noted that annotating while reading facilitated more critical thinking as reflected in students' essays, and that the students with good annotating skills made exceptional progress in their writing.

Utility in CASTs: An example of a CAST that implements the annotating pattern is *Tableau*. Figure 13 shows a user analyzing the money dedicated to the economic development and welfare of developing countries. During the activity, she notices that Russia's provision of aid is comparatively small. She then remembers reading a report that provided more information, and decides to annotate the VR with this personal meta-information to act as a reminder.

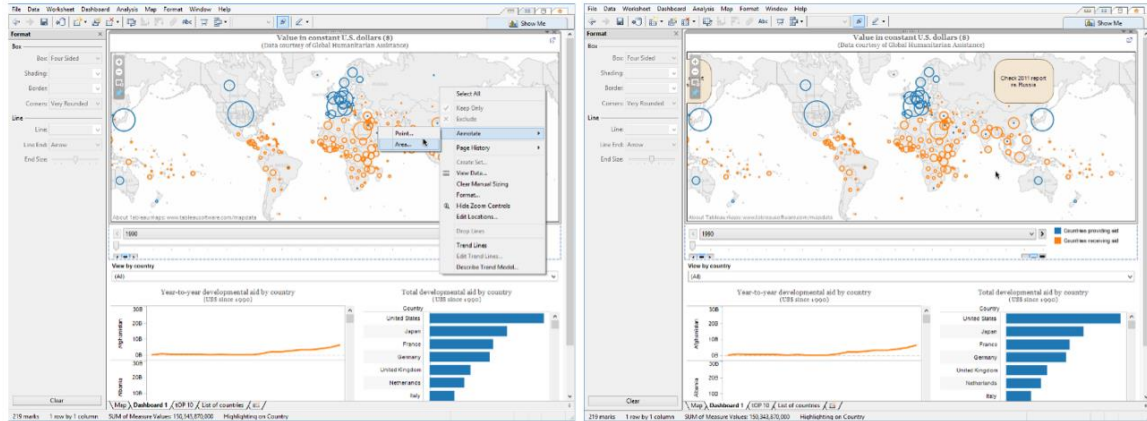


Figure 10-1 An implementation of the annotating pattern: Acting upon a VR to add a layer of personal meta-information

Note: Visualization by Stuart A. Thompson

www.tableausoftware.com/public/gallery/economic-development-aid

Other usage scenarios: In a CAST containing VRs encoding a microbiology information space, given an image of a cell, learners may want to annotate it with some linguistic comments. In an adventure digital game, given a set of VRs encoding resources, players may want to attach a mark to a particular resource to be used later on. In a data analysis CAST containing a plot, users may want to attach labels or explanations to sub-systems of the plot (e.g., its data elements).

10.1.1.2 Arranging

Characterization: Acting upon VRs to change their order. Some variations of arranging are moving, ordering, sorting, organizing, configuring, classifying, positioning, and ranking.

Utility: Among others, this action facilitates reasoning, problem solving, and sense making (Kirsh, 1995; Kastens et al., 2008; Peng, 2005; Yang et al., 2003; Siirtola, 1999; Pirolli and Rao, 1996; Spence, 2007). Arranging allows users to explore and detect underlying patterns, dependencies, trends, correlations, and relationships in the represented information (Spence, 2007; Stolte et al., 2002; Siirtola, 1999). Arranging can

also aid with the simplification of a representation space, trigger associations in the mind by presenting a fresh way of viewing the information, and aid with the organization of information (Kirsh, 1995; Kastens et al., 2008). For instance, often only by arranging rows and columns in a table, patterns and trends in information can emerge (Stolte et al., 2002). Arranging can affect a tool's perceived clutter and structure (Peng, 2005). Arranging by bringing different entities of a VR closer together can be useful since the relationships among proximate elements are easier to detect than relationships among elements positioned far from each other (Yang et al., 2003).

Utility in CASTs: An example of a CAST that implements the arranging pattern is *Table Lens*, an information visualization tool for making sense of multivariate datasets (Rao and Card, 1994). In this CAST, users can interact with a table by arranging (e.g., sorting) its rows and columns, thereby discovering correlations between different variables (Pirolli and Rao, 1996).

Other usage scenarios: In a pollution analysis tool, given a geographic map with icons representing different pollution-generating entities (e.g., factories, power plants, etc.), users may want to move a factory from one location to another to see its effect on the amount of pollution in a geographic region. In a CAST for making sense of financial data, given a tree diagram, users may want to re-arrange its sub-trees to experiment with different dependency relationships.

10.1.1.3 Assigning

Characterization: Acting upon VRs to bind a feature or value to them (e.g., meaning, function, or behaviour). Some variants of this action pattern are designating and attributing.

Utility: Among others, this action facilitates sense making, investigating, reasoning, problem solving, and learning (MacKeracher, 2004; Kieran, 1989; Radford, 2002, 2006; Renkl, 1997). In mathematical problem solving and reasoning, assigning values to algebraic statements can facilitate reasoning about the generalization of patterns (Radford, 2006; Kieran, 1989). Assigning values to symbols in an algebraic statement

can make it possible to see how higher-order meanings are made available for further affirmation (Radford, 2002). Assigning is also useful for forecasting activities—that is, predicting what will happen in the future (MacKeracher, 2004).

Utility in CASTs: An example of a CAST that implements the assigning pattern is *NetLogo* (Wilensky, 1999), a multi-agent programming language and modelling environment for simulating natural and social phenomena. Users can assign behaviours to hundreds or thousands of “agents” all operating independently. For example, while learning about the stability of predator-prey ecosystems such as those involving wolves and sheep, by assigning behaviours to the wolves or sheep, users can explore the connection between the micro-level behaviour of individual information elements and the macro-level patterns that emerge from the interaction of the collection of the individuals.

Other usage scenarios: In a CAST for exploring mathematical functions, given both a graph and a symbolic algebraic statement, learners may wish to assign different values to symbolic VRs to see what subsequent changes occur in the graph. In a problem solving CAST, given symbolic VRs representing agents that can carry out simple tasks, to solve problems and overcome obstacles users may want to dynamically select from a set of behaviors, functions, and capabilities and assign them to the symbolic entities to explore different problem solving strategies (e.g., as in the children’s game *Lemmings* in which the characters are assigned different functional properties).

10.1.1.4 Blending

Characterization: Acting upon VRs to fuse them together such that they become one indivisible, single, new VR. Blending is different from composing in that once VRs are blended together they are not meant to be separated again. The original VRs become indistinguishable from one another when blended together. Some variants of this action pattern are merging, fusing, and melding.

Utility: Little research has focused on the cognitive utility of this action pattern. However, it is likely that blending facilitates analysis, problem solving, and planning. In collaborative work environments, for example, multiple users often work with different

copies of a VR. After working with these VRs, they can act upon the VRs to fuse them into one new VR, which can then be used to support group planning and decision making. In a similar fashion, a single user may be working with multiple copies of a VR and wish to blend them so that all of their features are incorporated into one new VR. Such is a common action in many productivity CASTs such as *Microsoft Office*.

Utility in CASTs: Hao et al. (2012) discussed an example of an implementation of blending in the context of visual analytics. They introduced an interaction technique called ‘motif merging’, which facilitates the exploration of frequently occurring patterns in time-series datasets. Thousands of items can be encoded within such large and complex datasets, resulting in visual clutter that hinders task performance. The authors’ technique allows the user to act upon a slider to set a threshold value, causing VRs within the specified value to fuse together. They suggest that this blending action reduces clutter and consequently facilitates the analysis activity.

Other usage scenarios: In a CAST for personal information management, a user may have a set of notes and ideas that are fragmented across different VRs within the tool. The user could select such VRs and act upon them to merge them together into one new VR. In a CAST for learning about chemical substances, a user may be working with a number of different VRs, each having different properties (e.g., solubility). As the user learns about each one, to support more complex higher-order thinking, the tool may encourage users to blend the VRs into one new VR that combines the properties of each. The new VR may then be used to enable and facilitate more complex tasks.

10.1.1.5 Cloning

Characterization: Acting upon VRs to create multiple identical copies of them. Some variant actions of cloning include copying, duplicating, multiplying, and replicating.

Utility: Among others, this action facilitates problem solving, investigating, and learning (Papadopoulos and Dagdilelis, 2008; Lamberty and Kolodner, 2002; Bauer and Wise, 2004; Clements et al., 2004; Jordan et al., 2006). In the context of problem solving and learning, Papadopoulos and Dagdilelis (2008) found that learners cloned VRs within a

CAST to verify intermediate results or statements, such as verifying hypotheses about the number of shapes needed to fill up an area. In addition, while programming, being able to clone portions of code allows a programmer to build a high-level representation of the generic solution to a problem and apply it to multiple instances (Détienne and Bott, 2002). Cloning code allows programmers to reuse portions of software programs. In this way, cloning facilitates solving large problems more efficiently (Hoadley et al., 1996). When learning about visual patterns, cloning can allow the creation of complex designs to occur more quickly. This can facilitate deeper learning (Lamberty and Kolodner, 2002). Additionally, providing learners with facilities to be able to copy numbers and text can be useful when building writing skills and learning about numbers (Bauer and Wise, 2004; Jordan et al., 2006).

