Exploring Geovisualization
J. Dykes, A.M. MacEachren, M.-J. Kraak (Editors)
© 2005 Elsevier Ltd. All rights reserved.

Chapter 35

Cognitively Plausible Information Visualization

Sara Irina Fabrikant, Department of Geography, University of California Santa Barbara, Santa Barbara, CA 93106, USA
André Skupin, Department of Geography, University of New Orleans, New Orleans, LA 70148, USA

Keywords: Information Visualization, spatialization, Cartography, spatial cognition, human–computer interaction

Abstract

Information Visualization is concerned with the art and technology of designing and implementing highly interactive, computer supported tools for knowledge discovery in large non-spatial databases. Information Visualization displays, also known as information spaces or graphic spatializations, differ from ordinary data visualization and geovisualization in that they may be explored as if they represented spatial information. Information spaces are very often based on spatial metaphors such as location, distance, region, scale, etc., thus potentially affording spatial analysis techniques and geovisualization approaches for data exploration and knowledge discovery. Two major concerns in spatialization can be identified from a GIScience/geovisualization perspective: the use of space as a data generalization strategy, and the use of spatial representations or maps to depict these data abstractions. A range of theoretical and technical research questions needs to be addressed to assure the construction of cognitively adequate spatializations. In the first part of this chapter we propose a framework for the construction of cognitively plausible semantic information spaces. This theoretical scaffold is based on geographic information theory and includes principles of ontological modeling such as semantic generalization (spatial primitives), geometric generalization (visual variables), association (source–target domain mapping through spatial metaphors), and aggregation (hierarchical organization). In the remainder of the chapter we discuss ways in which the framework may be applied towards the design of cognitively adequate spatializations.

35.1 Introduction

Timely access to relevant information has become a key element in a data-rich society. Graphic depiction of information is an interdisciplinary research endeavor involving human–computer interaction (HCI), visual data mining, exploratory data analysis, and related fields in a search for mechanisms to navigate in and access information from vast databases. Such Information Visualizations often rely on the use of spatial metaphors for depiction. These representations are also known as spatializations, or information spaces. Spatialization is defined here as a data transformation method based on spatial metaphors, with the aim of generating a cognitively adequate graphic representation (e.g., a depiction that matches human's internal visualization capabilities) for data exploration and knowledge discovery in multi-dimensional databases. Spatialization not only provides the construction of visual descriptions and summaries of large data repositories but also creates opportunities for visual queries and sense-making approaches.

Although information spaces are abundant and span a wide array of application areas mostly outside of Geography (Card et al., 1999), a structured approach based on solid theoretical foundations to formalize the underlying representational framework seems to be missing. Two key concerns should be addressed from a usability standpoint: the use of spatial metaphors as a data transformation strategy, and the effectiveness of spatial depictions for knowledge extraction. As argued in this chapter, an explicit and structured spatialization design strategy needs to be in place before usable information spaces can be constructed and tested for usability (Fabrikant and Buttenfield, 2001).

Improving knowledge discovery in data-rich environments by visual means is also a key concern in the GIScience community (Buckley et al., 2000; Buttenfield et al., 2000). It is surprising, however, that most of the spatialization work is carried out outside of GIScience, with the exception of a handful of geographers (for example, Couclelis, 1998; Skupin, 2000, 2002a,b; Fabrikant, 2000a,b; Fabrikant and Buttenfield, 1997; Kuhn and Blumenthal, 1996; Tilton and Andrews, 1994). It seems obvious that GIScience (particularly through its cartographic roots) is well positioned to address the challenges of designing information spaces, but GIScientists should also transfer their geovisualization know-how to the InfoVis community. GIScience provides the perspectives of space and place, as well as the necessary visual, verbal, mathematical and cognitive approaches to construct cognitively adequate spatial representations (National Research Council, 1997).

Cognitive adequacy extends the concept of cognitive plausibility, a term used by psychologists to assess the accuracy with which models are believed to represent human cognition (Edwards, 2001). We define cognitively plausible Information Visualization as a graphic display designed such that it matches human's internal visualization capabilities well. A cognitively adequate depiction is understood here as graphic display that not only supports humans' internal visualization capabilities optimally, but is able to augment people's mental visualization capabilities for complex reasoning and problem solving in abstract domains (Hegarty, 2002). The notion of cognitive plausibility aims at unifying aspects of usability and usefulness in Information Visualizations, as suggested by Fuhrmann et al., this volume (Chapter 28).

In this chapter we first propose a spatialization framework based on GIScience/geovisualization, including semantic generalization and geometric generalization as components of a two-step transformation process. In the second part of the chapter we show that the proposed framework can be linked to space conceptualizations and transformations by giving some examples in the context of text document visualization.

35.2 Spatialization Framework

The goal of this chapter is to devise a spatialization framework that is generic enough to be context independent, but specific enough to represent the domain appropriately. Due to its novelty, a major challenge for Information Visualization has been so far to identify relevant theoretical foundations to support rapid technical developments. We argue that without a solid theoretical foundation, measurement of success in Information Visualization (e.g., usability evaluation) may be hindered. Three main design challenges can be identified for generating cognitively adequate displays:

1. encoding database meaning into appropriate spatial representations for knowledge discovery (e g., database semantics represented with spatial metaphors);
2. employing adequate visuo-spatial structure to depict this meaning (e.g., space transformations, space types and symbology);
3. controlling the potentially experiential effects spatialized views have on information seekers when exploring semantic spaces to satisfy a particular information need (e g., navigation, visual browsing and knowledge construction).

This chapter will focus on design challenges one and two, thus omitting the third issue from the discussion, as it has been addressed elsewhere (Fabrikant and Buttenfield, 2001). Based on design challenges (1) and (2) in above list, we see the construction of cognitively adequate spatializations as a two-step transformation process (Fabrikant and Buttenfield, 2001). First, a semantic generalization is applied to the database. At a theoretical level, the identification of appropriate spatial metaphors to adequately capture the database semantics is of primary concern during this phase. Semantic generalization includes cognitive, experiential and perceptual components. An ontological approach is proposed for this step; we examine how people conceptualize space, and we investigate how these concepts can be metaphorically mapped to preserve their characteristics as spatializations are constructed.