Utility in CASTs: An example of a CAST that implements the cloning pattern is *Cytoscape* (Shannon et al., 2003). Figure 14 shows a user exploring a network of yeast proteins during a knowledge discovery activity. Figure 14 (L) shows the user selecting a subset of the network VR to make a copy of it so that he can interact with the copied VR and not affect the original. Figure 14 (R) shows the result of the action, where the subset of the VR is copied into a new window that the user can then work with.

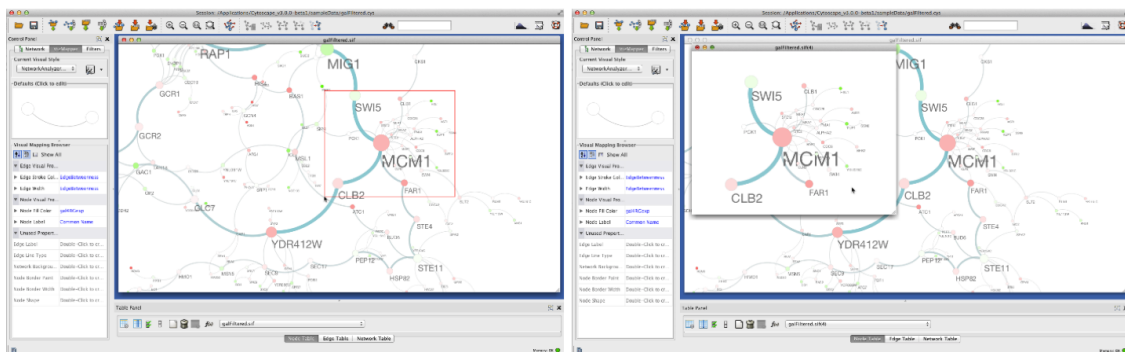


Figure 10-2 An implementation of the cloning pattern: Acting upon a VR of a protein network to duplicate a portion of it.

Other usage scenarios: In a virtual museum tool, users may wish to clone a digital artifact so they can explore it without affecting the original. In a drawing tool, while

creating a collage, users may want to clone a picture to use it multiple times in the collage.

10.1.1.6 Comparing

Characterization: Acting upon VRs to determine their degree of similarity or difference, where similarity and difference can be in terms of proximity of or distance between value, meaning, geometry, topology, and/or other properties. Comparing can also be a higher-level task, but here it is only discussed as an action.

Utility: Among others, this action facilitates learning, experimenting, problem solving, analytical reasoning, and sense making (Star and Rittle-Johnson, 2009; Keller and Keller, 1993; Gentner et al., 2007; Ross, 1987; Kurtz et al., 2001; Darian, 2003; Davidson, 2003). Comparing is useful when two or more VRs need to be analyzed without explicit ordering and with no rank implied for them (Keller and Keller, 1993). Comparing is integral to many analytical processes of thinking, such as observing, modelling, and quantifying (Darian, 2003; Smith and Medin, 1981; Novick, 1990; Ross, 1987). In the context of learning, comparing is recommended as an important learning strategy (NCTM, 2000), and its benefits have been demonstrated in multiple case studies (Fraivillig et al., 1999; Huffred-Ackles et al., 2004; Lampert, 1990; Silver et al., 2005). Additionally, comparing may be a fundamental pathway to flexible, transferable knowledge (Rittle-Johnson and Star, 2007; Gentner et al., 2003).

Utility in CASTs: An example of a CAST that implements the comparing pattern is *Multidatex* (Wu et al., 2006), a tool for making sense of multivariate datasets. By providing several interactive, dynamically-linked VRs, this tool allows users to explore correlations in multivariate datasets. Two such VRs are a parallel coordinate plot and a network graph. Users can investigate how variables that affect air pollution, for example, are correlated, through comparison of the observations in the dataset. To compare and determine their degree of similarity, the user can select two or more observations from the parallel coordinate plot. Alternatively, the user can select a group of observations and request the tool to draw a network graph, where its nodes correspond to observations and its links represent the degree of similarity between the observations.

Other usage scenarios: In a visualization tool, given a topographic map, users may want to compare the length of different routes through the map. In a CAST for supporting software development, given multiple versions of software code, programmers may want to compare them to determine the changes made over time.

10.1.1.7 Drilling

Characterization: Acting upon VRs to bring out interior information that is not currently displayed. Drilling is usually not intended to alter VRs. Its main function is to penetrate into perceptually inaccessible, deep information items of the space and make them available for further investigation.

Utility: Among others, this action facilitates learning, reasoning, and investigating (Peng, 2005; Jonassen and Grabowski, 1993; Yi et al., 2007; Hannafin and Hooper, 1993; Buchel and Sedig, 2011). Drilling involves selective attention and encoding and is a fundamental action in many activities. It is a details-on-demand action (Pylyshyn, 2003). Drilling can help make interesting objects easier to examine (Peng, 2005; Jonassen and Grabowski, 1993). Human attention plays a central role in most mental activities; however, it is a limited resource, and in complex fields of information users cannot attend to all information at once (Ormrod, 1995; Halpern, 2003). Consequently, by allowing users to focus attention on discrete items of information in detail, drilling can support convergent, narrow reasoning. Drilling usually involves shifting the focus of attention from broad scanning of an information space to narrow awareness of discrete elements in the space (Jonassen and Grabowski, 1993). In the context of learning, drilling allows users to process desired information more deeply, an important requirement for higher-order mental activities (Hannafin and Hooper, 1993).

Utility in CASTs: An example of a CAST that implements the drilling pattern is *VICOLEX* (Buchel and Sedig, 2011), a map-based visualization tool that acts as the front-end to a digital library. It supports users' sense making of document collections. During a sense making activity, users can drill into VRs of geographical regions to get on-demand information about a collection and its different properties.

Other usage scenarios: In a geovisualization decision support tool, given a map with icons representing different localities, users may wish to drill an icon to have more information about a particular locality before deciding on a destination. In an exploration or decision-making tool, given a treemap visualization of different universities within different states, users may want to perform multi-level drilling (e.g., drill a state to get a listing of its universities and drill one of the universities to get its physical map).

10.1.1.8 Filtering

Characterization: Acting upon VRs to display a subset of their elements according to certain criteria. Filtering allows users to exclude some of the sub-systems of representations from view.

Utility: Among others, this action facilitates reasoning, problem solving, decision making, sense making, understanding, and learning (Stolte et al., 2002; Kastens et al., 2008; Strothotte, 1998; Stone et al., 1994; Marsh et al., 2004; Desimone and Duncan, 1995; Spence, 2007). As stated before, attention is a limited resource, and users often cannot attend to all information at once. Filtering allows users to notice trends and patterns in information, which is an integral part of analytical reasoning (Stolte et al., 2002). Filtering also allows users to have control over the degree of detail of a VR, sometimes removing non-essential details from the surface of the VR. Adjusting the level of detail is an important feature of the process of abstraction in the exploration of complex information spaces (Strothotte, 1998). Examining issues at a higher level of abstraction and with less detail, noise, and complexity is an essential aspect of most complex cognitive activities that involve generalization, categorization, and induction. For instance, in decision making, filtering can decrease perceptual and cognitive load by reducing the number of elements competing for attention in the visual field, allowing users to focus on a smaller subset of information (Strothotte, 1998; Desimone and Duncan, 1995).

Utility in CASTs: An example of a CAST that implements the filtering pattern is *Global Council Interlinkage*, a tool that supports exploration of survey data from Global Agenda Councils of the World Economic Forum. Users are initially presented with a VR that

encodes hundreds of relationships, and is therefore too dense for most tasks. Users can act upon the VR to filter it such that only particular relationships are displayed, thus facilitating the performance of numerous tasks.

Other usage scenarios: In a personal information management tool (e.g., *Microsoft Outlook*), given a table (e.g., address book), users may wish to filter the elements based on a name or address criterion. In an educational tool, given a table (e.g., periodic table of elements), learners may wish to filter the table's elements based on criteria such as group or year of discovery.

10.1.1.9 Measuring

Characterization: Acting upon VRs to quantify some of their items. Examples of measurable items of information include area, length, volume, mass, temperature, time, duration, speed, and distance from other items. Variations of measuring are calculating and quantifying.