The second phase of the spatialization process deals with depicting the semantics encapsulated in spatial metaphors with appropriate visual variables for visual information discovery and knowledge construction (e.g., geometric generalization). By means of cartographic generalization we propose in §35.2 how data attributes can be condensed to represent their essential relationships (semantic generalization), and how this meaning can be preserved in geometric characteristics of the depicted features (graphic generalization).

35.2.1 Cartographic generalization

Cartographic generalization is the process of reducing multi-dimensional real-world complexity for depiction in a typically 2D map. Generalization entails reduction in detail as a function of depicting the world at a smaller scale. Two cartographic generalization types are distinguished – geometric generalization, sometimes referred to as graphic generalization, and semantic generalization, also known as object or conceptual generalization (Hake et al., 2002). Generalization is not just about information loss.

35.2.2 Semantic generalization in spatialization

The InfoVis community has been applying a wide array of spatial metaphors in a very diverse set of information space designs (Chen, 1999; Spence, 2001; Ware, 2000). Spatial metaphors are typically used in Information Visualization as semantic vehicles for the spatialization process. One may even argue that some InfoVis researchers are reinventing the cartographic wheel, considering that many information spaces attempt to depict large databases as maps. Information items in such visualizations are typically rendered as points in Euclidean space, and relationships between the data points are depicted with straight lines, or alternatively, with 2D or 3D surfaces (Skupin, 2002b; Fabrikant, 2001a,b).

Analogous to semantic generalization in Cartography, semantic generalization in Information Visualization is about identifying a phenomenon's essential characteristics from a large set of attributes describing it, and mapping those onto an abstract construct (metaphor) for subsequent depiction (graphic symbol). It is important to realize that a metaphor is only like the real thing, not the thing itself (Lakoff, 1987). This means that a metaphor may include only some, but not all characteristics, and may in fact have additional (magical) properties. Consider a digital folder in a computer filing system, for instance. The digital folder exhibits similar properties to a real manila folder in that "files" can be stored in it. However, the digital folder cannot be bent, and files never fall out if it gets too full. In addition, the digital folder exhibits "magical" powers in that it can hold many hierarchically stacked folders, and potentially store an infinite number of files (provided an infinite amount of digital storage space is available). Key questions in Information Visualization that remain include: which spatial metaphors should be utilized for particular data sets (and why), and which metaphors are particularly suited for specific knowledge discovery context?

We propose an ontological approach for semantic generalization in Information Visualization. The ontological framework is based on a metaphorical mapping process from a physical source domain (e.g., geographic space) into a conceptual target domain (e.g., semantic document space), as shown in Figure 35.1. Before the spatial metaphors can be depicted, it is necessary to identify the source domain's essential characteristics and formalize the appropriate source–target domain mapping rules.

For example, a geographic landscape may serve as a rich source domain for spatialization, as this metaphor includes many sub-metaphors that lend themselves to representing relationships of semantic entities in a data archive. The geographic source domain may provide metaphors, such as feature locations in space (information landmarks), distances between features (similarity between information entities), boundaries delineating regions (information density and information zones), and scale (level of detail) (Fabrikant, 2000b). The feature term used on the left-hand

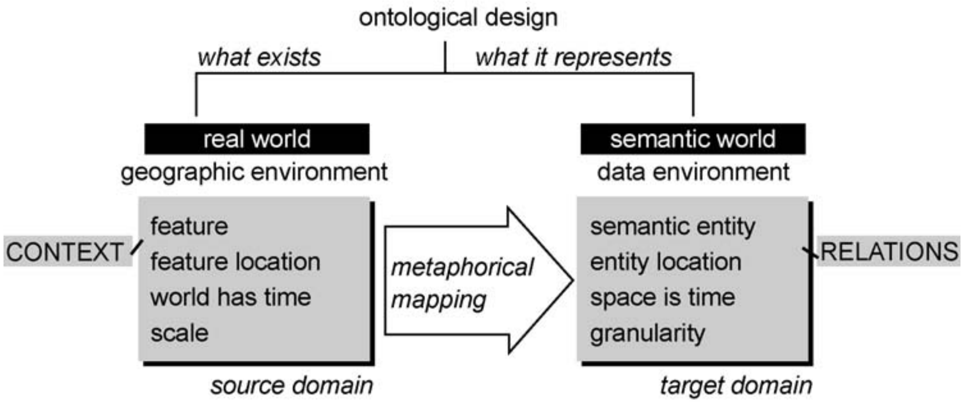


Figure 35.1. Semantic generalization process.

side in Figure 35.1 suggests a phenomenon embedded within geographic context (i.e., context label).

The time dimension is experienced as a sequence of events in the real world (“world has time” in Figure 35.1). However, humans use spatial metaphors verbally and graphically to represent and make sense of the sequential time concept (“space is time” in Figure 35.1). The phrase “We are approaching (or close to) the end of the test” to indicate the imminent end of a time period, or “our summer vacation has flown by” to suggest how quickly a period of time has passed, are two examples in common speech for a metaphorical time–space mapping. A face of a clock is a good graphic example for this. The partitioning of a circle into equal slices representing time units, and the clock hand moving along the “circular time line”, are both graphic, spatial metaphors used to indicate the passage of time. The spatial metaphor of a “linear time line” is also very often used for representing departure and arrival times in train or bus schedules. In a spatialized view, time can be represented by spatial metaphors as well. For example, more current items can be placed in the foreground of a spatialization. As time goes by, older items would be pushed towards the back of the display.

A metaphorical mapping (i.e., semantic generalization), as shown in Figure 35.1, may seem a straightforward process, if one assumes a simple one-to-one mapping between source and target domain. However, a geographer may take many different perspectives when conceptualizing the geographic domain, depending on the use or analysis context. We define these different contexts as spatial perspectives as shown in Table 35.1. For instance, one may conceptualize geographic space differently when navigating in it (navigable perspective), when analyzing patterns and spatial configurations (vista perspective), when formalizing it mathematically (formal perspective), when conceptualizing it mentally (experiential perspective), or when focusing on spatial processes over time (historic perspective). Regardless of the chosen spatial perspective, the appearance of the information space should change according to the semantic level of detail at which an information seeker wishes to explore the data space. For example, sometimes an information seeker may be interested in an individual

Table 35.1. Source domains are listed for each possible combination of geographic perspectives with semantic primitives.

	Geographic perspectives				
Semantic primitives	**Navigable**	**Vista**	**Formal**	**Experiential**	**Historic**
Locus	Landmark	Feature	Occurrence	Object	Point in time
Trajectory	Path	Route	Relation	Link	Period over time
Boundary	Edge	Border	Partition	Boundary	Change
Aggregate	District	Region	Set	Container	State

document, while at other times broader information themes or topics may satisfy information need. Consequently, the chosen spatial metaphors should contain a deep enough structure of coherent sub-metaphors to represent information spaces at various levels of database detail. This relates to the scale problem, a well-known phenomenon in Geography. The scale continuum is a fundamental characteristic of geographic analysis.

We argue that even abstract information space designs should consider user's bodily experiences with the real world, as the power of the metaphor lies in the transfer of the familiar into the abstract for better understanding. Good metaphors not only combine semantic and geometric properties from a source domain, but also ideally contain cognitive, emotive and experiential aspects (Lakoff, 1987; Lakoff and Johnson, 1987). Similarly, geographic space is not only characterized by physical or geometric principles but also carries experiential meaning, reflected in human's knowledge structures (Lakoff, 1987; Lakoff and Johnson, 1987) and manifested in cognitive affordances (Gibson, 1979).

The key question is whether it may be possible to identify fundamental representational primitives associated with a range of geographic source domains, to make metaphorical mappings useful for information exploration. Table 35.1 suggests a selection of semantic primitives that map onto a set of possible spatial metaphors. The metaphors are grouped by a selection of geographic perspectives. Lynchian (Lynch, 1960) feature types such as, landmarks, paths, edges and districts become important when navigating within a space (column 2: navigable space). Spatial configurations or patterns can be identified and described with geographic source domains when looking down onto a space from high above, or when flying over a space (column 3: vista space). A formal geographic perspective is useful when describing spatial relations mathematically, to be able to simulate spatial behavior or formulate spatial database queries (column 4: formal space). Lakoff-Johnsonian (Lakoff-Johnson, 1987) cognitive image-schemata become important when building a cognitive map of the space being explored. Finally, a historic perspective is important to integrate space and time concepts. The list of geographic perspectives and their respective source domains for metaphorical mapping is by no means exhaustive, but it covers a range of information exploration tasks a user may perform when using a spatialized display (Table 35.1). We have identified four semantic primitives that are particularly important concepts applicable to a range of information types. They are locus, trajectory, boundary and aggregate as shown in Table 35.1.

The left most column lists the semantic primitives that encapsulate essential attributes common to the spatial concepts listed as possible source domains (by row in Table 35.1), based on five geographic perspectives (by column in Table 35.1). Spatialized data can take the form of one (or more) of the four semantic primitives listed in Table 35.1.

- *Locus*. An information item should have a meaningful location or place in an information space. Based on a logical frame of reference, an item's relative location is determined by its semantic relationships with other information items in the data space. At its location of origin (locus), the information item is not only represented at its highest level of spatial detail but also at its highest possible database granularity. In some cases this may be a single document, in others one concept in a text, or maybe a pixel in an image. Based on the adopted geographic perspective (five examples are in Table 35.1) an information item may have the function of a landmark in a spatialization, when a user is navigating in the information space, for instance. At other times, when information seekers may want to get an overview of the database, the information item may simply be a structuring feature in the information space, such as a mountain or a depression (i.e., a surface discontinuity).
- *Trajectory*. This is a linear entity type. We use the general meaning of the term trajectory to encompass concepts such as path, progression, or line of some type of development (Merriam-Webster Inc., 2003). In essence, trajectories are semantic relationships between information entities at different locations. For example, a semantic relationship may be a directed or a non-directed link, or a cross-reference between two information entities shown at two specific locations in a data space. The geographic analog would be a path or a route connecting information landmarks. Trajectories may also represent user activity in an information space, for example, search trails an information seeker may have left behind while navigating along a sequence of documents in a semantic space.
- *Boundary*. This constitutes a second linear entity type. Boundaries represent discontinuities (borders) in real spaces and in information spaces. They help partition an information space into zones of relative semantic homogeneity. Boundaries delineate semantic regions.
- *Aggregate*. This represents an areal entity type. Aggregates are the result of classification processes. First, quantitative or qualitative types are assigned to data items (i.e., taxonomy), and then the types are aggregated into groups (i.e., classification). In Geography, a regional system is a spatial classification system, where information entities cluster to form semantic aggregates in 2D (e.g., regions) or 3D (e.g., mountains). The aggregate primitive is not only understood here as a collection of items (e.g., many trees forming a forest) but also as a homogenous zone (with or without a discrete boundary) that can be distinguished from other zones (e.g., a mountain from a depression).

35.2.3 Geometric generalization in spatialization

In analogy to geometric generalization in Cartography, geometric generalization in spatialization entails a graphic transformation process where graphic marks are assigned to depict the data. The transformation process follows Saussure's (1993) notions of assigning graphic marks or signs (i.e., the signifier) to the semantic primitives described above (i.e., the signified). The transformation of large heterogeneous data sets into visually accessible information displays at various levels of detail for knowledge acquisition is a longstanding cartographic tradition (Bertin, 1967, 1998). Bertin's system of visual variables has also become known in the information design and Information Visualization communities (van der Waarde and Westendorp, 2001; Mackinlay, 1986). Not only are geovisualizers well positioned to address semantic generalization issues in spatialization, but Cartography also provides a solid generalization framework for identifying effective graphic design solutions, and resolving graphic density issues in Information Visualization.