Utility: Among others, this action facilitates decision making, learning, reasoning, and understanding, particularly in contexts that require quantification of information (Berka, 1983; Henshaw, 2006; Clements et al., 1997; Reynolds and Wheatley, 1996; Bishop, 1991). Measuring can be useful in the development, understanding, analysis, and solving of mathematical problems and ideas (Romberg and Kaput, 1999; Clements and Stephan, 2004; Miller, 1989). For instance, Norback and Love (1977) demonstrated that it is possible to solve the travelling salesman problem by measuring angles between cities on a 2D plane. Measuring can facilitate transitive reasoning⁷, which subsequently allows reasoning about units and iteration (Clements and Stephan, 2004; Piaget et al., 1960; Long and Kamii, 2001). Measuring can also facilitate comparative decision making (Bishop, 1991).

⁷ This is a form of reasoning involving the use of an item as a referent by which to compare objects and to deduce a relationship between them.

Utility in CASTs: An example of a CAST that implements the measuring pattern is *GeoGebra*. Figure 15 (L) shows how a user has drawn a shape and is about to measure the angle between three of its entities (i.e., points). Figure 15 (R) shows the result of the action.

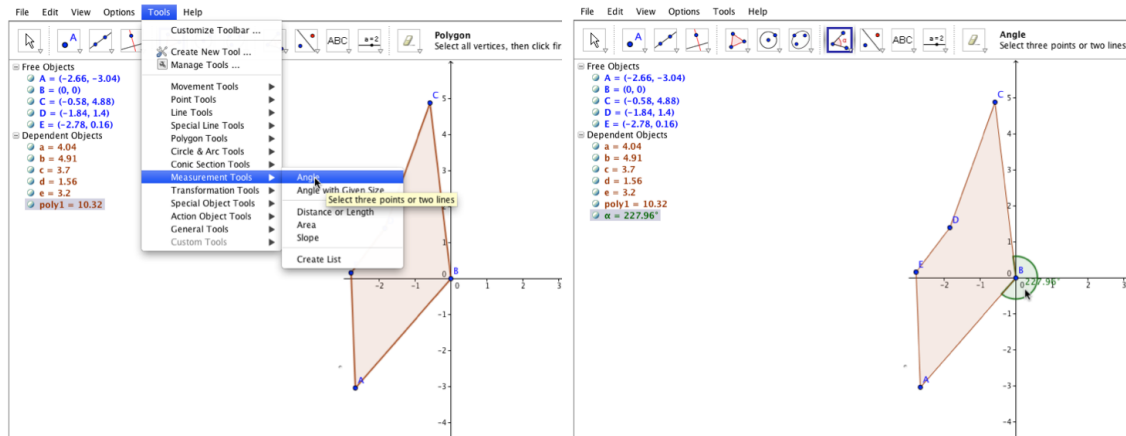


Figure 10-3 An implementation of the measuring pattern: Acting upon a VR to quantify one of its angles.

Other usage scenarios: In a virtual museum tool, users may wish to measure the dimensions of ancient artifacts. In a digital library, users may wish to measure the number of words in a document. In a geovisualization tool, a user may wish to measure the distance between two locations.

10.1.1.10 Navigating

Characterization: Acting upon VRs to move on, through, and/or around them.

Navigating can also describe higher-level tasks, in which case it involves subtasks such as identifying objects, moving, modelling, interpreting, and way finding. In this paper, however, navigating only concerns the action of moving. Navigating does not alter the representation on which it acts. Its variations in terms of utility are scanning and browsing.

Utility: Among others, this action facilitates learning, sense making, forming of concept maps, investigating, and knowledge discovery (Jul and Furnas, 1997; Dahlbäck, 1998; Spence, 1999; Jonassen and Wang, 1993; Lawless and Brown, 1997; Liang and Sedig,

2009; Sedig et al., 2003, 2005b). Navigating VRs helps with the formation of cognitive maps of an information space such as developing knowledge of its elements (or landmarks), relations (or routes), and structure (Liang and Sedig, 2009). As users navigate a VR, they acquire and modify their knowledge of its structure, integrate knowledge of several routes into one network of routes, all being part of the process of creating an internal cognitive map of a VR. In learning, allowing learners to navigate and map their own paths of motion in an information space has positive outcomes (Jonassen and Wang, 1993; Fischer and Richards, 1995; Lawless and Brown, 1997). Navigation can also facilitate understanding semantic relationships between pieces of information, such as links between two elements in a VR. Additionally, navigating a VR that encodes social relationships can help users develop an understanding of such relationships.

Utility in CASTs: An example of a CAST that implements the navigating pattern is *3DLatticeViewer* (Liang and Sedig, 2009), a tool that supports activities pertaining to 3D lattice structures. Figure 16 (from L to R) shows how a user can start from a point on the 3D lattice, which represents a chemical compound, and continuously move over its edges. By performing this action, the user can examine each connection in order to eventually discover how the chemical compound is structured.

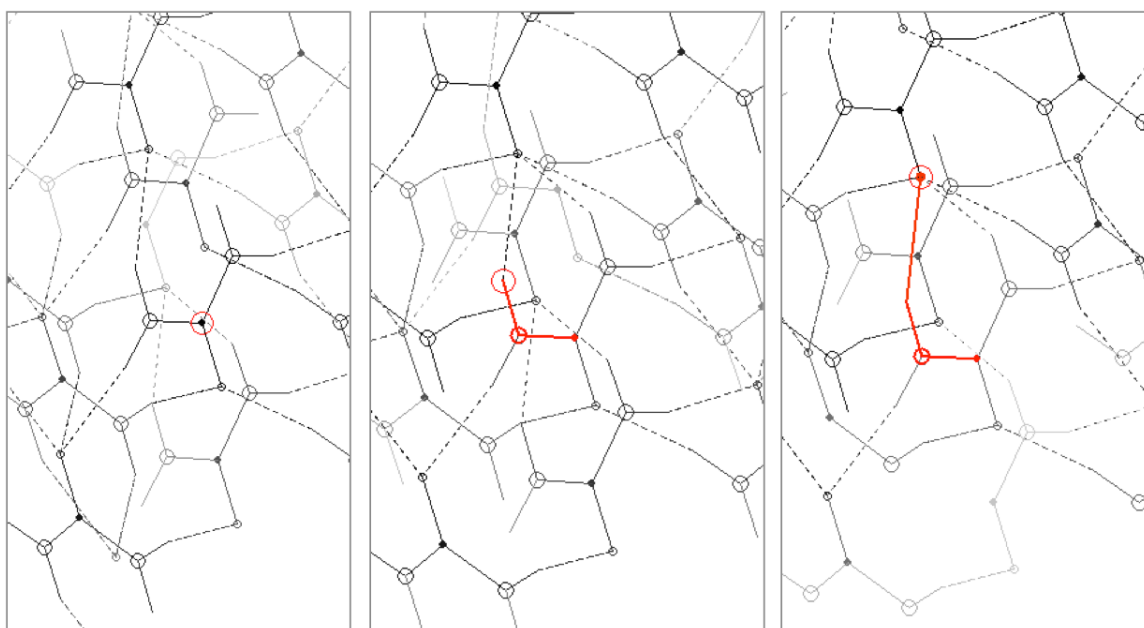


Figure 10-4 An implementation of the navigating pattern: Acting upon a VR to move across its components.

Other usage scenarios: In modelling software, given a 3D model, users may want to navigate around the model to view it from different angles. In virtual museum software, users may want to navigate through a virtual room to see its artifacts. In a CAST visualizing the network setup of an organization, an administrator may want to navigate a VR representing the network to see if all of the links work properly.

10.1.1.11 Searching

Characterization: Acting upon VRs to seek out the existence of or locate the position of specific items, relationships, or structures that satisfy certain criteria. Some variations of searching include seeking or querying.

Utility: Among others, this action facilitates sense making, understanding, investigating, and problem solving (Rowley and Hartley, 2008; Marchionini, 1997, 2006; Wolfe, 1998; Fast and Sedig, 2011). Searching is useful when users are aware that there is a knowledge gap, namely the idea that there is a distance between their contextual situation and the desired outcome (Marchionini, 1997; Kuhlthau, 1993; Dervin, 1992, 1997). When searching, users are actively attempting to answer questions or develop understanding around a particular question or idea. Users must generate the search and evaluate the results. Since it is impossible to fully process all of the stimuli in our visual field at one time (Tsotsos, 1990), searching supports the detection and selection of relevant information (Hannafin, et al., 1999). Searching allows users to actively replace or update mental models to make sense of a given situation (Klein et al., 2007; Marchionini, 1997; Dervin, 1977, 1983). Searching is often considered useful in problem solving (Marchionini, 1997; Gaslikova, 1999). Users may anticipate the content and possible sources of necessary information needed to solve a problem and execute a direct search, with which they can weigh the applicability of the results to their situation. Gaslikova (1999) notes that once a problem is structured and purposes are formulated, the strategy of information searching by means of exact retrieval requests seems to be the best strategy.