Once the semantic primitive locus, trajectory, boundary and aggregate are accepted as ontological building blocks for the semantic transformation process, they can be straightforwardly represented graphically, using visual variables (Bertin, 1967), including the extensions proposed by MacEachren (1995) and DiBiase et al. (1992). Figure 35.2 outlines how semantic primitives can be depicted as spatial metaphors in a semantic space using visual variables suggested by MacEachren (1995). A cartographer typically tries to match the dimensionality of the graphic symbols used for representation with the dimensionality of the represented feature. Depending on the

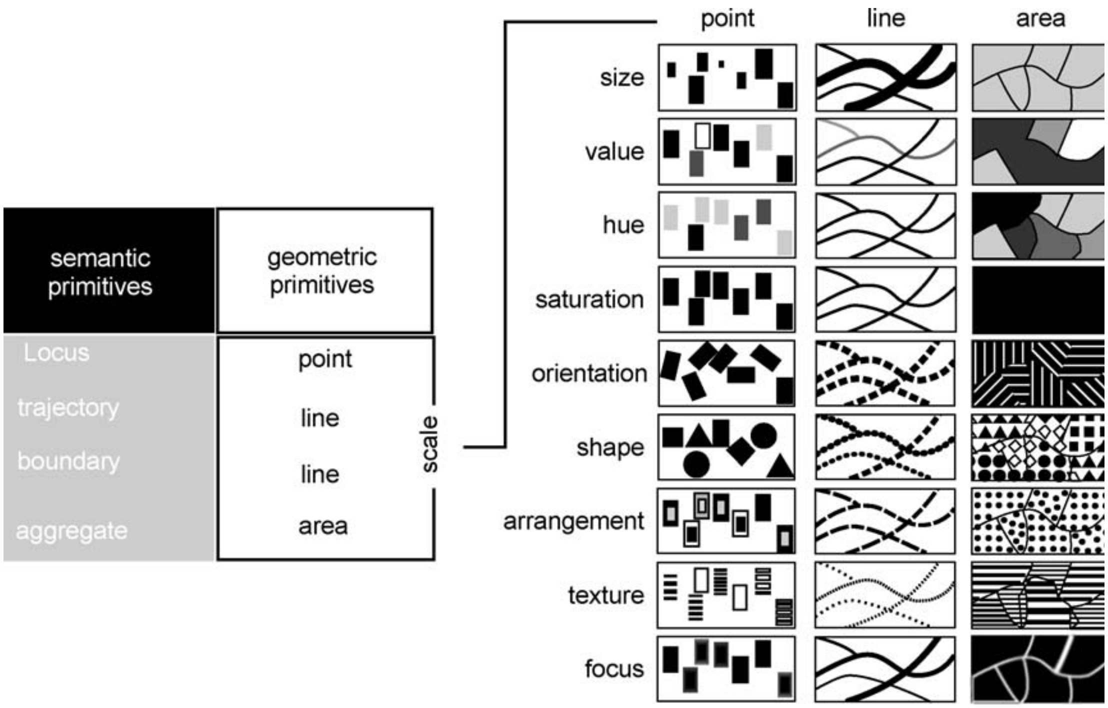


Figure 35.2. Semantic primitives matching geometric primitives and visual variables.

display scale, the semantic primitive locus may be represented by a point or an area, the linear primitives trajectory and boundary by a line, and the aggregate primitive by a point or an area symbol. Furthermore, a cartographer will select from a set of visual variables (Figure 35.2) the visual property of a symbol such that it conveys the data characteristics best.

35.3 Applying the Spatialization Framework

A designer can apply adequate geometric generalization principles, as suggested by the proposed theoretical framework, to effectively represent, and maximize the graphic information density in a spatialization (Figures 35.3 and 35.4). Figure 35.3 is an example of a typical Information Visualization devised by two computer scientists from the InfoVis community (Chen and Carr, 1999), based on the Pathfinder Network Scaling (PFNet) technique (Schvaneveldt, 1990).

Figure 35.3 contains a static snapshot of a 3D VRML information space. Four variables are shown in this spatialization, depicting a database of conference papers from the ACM conference proceedings on Hypertext, over a period of nine consecutive years. The four variables are:

1. an author's location derived from co-citation relationships with other authors in the database (cyan spheres). Heavily cited authors are located in the center of the spatialization, illustrating their central role in the field.
2. a network of dominant citation links between authors, depicting who is mostly citing whom (orange pipes).
3. the amount of citations per author (height of vertical columns), within …
4. a three-year sliding window along the overall nine-year period (color-coded stacked columns).

The semantic primitive locus for the authors (e.g., act as information landmarks) and trajectory to depict the information flow between authors (e.g., co-citations as links between nodes) are well-chosen spatial metaphors, according to the proposed framework. However, we intend to show below how the spatialization in Figure 35.3 could be graphically improved following the geometric generalization process presented earlier.

An information designer may critically argue that the information density is quite low in this spatialization, as the authors needed three dimensions to show four variables. In fact, the third dimension is mostly used for graphic effects (e.g., shaded pipes and spheres), thus lowering the data–ink ratio, which might be used as a measure of graphic effectiveness (Tufte, 1983). In this spatialization, the potential information increase afforded by adding an additional (third) dimension does not outweigh the disadvantages of cognitively, and technologically, more demanding 3D navigation (Westerman, 1998; Westerman and Cribbin, 2000; Ware and Plumlee, this volume (Chapter 29)). Using stacked columns, the designers follow Bertin's principle of encoding magnitude differences by means of the visual size variable. However, many of the 3D nodes are occluded by the stacked columns, even when exploring the space at