Utility in CASTs: An example of a CAST that implements the searching pattern is *Health InfoScape*, an e-health solutions tool. Figure 17 (L) shows the VR with which users are initially presented. Using this VR, it can be difficult to locate or discover the existence of specific items. Figure 17 (R) shows the result of the user searching for ‘neck pain’, in which case the relevant items are located and brought forward for viewing. After locating them, the user can perform further actions, such as drilling it for more information.



Figure 10-5 An implementation of the searching pattern: Acting upon a VR to seek out the existence of items related to 'neck pain'.

Other usage scenarios: In a complex and noisy network visualization tool, users may want to search a VR for smaller, constituent nodes representing information items. In a financial spreadsheet, users may want to search to locate a specific information item. In a CAST for investigating insurance fraud, given a large network diagram, an analyst may wish to search out the existence of a specific individual, transaction, or date.

10.1.1.12 Selecting

Characterization: Acting upon VRs to focus on or choose them. When applied to a set of VRs, selecting can perform a grouping function.

Utility: Among others, this action facilitates learning and investigating (Dalgano, 2004; Yi et al., 2005; Ward and Yang, 2004). Selecting can reduce cognitive demand (Brown, 1998). As we greatly depend on external information to reduce memory load, selecting a VR to set it apart or make it stand out can alleviate the cognitive load required to remember and/or keep track of it among other VRs. Selecting often precedes and is

necessary for performing other actions within a CAST (Dalgarno, 2004). By selecting a VR and making it visually distinctive, users can easily keep track of it within a large amount of information, even when the VR is going through some changes (Yi et al., 2005). Selecting a set of VRs to group them together into a perceptual or cognitive unit has utility across a set of activities as well, such as reasoning, decision making, problem solving, learning, and investigating (Kastens et al., 2008; Henry and Fekete, 2006; Cooper, 1998; Kirsh, 1995; Lane et al., 2000; Munyofu et al., 2007). Group-based selection helps users deal with an aggregate entity rather than a larger number of individual objects (Newel and Simon, 1972; Cooper, 1998; Gobet, 1998). Dealing with aggregate rather than atomic items can alleviate memory load (Newell, 1994; Cowan, 2001). Grouping also facilitates cognitive processes involved in encoding, extracting, remembering, and understanding information (Gobet et al., 2001). Group-based selection supports rapid pattern recognition at perceptual and cognitive levels, a common strategy used by expert problem solvers (Feltovich et al., 2006; Roberston, 2001; Halpern, 2003). This action can also facilitate decision making and organization (Foster and Stefik, 1986). For instance, in many strategy exploration CASTs, allowing users to select objects into groups enables them to investigate group behaviour and decide how to organize and focus resources. Finally, when exploring VRs, selecting can provide various benefits: 1) it can encourage selective exploration and analysis; 2) it can invite conjectures of both similar and dissimilar attributes of elements; 3) it can facilitate focusing on a subset of elements of the VR; 4) it can support comparative reasoning of elements within groups and among groups; and 5) it allows performing operations on entire groups.

Utility in CASTs: An example of a CAST that implements the selecting pattern is *Gapminder*. This tool can be used, for example, to support sense making of relationships between income and life expectancy of multiple countries. When presented with a scatterplot, users can select a country or a group of countries in order to keep track of them. Doing so helps users to reason about their changes in relation to other countries as the tool displays temporal changes in the information space.

Other usage scenarios: In a chemistry visualization tool, given a set of symbols encoding different gas particles, users may want to select one of the symbols so as to keep track of

it while adjusting parameters to do with pressure. In a sports analysis tool, given a video of a game, a coach may want to select one of its elements (i.e., a player) to monitor and analyze its movement. In a CAST for investigating trends in the stock market, users may wish to select a specific stock in order to keep track of it and see its temporal changes.

10.1.1.13 Sharing

Characterization: Acting upon VRs to make them accessible to other people or agents.

Utility: Among others, this action facilitates learning, planning, and decision making (Kirschner et al., 2009; Leidner and Fuller, 1997; Wu et al., 2009). Sharing has particular utility when a user is faced with a complex task, in that it allows the cognitive load required to perform the task to be distributed across the cognitive systems of multiple individuals. Kirschner et al. (2009) suggest that although such distribution requires information to eventually be reintegrated into the sharer's mental space, when tasks require large amounts of cognitive processing, such costs are minimal compared to the gain achieved by the sharing. In contrast, they suggest that such costs may not be worthwhile in cases where tasks require only minimal cognitive load. Therefore, in terms of complex cognitive activities of a single user, the cognitive utility of sharing can be positively correlated with the complexity of the task at hand. In the context of performing collaborative complex cognitive activities, however, where all of the relevant information is not required to be integrated into one individual's mental space, sharing seems to always have a positive effect. In the context of information systems and knowledge management, for instance, researchers have noted that organizational knowledge assets grow only at the rate at which individuals share information with others in a team or organization (Davenport and Prusak, 1998). In the context of complex decision making using map-based VRs, Wu et al. (2009) suggest that sharing can facilitate collaborative planning and decision making.

Utility in CASTs: An example of a CAST that implements the sharing pattern is *Mendeley*, a tool for organizing and managing research documents. With this tool, researchers can import papers that seem relevant to a task or activity to read at a later

time. As a user discovers a paper of interest, she can act upon a VR of the paper to share it with her research team to support a collaborative activity.

Other usage scenarios: Using a visual analytics tool, after discovering an interesting trend, an epidemiologist may need to share a VR with a clinician or with a policy maker. In a CAST for organizational decision making activities, a user may be working with VRs to forecast revenue figures and wish to share it with a team of decision makers. With a CAST for genome analysis, a user may be working with a VR and at some point need to share it with another information processing agent (e.g., another tool) that will run some tests using the shared VR.

10.1.1.14 Transforming

Characterization: Acting upon VRs to change their geometric form. This action can alter the size, look, or orientation of VRs by rotating, scaling, magnifying, bending, folding, distorting, dilating, stretching, resizing, shrinking, and/or twisting them.

Utility: Among others, this action facilitates problem solving, learning, reasoning, sense making, understanding, exploring, and investigating (Wu and Shah, 2004; Peng et al., 2004; Elmqvist et al., 2010; Pinzger et al., 2008; Ward and Yang, 2004; Spence, 2007). While reasoning and understanding, transforming VRs can provide users with new perspectives on the information. Rotating, for instance, can facilitate sense making and reasoning about the structure of 3D objects that are presented in a 2D plane (Proffitt et al., 1992; Todd and Norman, 1991). In an experiment done by Wu et al. (2000), all students who were highly engaged in a CAST rotated diagrams of a molecular structure, which the researchers concluded was a crucial action in helping users to make sense of the novel diagrammatic structure. Transforming VRs in various ways can facilitate the exploration of large information spaces (Leung and Apperley, 1994; Elmqvist et al., 2010; Spence, 2007), especially when display area is limited. Transforming VRs can be useful for allowing users to quickly explore their details without losing the larger context. Distorting, for instance, maintains visual and psychological continuity since users are able to see connections between the local detail and overall context (Card et al., 1999). A number of techniques have been developed in the information visualization community

that can be used to transform VRs, such as fisheye, rubber sheet, hyperbolic, and x–y distortions (Card et al., 1999; Spence, 2007).

Utility in CASTs: An implementation of the transforming pattern is shown in Figure 18. This figure shows a distortion technique, *Mélange* (Elmqvist et al., 2010), that facilitates the exploration of large spaces; in this case a social network. As the VR encodes a large amount of information, it is impossible to investigate a portion of it closely while still retaining an overview of the whole VR. In a CAST that implements the transforming pattern, users can act upon the VR to alter its geometric form by folding it, enabling the investigation of portions of it in more detail without losing the larger context.

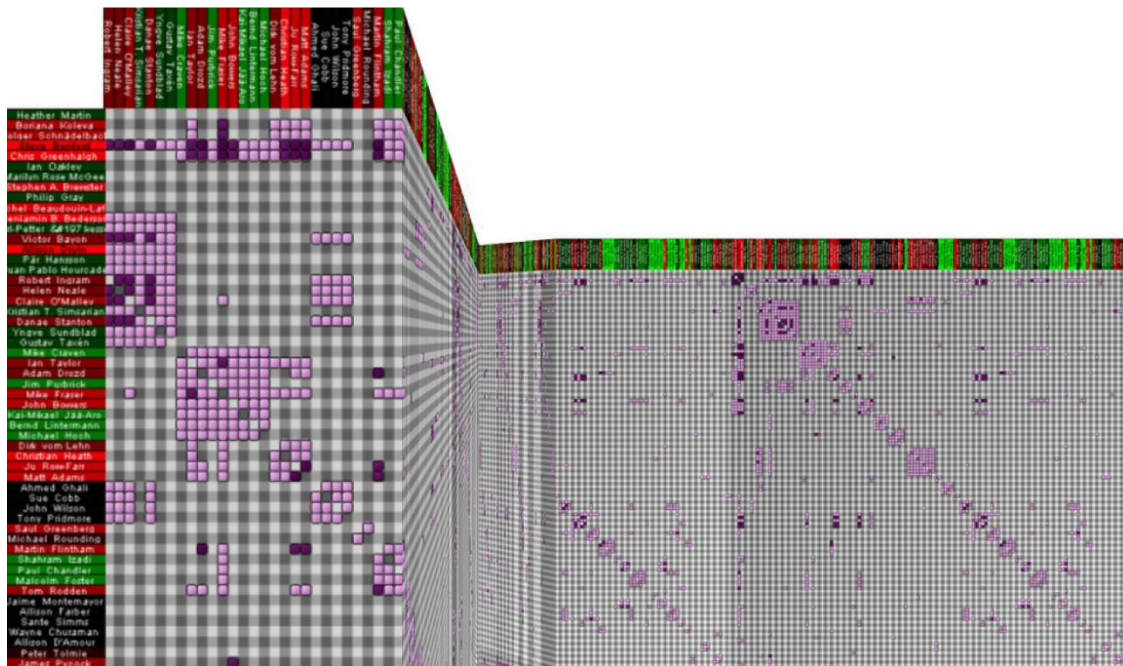


Figure 10-6 An implementation of the transforming pattern: Acting upon a VR to fold it © 2010 IEEE.

Other usage scenarios: In a forensic analysis tool, given an image of a fingerprint, an analyst may want to magnify the VR. In a mathematical visualization tool, given a plot in a Cartesian coordinate system, a learner may want to distort the coordinate system to observe its effect on the plot.

10.1.2 Bipolar Actions

10.1.2.1 Accelerating/Decelerating

Characterization: Acting upon dynamic VRs to increase the speed of movement of constituent components, or oppositely to decrease the speed.

Utility: Among others, this action facilitates learning, investigating, and sense making (Bétrancourt, 2005; Plass et al., 2009; Schwann and Riempp, 2004). A rigid pace of movement in dynamic VRs can put considerable cognitive load on users' working memory (Hegarty, 2004), particularly if users cannot keep pace with the speed of movement of VRs (Hegarty et al., 2002). The pace of movement in a VR must be suitable for users so that they can make sense of a sequence of events (Tversky et al., 2002). Giving users control over the pacing of the presentation of dynamic information can improve both learning and comprehension (Plass et al., 2009; Tversky et al., 2002). A study conducted by Schwan and Riempp (2004) compared performance of subjects who could control (i.e., accelerate and decelerate) the speed of a video (i.e., dynamic VR) to those who could not, and results showed a significant decrease in time required to master the task by the former group. They also found that such actions were used more frequently when the information space was more complex. In addition, accelerating and decelerating a VR allowed the users to speed through or skip parts of a video that were perceived as easy to understand, and to focus on the more difficult parts (Schwan et al., 2000; Schwan and Riempp 2004).

Utility in CASTs: An example of a CAST that implements these two patterns is *Netlogo* (Wilensky, 1999), a multi-agent programming language and modelling environment for simulating natural and social phenomena. For example, while performing an expected-value analysis simulation—analyzing of the “value” of outcomes in probability experiments in terms of some utilitarian framework, such as money or points—*Netlogo* provides the ability for users to accelerate and decelerate dynamic VRs in order to support an overall analysis activity.

Other usage scenarios: In a physiology CAST, given a dynamic image (e.g., video) demonstrating the functioning of a human heart, users may want to accelerate or decelerate the contractions of the heart to support learning. In an educational tool, given an animation of nuclear decay, users may want to accelerate or decelerate the process of decay of atoms. In a CAST for studying astronomy, given an animation of the motion of the planets in a solar system, users may want to accelerate or decelerate the animation.

10.1.2.2 Animating/Freezing

Characterization: Acting upon dynamic VRs to generate movement in constituent components, or oppositely to stop the motion. Animating a VR causes a series of sequential VRs to appear in time, with each subsequent VR denoting a later temporal stage.

Utility: Among others, these actions facilitate problem solving, reasoning, learning, and sense making (Wong, 1994; Shah and Miyake, 2005; Rieber, 1990; Jones and Scaife, 2000; Sedig et al., 2003; Lawrence et al., 1994). In learning and sense making, animating VRs can impart more information about the dynamics of systems than could otherwise be obtained from equivalent static VRs. Animating can be used to illustrate complex structural, functional, and procedural relationships among objects and events (Jones and Scaife, 2000; Park and Gittleman, 1992). It helps users make sense of physical systems—e.g., lifted weights (Kaiser and Proffitt, 1987) and pendulums (Pittenger, 1985). When reasoning about spatial information, animating can help users perceive the shape and structure of 3D objects projected onto a 2D plane (Ullman, 1979). Additionally, animating can make spatial information and depth order salient, reduce spatial ambiguities within VRs, and help overcome users' perceptual and cognitive biases that can be acquired from reasoning with static representations (Kaiser and Proffitt, 1987). For instance, Kaiser and Proffitt (1987) observed that many of the misconceptions that people have when asked to reason about physical systems do not occur when the same people are asked to make judgements about animated displays. Animating can also be very useful for making sense of information that has hidden and abstract meaning

(Caraballo, 1985; Wong, 1994). For instance, it can be used to enhance understanding of dynamic physical or hidden biological processes such as the flow of blood in the human heart (Dwyer, 1994; Rieber, 1990; Rieber and Kini, 1991).

Utility in CASTs: An example of a CAST that implements these two patterns is *Step*, an educational tool that supports activities related to physics information spaces. Using this tool, users construct a simulation by repeatedly inserting information items (e.g., springs, particles, forces) into a VR. Users then act upon the VR to animate it, where the dynamic VR demonstrates the behaviour of gas particles under certain conditions, for instance. Users can animate and freeze the VR numerous times while performing a task or activity. This can aid users in understanding ideas that can be difficult to comprehend using static VRs.

Other usage scenarios: In a biology learning tool, given a VR of a cell, users may wish to both animate and freeze the process of cellular growth. In a tool for studying physical phenomena, given a VR of a wave, users may wish to animate it, and then freeze it part way through to make sense of the effect of wave interference. In a medical informatics tool, given a visualization of the spread of a particular disease, users may want to animate the visualization to observe the pattern of the spread of the disease.

10.1.2.3 Composing/Decomposing

Characterization: Acting upon VRs to assemble them and join them together to create a new, whole VR, or oppositely, break whole entities up into separate, constituent components. The goal of composing is often to build a larger VR than its constituent subcomponents; but the constituent elements or sub-systems need not be strongly associated. Variants of composing include assembling, building, and combining. Some variants of decomposing are fragmenting, disassembling, partitioning, and segmenting.

Utility: Among others, these actions facilitate problem solving, planning, learning, and reasoning (Gotz and Zhou, 2008; Abrahamson, 2006; Jane, 2006; Frederickson, 2003; Olive, 2000). Composing VRs can facilitate different forms of reasoning, such as analytical, deductive, syllogistic, and causal (Grossen and Carnine, 1990). In the context

of syllogistic reasoning and problem solving, Grossen and Carnine (1990) found that children who were given the opportunity to compose diagrams achieved higher scores than those who worked with pre-drawn diagrams. The opposite action, decomposing, can lead to deeper thinking by allowing users to focus on both the aggregate as well as the individual items that compose a VR (Markman, 1979) and provides opportunities for discovering how the mechanisms in systems, such as tools, gadgets, and simple machines, work (Jane, 2006). While reasoning, decomposing can lead to perceptual and cognitive distinctions among discrete information items, and allows users to analyze information in terms of smaller units (Gotz and Zhou, 2008; Rucker, 1987; Nickerson, 2004; Frederickson, 2003). In learning, decomposing can be critical to the development of increasingly complex concepts (Olive, 2000; Harel and Confrey, 1994; Lamon, 1999).

Utility in CASTs: An example of a CAST that implements these two patterns is *SmartJigsaw* (Ritter et al., 2002). With this tool, users are presented with numerous VRs of different components of the human foot. Depending on the task, users either act upon a VR to decompose it and create many separate VRs, or act upon VRs to bind them together into one whole VR (see Figure 19). Ritter et al. (2000; 2002) found that performing such actions with this CAST supported students' learning and helped them to rehearse surgical procedures and dissection of cadavers.