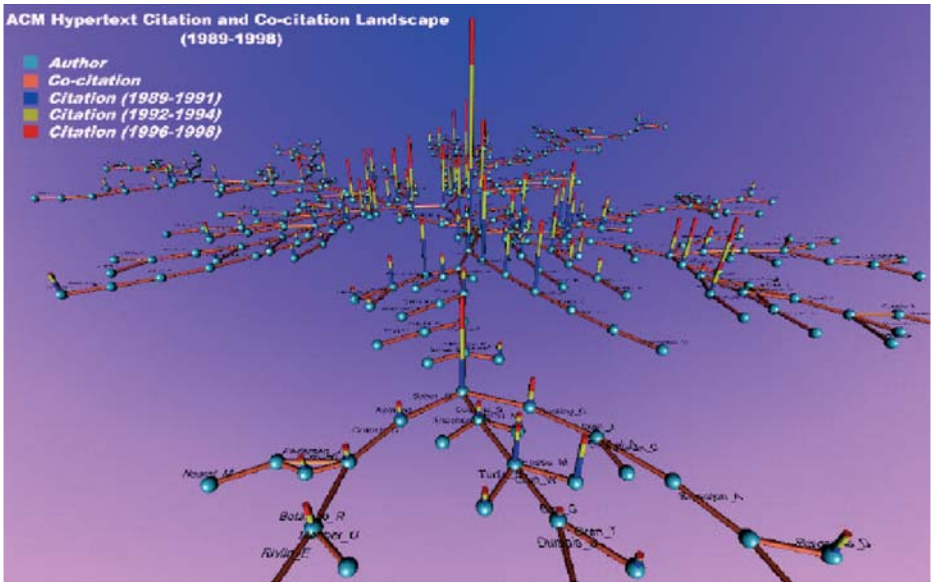


Figure 35.3. Co-Citation "landscape" (Chen and Carr, 1999). Chaomei Chen's permission to use this figure is gratefully acknowledged.

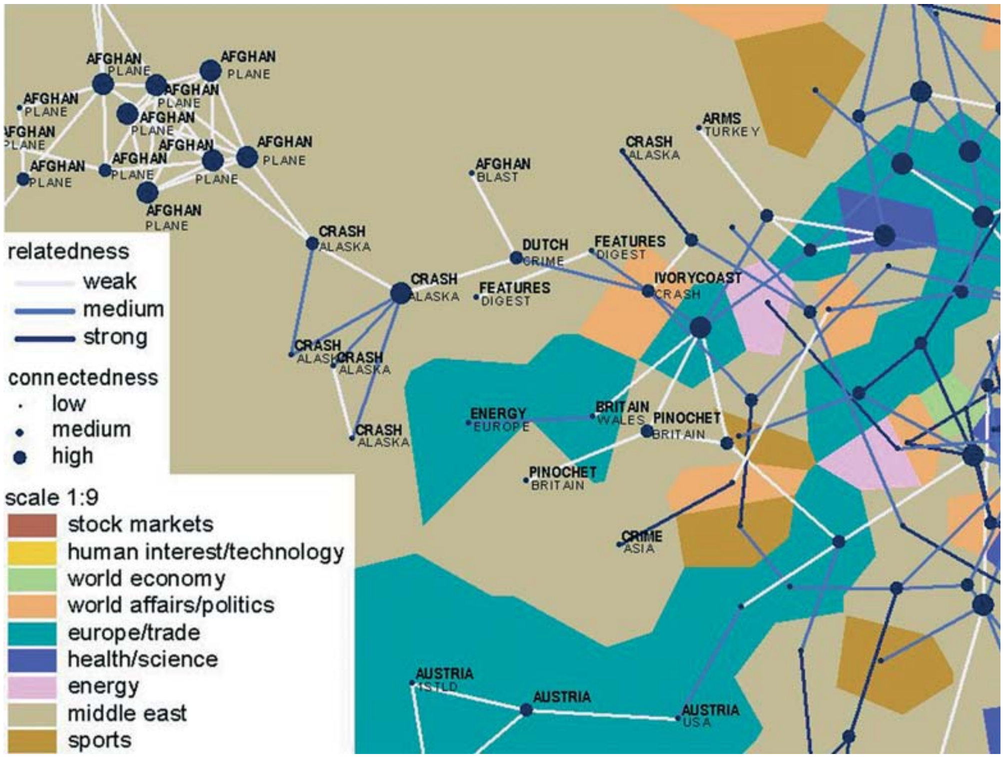


Figure 35.4. Section of the Reuters news map. An interactive application that matches geometric primitives with semantic primitives as level-of-detail (scale) is varied interactively.

different oblique viewing angles. Flat labels suggest the orthographic (e.g., top–down or birds–eye) perspective as the ideal exploration orientation, which, if chosen, would make the information encoded in the stacked columns obsolete.

Figure 35.4 is based on the same spatialization technique (i.e., network scaling) as the previous figure, but we depict a 2D data space following the geometric generalization principles of the spatialization framework as proposed above.

This 2D spatialization depicted in Figure 35.4 shows semantic relationships of Reuters news stories over a two-day period in 2000. The information space can be interactively explored in an off-the-shelf geographic information system (GIS). Earlier in this chapter it was argued that multiple geographic perspectives might be a source for spatial metaphors (Table 35.1). Similarly, multiple viewing perspectives (graphic solutions) should be provided to depict the chosen metaphors. For instance, users should be able to switch graphic (or geometric) perspectives by controlling the viewing angle (i.e., rotation in 2D, and azimuth in 3D), by selecting the location of the viewing footprint (i.e., panning), and being able to alter the graphic and semantic levels-of-detail depicted (i.e., zooming). Although the map in Figure 35.4 is in 2D, it can be dynamically rotated around its graphic center, to change the viewing perspective. The labels are always visible and readable, regardless of the chosen viewing perspective.

One should be able to zoom in and out of the map to explore the information at various levels of graphic and semantic detail, adhering to the geographic scale principle discussed earlier. Contrary to this, when zooming in or out of the space depicted in Figure 35.3, the spheres and pipes will get bigger or smaller (i.e., graphic zoom). The symbology or geometry of the depicted features does not change according to the semantic level of detail. In cartographical scale changes, a feature may be shown with a point symbol on a small scale map (e.g., cities on an airline map), but the same feature may be shown with an areal symbol on a larger scale topographic map.