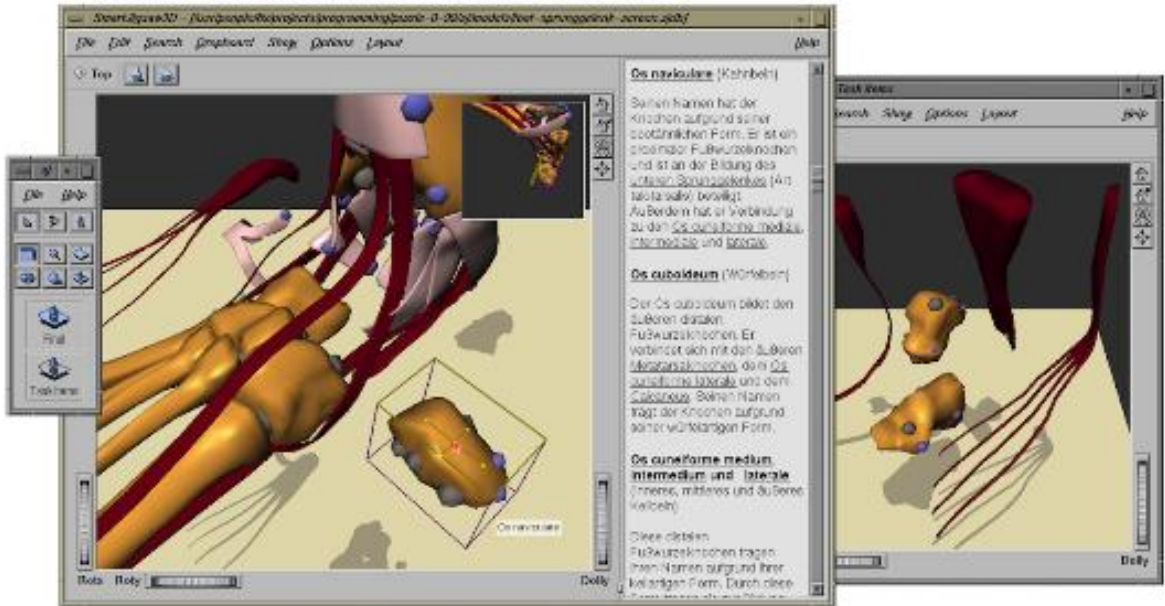


Figure 10-7 An implementation of the composing/decomposing patterns: Acting upon VRs to bind them to create a VR of the human foot or to break them into constituent components.

Other usage scenarios: In a circuit exploration tool, given a set of VRs representing circuit components, users may want to assemble the components differently to study different types of circuits. In a digital library, given a VR of a document, users may want to decompose it to examine the different constituent components of the document.

10.1.2.4 Gathering/Discarding

Characterization: Acting upon VRs to place them into a collection, or oppositely to throw them away completely. Gathering is different from storing (discussed later) in that its purpose is short term. One can gather pieces of information into a pile to decide which ones to store to use at a later time. Gathering may be discussed in the context of higher-level tasks; here, however, we are referring to it specifically at the level of action.

Discarding a VR has a permanent effect in that the VR gets completely expunged from the CAST and the user will not have any more access to it. Some variants of gathering are collecting and piling, and of discarding are scrapping, junking, annihilating, eliminating, and expunging.

Utility: Among others, these actions facilitate learning, problem solving, and planning (Hannafin et al., 1999; Price et al., 1998; Jones, 2004). In learning activities, gathering potentially important information can allow the information to be studied in closer detail or divided into subsets relevant to individual learning needs (Hannafin, et. al, 1999). In problem solving, for instance, collecting information into multiple folders in order to organize a problem space can be useful. Discarding supports all the above activities by getting rid of information that is of no interest.

Utility in CASTs: An example of a CAST that implements these two patterns is *Hunter Gatherer* (Schraefel et al., 2002), a tool that allows users to gather VRs from web pages into a collection for personal research and resource sharing. Figure 20 shows how users can select a VR List from a web page, and by pressing a keyboard command, cause the VR to be gathered into a temporary collection. Users can also discard VRs that are no longer of use. According to the authors of the tool, users rarely gather VRs into such collections, in large part because of poor interaction design, and due to the fact that little focus has been given to the action of gathering itself (ibid.).

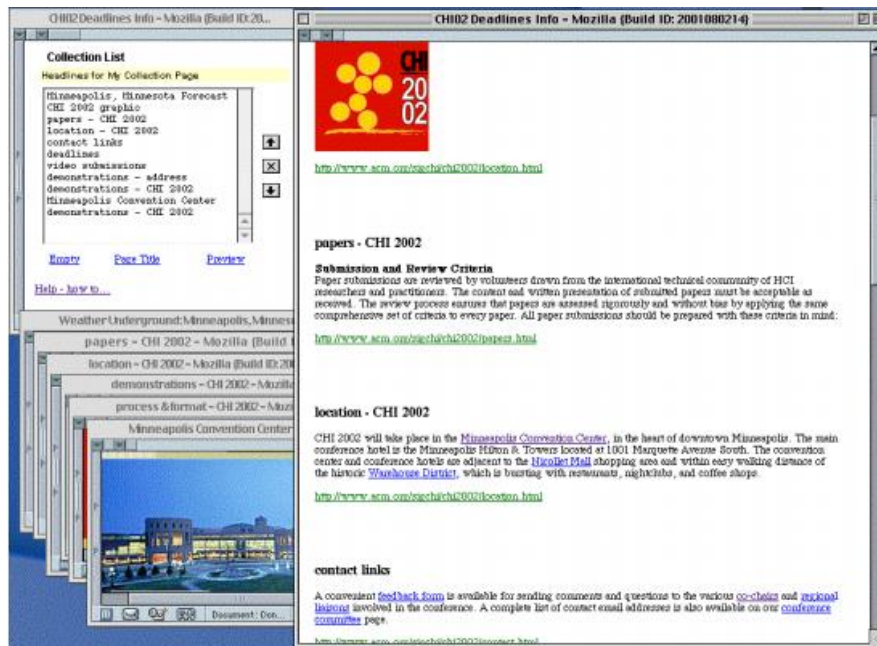


Figure 10-8 An implementation of the gathering/discarding pattern: Acting upon VRs to place them into a temporary collection.

Other usage scenarios: In a digital library, given VRs of different research articles, users may want to gather together the VRs that seem interesting, and discard them after closer inspection later. In a visual analytics tool, users may wish to gather a number of VRs together in order to analyze their relationships.

10.1.2.5 Inserting/Removing

Characterization: Acting upon VRs to interject new VRs into them, or oppositely to get rid of unwanted or unnecessary portions. Inserting is different from annotating, as the added information is not meta-information; rather it is inserted in between the VRs' elements and becomes an integral part of the existing VR. The difference between removing and discarding is that the removed information is not completely destroyed. Variations of inserting include embedding, enclosing, implanting, and adding.

Utility: Among others, these actions facilitate experimenting, reasoning, sense making, and problem solving (Avouris et al., 2003; Cohen and Gordon, 2008; Komis et al., 2002; Li et al., 2004; Sedig and Sumner, 2006). For instance Komis et al. (2002) investigated a problem solving tool that supports simultaneous development of diagrammatic VRs between dispersed collaborating partners. Either of the two participants can insert objects into a shared window to create multi-layered diagrams to solve problems collaboratively. Insertion of text in documents has been around for many years. Insertion may facilitate exploration and creative thinking, allowing users to pose what-if types of questions by interjecting information into VRs and observing the effect. Removing particular elements or regions of VRs allows users to focus on and work with relevant parts of information for further analysis. Removing can be a beneficial action for making sense of VRs that are composed of repetitive patterns, since only a portion of the pattern is needed for understanding the entire structure (Sedig and Sumner, 2006). Removal of image portions has been around for many years and is popular in film, television, publication, and photography (Li et al., 2004).

Utility in CASTs: An example of a CAST that implements these two patterns is *ModellingSpace* (Avouris et al., 2003), a tool that supports collaborative problem solving.

With this tool, users take turns inserting VRs into and/or removing VRs from the representation space, enabling a gradual and collaborative problem solving process.

Other usage scenarios: In a chemistry simulation tool, given a VR of a container of water, a user can insert new salts into the VR and observe the changes in terms of solubility. In a visual analytics tool, an analyst may wish to insert hypothetical VRs (e.g., representing damage estimates for an insurance claim) into the representation space in order to see the effect on other VRs (e.g., of insurance premiums).

10.1.2.6 Linking/Unlinking

Characterization: Acting upon VRs to selectively establish a relationship or association between them, or oppositely to dissociate them and disconnect their relationships. This action is different from composing in that the original VRs do not become combined into one whole; rather, they can remain as individual VRs that are linked to each other. Some variations of linking include connecting, relating, and associating.

Utility: Among others, these actions facilitate problem solving, planning, learning, sense making, understanding, and decision making (Uren et al., 2006; Yi et al., 2007; Wycoff, 1991; Peterson and Snyder, 1998; Dansereau, 2005; Foster and Stefik, 1986; Kaput, 1989). Linking VRs facilitates the establishment of connections between information items, which allows users to reason about relationships in the information space (Kaput, 1989; Spiro and Jehng, 1990; Godshalk et al., 2004). Thinking about possible connections or dissociations among information items is at the heart of reflective as well as divergent thinking (Zull, 2002; White and Gunstone, 1992). With the aid of linking, users can create different kinds of connections among VRs, such as causal, structural, semantic, temporal, and topological relationships (Markman, 1999; Jonassen, 2000). When a creative new idea is born, it usually consists of associations among information items in ways that may not have been previously considered (Masseti, 1996). Linking and unlinking allow users to experiment with different possible information scenarios. For instance, in the context of reasoning and understanding, linking and unlinking can facilitate critical thinking and allow users to see complex ideas in new ways, leading to deeper understanding of information spaces (Jonassen, 2000; Kaput, 1989).

Utility in CASTs: An example of a CAST that implements these two patterns is *MindJet*, a tool that supports planning, brainstorming, and task management. Figure 21 shows a user creating a concept map. In this instance, the user is explicitly linking VRs together by connecting them with lines. This type of linking allows users to make sense of how different concepts are related in a domain and to take a holistic approach to thinking about the concepts. The user can also unlink the concepts to explore new avenues of thought.

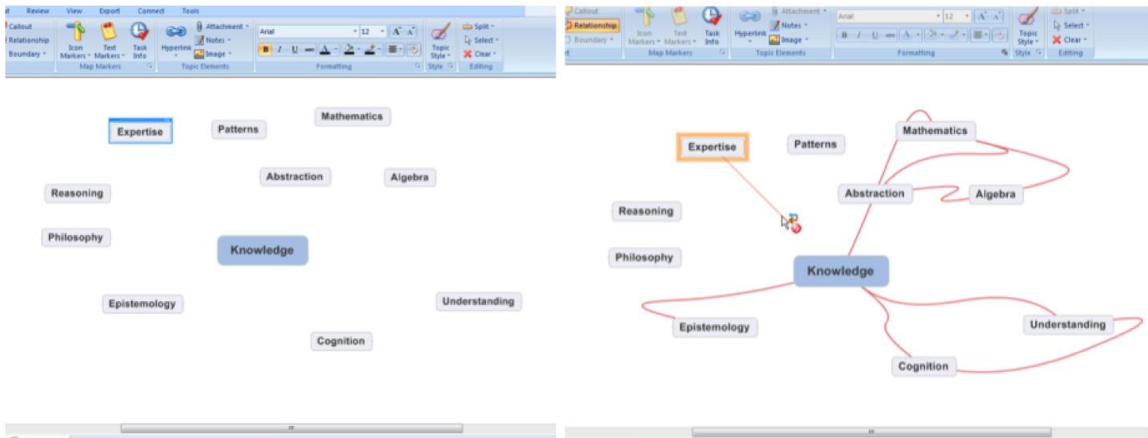


Figure 10-9 An implementation of the linking/unlinking patterns: Acting upon VRs to explicitly establish relationships among them.

Other usage scenarios: In a financial analysis tool, given a map with icons representing different countries, users may want to explore different trade relation options by linking and unlinking the icons. In a data analysis tool, given multiple VRs, users may wish to link them together so that changes in one are propagated and reflected in others.

10.1.2.7 Storing/Retrieving

Characterization: Acting upon VRs to put them aside for later use, or oppositely to bring VRs that have been put away into long-term storage back into usage in the working environment of a CAST. Storing is a more long-term action than gathering and allows users to save information for some anticipated future need. Some variations of storing include filing, saving, shelving, and archiving. The main variant of retrieving is restoring.

Utility: Among others, these actions facilitate problem solving and planning (Jones, 2004, 2008; Liu and Satsko, 2010; Gotz and Zhou, 2009; Anderson, 2000). Storing can be useful when users do not need information right away, do not have time to process it, or when users are interrupted and wish to maintain their current state to be resumed later (Jones, 2008; Czerwinski et al., 2004; Abrams et al., 1998). Both actions are generally useful for activities that take place over extended periods of time. When presenting users with VRs that represent large information spaces, giving them the option of storing and retrieving parts of the information is important (Barreau, 1995). In doing so, the cognitive burden of dealing with large amounts of information can be alleviated (Abrams et al., 1998; Norman, 1993). Additionally, users often have serendipitous encounters with VRs while performing tasks, where the information is not of immediate use, but has some perceived future benefit (Marshall and Jones, 2006). In such situations, storing and retrieving can be helpful to them. In the context of planning, storing allows users to put aside information of interest with which they can plan events (Jones, 2008); for instance, storing information into specific organizational schemes such as folders can facilitate planning (Jones, 2004). In problem solving, often during its creative thinking and discovery component, users may reach a mental impasse, at which point it is often useful to save the current state of a problem and return to it after a delay; this delay, or incubation, can often facilitate the solution of the problem (Olton and Johnson, 1976; Smith, 1995; Simon, 1978; Anderson, 2000). Storing information to allow for incubation and future retrieval can contribute to insight experiences because the passage of time allows consciousness to fluctuate (Smith, 1995).

Utility in CASTs: An example of a CAST that implements these two patterns is *Cytoscape* (Shannon et al., 2003), a tool intended to support the exploration of complex networks (e.g., social networks, semantic networks, and molecular and genomic interaction networks). A user may be performing an analysis on a network, and after adjusting some of the properties of the network, wish to store it to be accessed in the future. The user can then retrieve the VR at some later time.

Other usage scenarios: In a digital library, while browsing, users may wish to bookmark or save an interesting VR for later access. In a visual analytics tool, when exploring an

information space for the purpose of identifying financial fraud, users may notice a peculiar case and wish to archive it to examine it more closely later on.

10.2 List of Examined CASTS for EDIFICE-PVR⁸

Domain	CASTs
--------	-------

⁸ Full references are given in section 4.9

(Information, Data, Geo, Scientific, Visualization, Visual Analytics)	<p>Action Science Explorer (Gove et al., 2011), Carbon Calculator (http://viz-carbontool.appspot.com), CGV (Tominski et al., 2009), ChronoZoom (www.chronozoomproject.org), City'O'Scope (Brodbeck & Girardin, 2003), CrimeSpotting (www.crimespotting.org), Cytoscape (Shannon et al., 2003), Datascape (www.daden.co.uk/solutions/datascape), Docuburst (Collins et al., 2009), Dust & Magnet (Yi et al., 2005), EdgeMaps (Dörk et al., 2011), EpiNome (Livnat et al., 2011), EpiScanGis (Reinhardt et al., 2008), Film Finder (Ahlbert & Shneiderman, 1994), Gapminder (www.gapminder.org), GeoTime (Eccles et al., 2008), GeoDa (Anselin et al., 2005), Gephi (Bastian et al., 2009), HARVEST (Gotz et al., 2010), Health Infoscape (visualization.geblogs.com/visualization/network), INSPIRE (in-spire.pnnl.gov), Jigaw (Stasko et al., 2008), Hierarchical Clustering Explorer (Seo & Shneiderman, 2005), Jellyfish (www.carohorn.de/jellyfish), Miner3D (www.miner3d.com), Mondrian (Theus, 2002), Multidatex (Wu et al., 2006), NetLens (Kang et al., 2010), Newsmap (newsmap.jp), NFlowVis (Mansmann et al., 2009), OECD eXplorer (stats.oecd.org/OECDregionalstatistics), Panopticon (www.panopticon.com), PanViz (Afzal et al., 2011), Polaris (Stolte et al., 2002), SeeSoft (Eick et al., 1992), SocialAction (Perer & Shneiderman, 2006), Spatio-Temporal Epidemiological Modeller (Ford et al., 2006), Spotfire (Ahlberg, 1996), Starlight (starlight.pnnl.gov), Table Lens (Rao & Card, 1994), Tableau (www.tableausoftware.com), time rime (timerime.com), Tulip (tulip.labri.fr), TNV (Goodall, 2011), TOPCAT (www.starlink.ac.uk/topcat/), VisANT (Hu et al., 2009), Visible Body (www.visiblebody.com), VisRa (Oelke et al., 2010), Vizster (Heer & Boyd, 2005), Well-Formed Eigenfactor (well-formed.eigenfactor.org)</p>
--	---