Providing multiple viewing perspectives on the visualized data also requires that appropriate geometric primitives be matched with semantic primitives depending on the chosen level-of-detail (scale). At the highest level-of-detail, a document may be an individual point in space, which, when clicked on, shows the actual content of the document. At lower levels-of-detail, one may only want to see themes or topics in the information space, for example, represented by homogenous zones, separated by boundaries. In the screen shot from the example application shown in Figure 35.4, geometric primitives are linked to semantic primitives. For example, thematic regions are shown by default at the lowest level of graphic detail (smaller scale map). Unwanted detail is filtered out by aggregating individual items to homogenous zones. The individual documents only become visible when zooming into higher levels of detail (larger scale map), that is, to depict increasing information density while the screen real-estate is kept constant.

Five variables are shown in the 2D map, in an attempt to increase the data–ink ratio. Users can dynamically switch variables on or off, to reduce visual complexity if desired. The network map represents:

(1) the location of news stories based on semantic relationships to other documents in the news archive (point symbols). Following people's expectation that similar

things form clusters in real space, documents similar in content tend to cluster in the 2D display space;

(2) a network of dominant semantic links between documents (line symbols);
(3) the magnitude of dominant semantic links between documents (color value of line symbols);
(4) the magnitude of document connectivity (graduated point symbols);
(5) dominant themes in the database (area symbols).

Unlike Figure 35.3, labels (first-level keywords) are fully visible at all times, and legible at any chosen viewing angle. Labels can also be switched off, if necessary (only a selection is shown in Figure 35.4). Depending on the semantic level of detail, additional labels can be shown (e.g., second- and third-level keywords).

35.3.1 Space types

A certain affinity of geographic and non-geographic Information Visualization becomes apparent as one investigates the procedures by which a high-dimensional input data set is first projected onto a low-dimensional space, then transformed within it, and ultimately visualized. Accordingly, a view of spatialization informed by Cartography and GIScience may contribute to making sense of the myriad of proposed techniques and systems for non-geographic Information Visualization. The ultimate goal of such a viewpoint is to derive methods that implement geographic metaphors in a more complete, and systematic manner than current approaches. For example, once traditional cartographic maps of different scale are understood as expressing geographic phenomena that actually operate at different spatial scales (e.g., global vs. regional vs. local), zoom operations in map-like Information Visualization can be detached from the level-of-detail (i.e., performance-driven) approach common in computer graphics. From the framework presented in Figure 35.2 it follows that the use of semantic primitives is dependent on the depiction scale. Individual entities represented as point features in the information space are useful at the highest level of detail, when navigating in the space, or looking down onto the space, for instance (Table 35.1, top row—Locus). When viewing the information space at coarser level of detail (e.g., overview), point features may aggregate to regions, and can be represented as homogenous zones (Table 35.1, bottom row—Aggregate).

Different 2D layout techniques such as multi-dimensional scaling (MDS), PFNet and self-organizing maps (SOM) may correspond to different conceptualizations of the fundamental make-up of an information space. In GIScience, geographic space is typically conceptualized in one of two ways (Longley et al., 2001): either as an empty space populated by discrete objects, such as point, linear, and areal entities (object/entity view); or as a continuous field, with an infinite number of locations, whose properties can be described by an infinite number of variables (field view). Depending on the phenomenon represented digitally, either a field view or an object view may be more appropriate. For example, human-made features such as houses or bridges are typically represented as discrete objects, while many natural phenomena such as, elevation or humidity, are commonly conceptualized as continuous fields. The conceptual distinction made between objects and fields tends to translate into a choice between vector and raster data structures in GIS implementations (Longley et al., 2001), and is relevant through all the stages of a GIS project.

Looking at the various approaches to dimensionality reduction utilized commonly in Information Visualization, one finds a similar object/field distinction (Skupin, 2002b). Use of a particular projection technique requires the *a priori* existence of either an object or field conceptualization of the high-dimensional space that is being mapped. This is reflected in the data models used for representing spatialized geometry, and in the ways in which certain depiction solutions can or cannot be used. The framework presented in Table 35.1 and Figure 35.2 is flexible enough to be utilized with either of the two space views. The "locus" primitive in Table 35.1 can be depicted with "pixels" (field view) or with point symbols (object view), for instance. The same is true for the linear and areal semantic primitives. They can be depicted with a linear series or group of pixels, as well as with line or areal symbols. The same applies to the other semantic primitives listed in Table 35.1. The remainder of §35.3 highlights some examples.

35.3.2 Object/entity view

Many techniques, like MDS (Kruskal and Wish, 1978) or pathfinder network scaling (Schvaneveldt, 1990), start out with a conceptualization of high-dimensional information space as consisting of distinct, discrete objects. This conceptualization is at play when these methods proceed with a pair-wise computation of object similarities, and finally produce discrete coordinate geometry for individual observations (MDS, PFNet), or explicit network topology between observations (PFNet).

Data models and formats used in vector GIS are at that point applicable. To those cartographers well versed in the use of desktop GIS, it is from here a very small step to create engaging, and visually compelling visualizations. Arguably, this is another reason for the current level of success enjoyed by cartographers engaged in non-geographic Information Visualization.

35.3.3 Field view

There are also techniques, like SOM (see Koua and Kraak, this volume (Chapter 33)), that employ a field-like conceptualization of abstract information (Kohonen, 1995). Instead of focusing on individual observations, these are interpreted as representative samples of an information continuum. It is through a tessellation of that high-dimensional continuum that visualization efforts are enabled to later implement semantic aggregates, as is necessary for such tasks as the labeling of document clusters (Skupin, 2002a).