Cognitive, Educational, and Learning Technologies and Digital Games	Archim (www.archimy.com), Archimedean Kaleidoscope (Morey & Sedig, 2004), Cabri (www.cabri.com), DEMIST (Ainsworth & van Labeke, 2001), Educational Virtual Anatomy (Petersson et al., 2009), GeoGebra (www.geogebra.org), Geometer's Sketchpad (www.dynamicgeometry.com), Hyperchem (www.hyperchem.com), Kalzium (edu.kde.org/applications/science/kalzium/), KAtomic (games.kde.org), Lattice Machine (Sedig et al., 2005), Living Liquid (Ma et al., 2012), Looking Glass (www.livinggraphs.com/enu/products/lg) ModellingSpace (Avouris et al., 2003), NCTM Illuminations (illuminations.nctm.org), NetLogo (Wilensky, 1999), PhET Simulations (phet.colorado.edu), PolygonR&D (Morey & Sedig, 2004b), Polyvise (Morey & Sedig, 2004a), SmartJigsaw3D (Ritter et al., 2000), Step (edu.kde.org/applications/science/step/), Stella (www.software3d.com/Stella.php), Sunaeon (www.sunaeon.com), Super Tangrams (Sedig & Klawe, 1996), TileLand (Sedig et al., 2002)
Personal Information Management, Information Retrieval, Knowledge Management, Digital Libraries, General Productivity	ActiveGraph (Marks et al., 2005), Butterfly (Mackinlay et al., 1995), Cat-a-Cone (Hearst & Karadi, 1997), Envision Digital Library Project (Fox et al., 1993), HotMap (Hoerber & Yang, 2006), Hunter Gatherer (Schraefel et al., 2002), Info Navigator (Carey et al., 2003), InfoSky (Andrews et al., 2002), LyberWorld (Hemmje et al., 1994), Mendeley (www.mendeley.com), MemoMail (Elsweiler et al., 2006), Microsoft Word, Microsoft Onenote, MindJet (www.mindjet.com), MindMaple (www.mindmaple.com), MyLifeBits (Gemmell et al., 2002), Phlat (Cutrell et al., 2006), PhotoMemory (Elsweiler et al., 2005), POLESTAR (Pioch & Everett, 2006), Stuff I've Seen (Dumais et al., 2003), TRIST (Jonker et al., 2005), VICOLEX (Buchel & Sedig, 2011), VisGets (Dörk et al., 2009), Visual Knowledge Builder (Shipman et al., 2004), xFIND (Andrews et al., 2001)

Curriculum Vitae

EDUCATION

PhD, Computer Science

Dissertation: *Cognitive Activity Support Tools: Design of the Visual Interface*

2013

Supervisor: Kamran Sedig

Western University, Canada

Bachelor of Computing

Specialization in Cognitive Science

2007

Queen's University, Canada

PUBLICATIONS

Refereed Journal Papers

- J1. **Parsons, P.** & Sedig, K. (in press). Adjustable properties of visual representations: Improving the quality of human-information interaction. *Journal of the American Society for Information Science and Technology*.
- J2. Sedig, K. & **Parsons, P.** (2013). Interaction design for complex cognitive activities with visual representations: A pattern-based approach. *AIS Transactions on Human-Computer Interaction* 5(2), 84-133.
- J3. Haworth, R., **Parsons, P.**, & Sedig, K. (2013). Some considerations for the design of digital cognitive games. *Cognitive Technology: Special Issue on Designing Educational Games* 18(1), 22-27.
- J4. Sedig, K., **Parsons, P.**, & Babanski, A. (2012). Towards a characterization of interactivity in visual analytics. *Journal of Multimedia Processing and Technologies: Special Issue on Theory and Application of Visual Analytics*, 3(1), 12-28.

- J5. Sedig, K., **Parsons, P.**, Dittmer, M., & Ola, K. (2012). Beyond information access: Support for complex cognitive activities in public health informatics tools. *Online Journal of Public Health Informatics*, 4(3).
- J6. Liang, H., **Parsons, P.**, Wu, H. & Sedig, K. (2010). An exploratory study of interactivity in visualization tools: 'Flow' of interaction. *Journal of Interactive Learning Research*, 21(1), 5-45.

Refereed Book Chapters

- B1. Sedig, K., **Parsons, P.**, Dittmer, M., & Haworth, R. (2013). Human-centered interactivity of visualization tools: Micro- and macro-level considerations. In W. Huang (Ed.), *Handbook of Human Centric Visualization* (pp. 717-743). Springer.
- B2. Sedig, K. & **Parsons, P.** (forthcoming, 2014). Interacting with digital information. *Encyclopedia of Information Science & Technology (3rd Ed.)*. Hershey, PA: IGI.
- B3. **Parsons, P.** & Sedig, K. (2013). Common visualizations: Their cognitive utility. In W. Huang (Ed.), *Handbook of Human Centric Visualization* (pp. 671-691). Springer.
- B4. **Parsons, P.** & Sedig, K. (2013). Distribution of information processing while performing complex cognitive activities with visualization tools. In W. Huang (Ed.), *Handbook of Human Centric Visualization* (pp. 693-715). Springer.
- B5. **Parsons, P.** & Sedig, K. (2012). The role of interactive representations in cognitive tools for learning. In S. Abramovich (Ed.), *Computers and Education* (pp. 27-45). Hauppauge, NY: Nova.
- B6. **Parsons, P.** & Sedig, K. (2011). Human-information interaction: An emerging focus for educational cognitive tools. In A. Mendez-Vilas (Ed.), *Education in a Technological World: Communicating Current and Emerging Research and Technological Efforts* (pp. 245-251). Badajoz, Spain: Formatex.
- B7. Sedig, K. & **Parsons, P.** (2011). Interactivity of information representations in e-learning environments. In H. Wang (Ed.), *E-learning: Cases and Frameworks* (pp. 29-50). Hershey, PA: IGI.

Refereed Conference Papers

- C1. Sedig, K. & Parsons, P. (2012). Enhancing the epistemic utility of physical spaces through digital information interfaces. In *Proceedings of IASTED International Conference on Human-Computer Interaction*. Baltimore, MD.
- C2. Parsons, P. & Sedig, K. (2012). Towards a holistic framework for human-information interaction. In *Proceedings of the 40th Annual Conference of the Canadian Association for Information Science*. Waterloo, ON.
- C3. Parsons, P. & Sedig, K. (2010). Utility of interaction in knowledge-oriented activities. In *Proceedings of World Conference on Educational Multimedia, Hypermedia and Telecommunications*. Toronto, ON.
- C4. Sedig, K. & Parsons, P. (2010). Representations of information spaces in educational tools. In *Proceedings of World Conference on Educational Multimedia, Hypermedia and Telecommunications*. Toronto, ON.

TALKS AND POSTERS

1. Achieving harmony in human-computer cognitive systems: On the distribution of information processing. *University of Western Ontario Research in Computer Science Conference*, 2013. London, ON.
2. Toward a holistic framework for human-information interaction (poster). *Canadian Association for Information Science 40th Annual Conference*, 2012. Waterloo, ON.
3. From HCI to HII: Towards a new science of interaction. *University of Western Ontario Research in Computer Science Conference*, 2012. London, ON.
4. Interactivity of visualization tools: A human-centered approach. *Western Research Forum*, 2012. London, ON.
5. Epistemology and design of human-information interaction (Received 3rd place award). *University of Western Ontario Research in Computer Science Conference*, 2011. London, ON.
6. Technology and the mind: Enabling effective human-information interaction. *Western Research Forum*, 2011. London, ON.
7. Cognitive tools and the knowledge society. *UWO Graduate Student Lecture Series*, 2010. London, ON.

8. Utility of interaction in knowledge-oriented activities. *World Conference on Educational Multimedia, Hypermedia, & Telecommunications*, 2010. Toronto, ON.
9. Representations of information spaces in educational tools. *World Conference on Educational Multimedia, Hypermedia, & Telecommunications*, 2010. Toronto, ON.
10. Designing cognitive tools to support effective human-information interaction (Received 3rd place award). *University of Western Ontario Research in Computer Science Conference*, 2010. London, ON.
11. Interaction in information visualization and visual cognitive tools. *Ph.D. Reading Course*, 2009. London, ON.

TEACHING

Instructor Positions

- Human-Computer Interaction—Winter 2011

TA Positions

- Computing & Informatics for Life Sciences—Fall, 2012
- Object-Oriented Design Principles—Winter, 2012
- Computer Science Fundamentals II—Fall, 2011; Summer, 2012
- Human-Computer Interaction—Winter 2010
- Introduction to Software Engineering—Fall 2008, 2009, 2010; Winter 2009
- Multimedia and Communications—Fall, 2007; Winter, 2008

AWARDS AND GRANTS

Ontario Graduate Scholarship	2012-2013
MITACS Accelerate Grant, declined	2012-2013
Project: <i>Interactive Geo-Spatial Visualization for Making Sense of Medical Education Data</i>	
UWO Research in Computer Science Conference, 3 rd Place	2011
UWO Research in Computer Science Conference, 3 rd Place	2010

UWO Graduate Student Teaching Award Nomination 2008

PROFESSIONAL ACTIVITIES

Reviewer, Encyclopedia of Information Science & Technology (3 rd Ed.), IGI Global.	2013
Research in Computer Science Conference Organizing Committee, UWO	2012
Computer Science Graduate Student Council Secretary, UWO	2011- 2012
Graduate Student Lecture Series Chair, UWO	2011- 2012
Research in Computer Science Conference Session Judge, UWO	2011- 2013
Computer Science Graduate Student Council Communications Officer, UWO	2010- 2011
ED-MEDIA Conference Volunteer, Toronto	2010
Research in Computer Science Conference Organizing Committee, UWO	2010