Raster data models are the most common approach to representing fields in GIS. SOMs do in fact also utilize a raster model, usually with either square or hexagon elements. The transparent, interchangeable use of regular point lattices and pixel grids for training and outputting a SOM, again bears close similarity to how such data are handled in GIS. This raster-like nature also provides a natural control over granularity. When SOMs are used for classification, changing granularity simply leads to finer or coarser classification. When used for visualization, the change of SOM granularity amounts to a control over the scale of the representation. The differences between a 10,000-node SOM and a 50,000-node SOM can thus be considered similar to the differences between satellite images of different spatial resolutions. Armed with this realization, one can thus begin to draw on advances in scale-dependent geographic analysis (Quattrochi and Goodchild, 1997; Wood, this volume (Chapter 15)), including fractal analysis, towards new forms of information space investigations.

Another implication of the object vs. field conceptualization of an information space relates to how observations are handled that are not part of the original data set. Field conceptualization allows the mapping of new observations onto an existing spatialization. In a SOM, the high-dimensional continuum is chunked into a limited number of pieces. Each of these will eventually occupy a portion of low-dimensional real estate, as well. Mapping a new observation is simply a matter of finding the high-dimensional chunk into which it falls and then finding the low-dimensional location of that chunk. All this is not easily possible with object-based methods, like MDS or spring models (see Rodgers, this volume (Chapter 7)) since the high-dimensional space between original observations remains an ill-defined void.

35.3.4 Space transformations

In geovisualization, including GIS, data required for spatial analysis and display are rarely available in a directly usable form. Thus it becomes important to know the semantic and geometric characteristics of the data used, and how spatial data from different sources (and in different formats) can be fused such that they work jointly for multi-variate analyses. Examples of geometric data transformations may include map projections, affine transformations to register two data sets, edge-matching, etc. Similarly, in non-geographic Information Visualization, transformation procedures become necessary when first projecting a high-dimensional input data set into a lower-dimensional space, then further transforming results of this initial projection towards actual depiction.

Once a low-dimensional, geometric configuration is established through a particular projection technique, further transformations on the basis of that geometry may be required in order to achieve a particular depiction. For example, a point configuration created by MDS could be transformed into a surface through interpolation in order to create a terrain-like visualization. The number of possible visualization methods and parameters traditionally used by cartographers is large, and so is consequently the number of transformation methods to achieve these visualizations. Some even see Cartography’s potential for transformation of spatial data as its most distinguishing characteristic (Tobler, 1979a,b).

Today, the design of Information Visualizations still tends to be closely linked to the characteristics of the geometric primitives (points, lines, areas) that are generated through a particular projection technique (Skupin, 2002b). For example, if a method like MDS assigns 2D coordinate pairs to a spatialized entity, then those observations tend to be visualized by point symbols. Further geometric transformation is the exception rather than the rule. Arguably, the fascination with such efforts as Themescapes (Wise et al., 1995; Wise, 1999) is in large part due to their attempt to go beyond the bounds of initial geometric configurations toward map-like representation via space transformation (i.e., surface interpolation in the case of Themescapes).

Knowledge of Cartography's potential for transformation and of the particular transformations it employs can inform non-geographic Information Visualization in a number of significant ways: It can help to derive from a given low-dimensional configuration a large number of alternative visual representations (Figures 35.5 and 35.6). Having a set of alternatives, one is then in a better position to choose a design which fulfills one or more of the following conditions:

- fitting certain known characteristics of the mapped high-dimensional domain (e.g., gradual vs. abrupt change);
- corresponding to the conceptualization of the high-dimensional domain underlying a particular projection technique;
- corresponding to our knowledge about users' cognitive abilities, preferences, or domain ontology (e.g., dependent on a geographic perspective, shown in Table 35.1);
- conveying a message pursuant to a certain agenda (in the best cartographic tradition).

These will often be conflicting goals, and are quite similar to design decisions cartographers need to make for geographic datasets. By means of geometric and semantic transformations one can derive spatialized views with different spatialization primitives in order to achieve a depiction that matches users' needs and cognitive capabilities best.

The depiction of discrete objects in Figure 35.5, or the field-based depiction in Figure 35.6 are two alternative realizations derived from the same data set, but highlighting different characteristics of the data, dependent on the depiction purpose. The proposed framework guided our design decisions. This included identifying the appropriate semantic primitives, and then matching the relevant geometric transformation technique used for depiction, as discussed in more detail below.

The same database of Reuters news stories represented in Figure 35.4 was used to derive different spatialization types in 2D and 3D, as depicted in Figures 35.5 and 35.6. Figure 35.5a illustrates the configuration of a subset of Reuters news stories as discrete semantic loci (depicted as points) in an empty, 2D information space. According to the proposed framework, these points act as landmarks in the otherwise empty semantic space (Table 35.1). Point locations are the result of a 2D spring embedder algorithm (Kamada and Kawai, 1989). In the second panel (Figure 35.5b), dominant semantic links connect document locations to a semantic network in 2D. The semantic links are an instance of the semantic primitive "trajectory". These links show semantic paths or routes

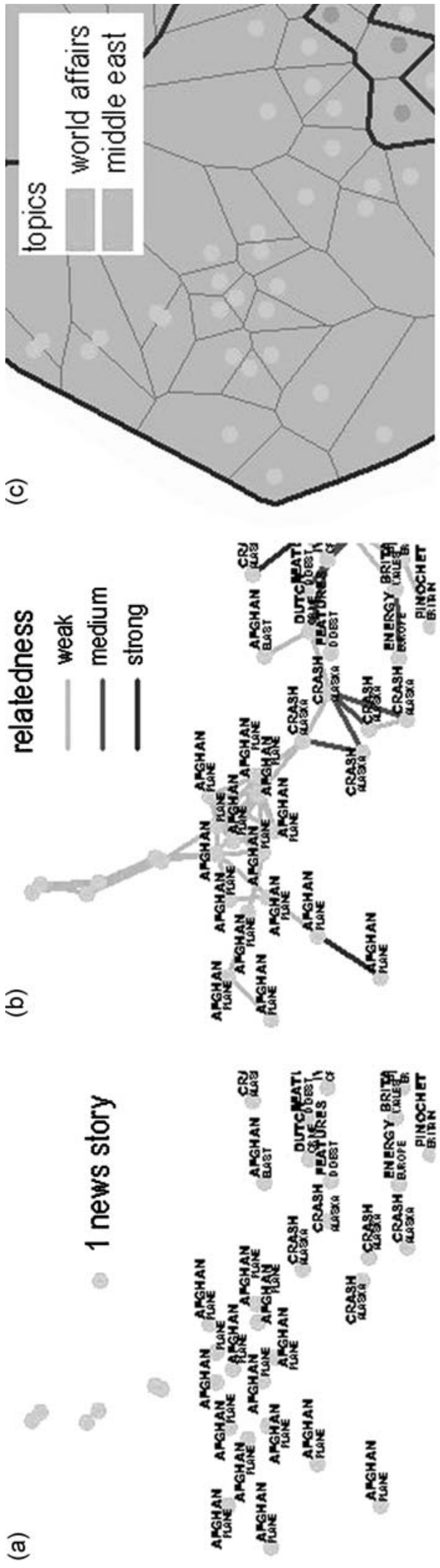
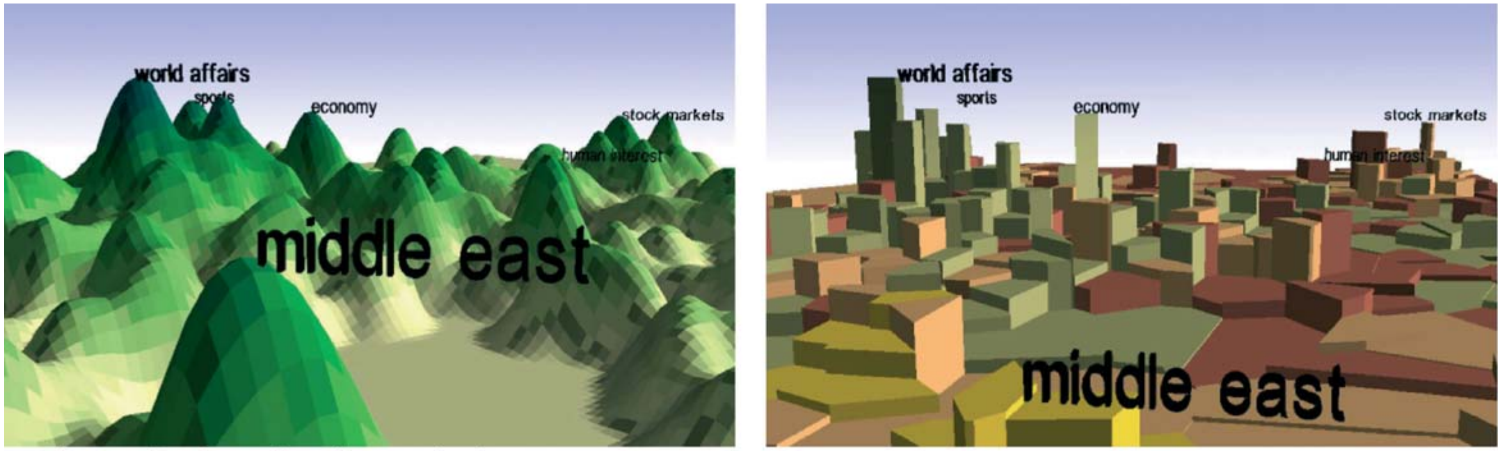
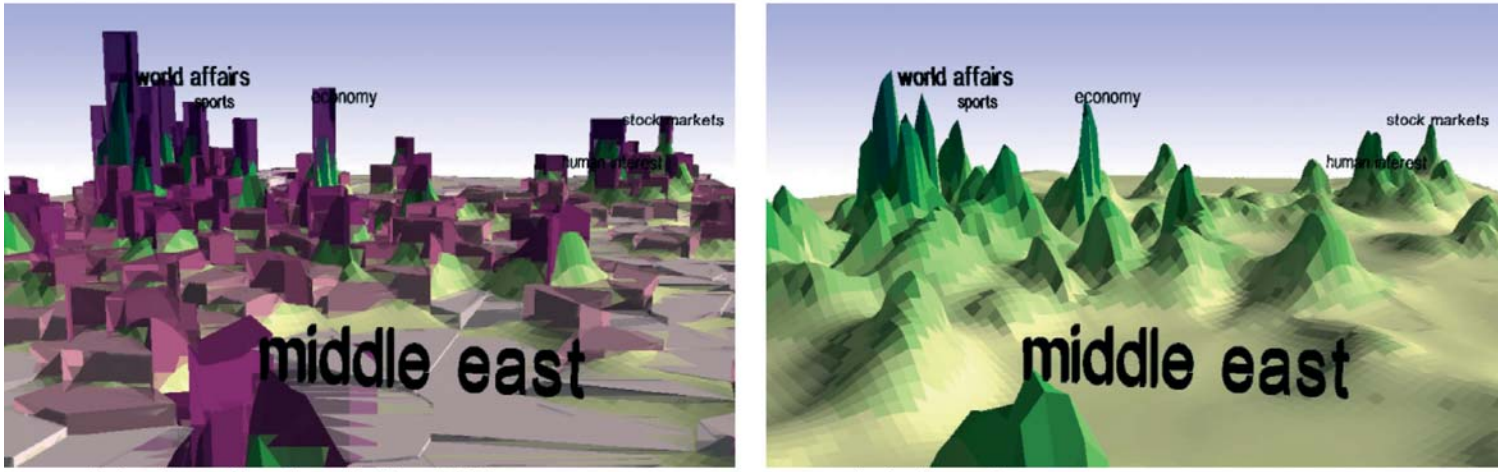


Figure 35.5. Geometric primitives and their transformations in 2D.



continuous density surface (from points)

stepped density surface (from voronoi polygons)



pycnophylactic reallocation (Tobler, 1979)

pycnophylactic surface

Figure 35.6. Four 3D visualizations derived from a single 2D configuration. (Skupin and Fabrikant, 2003; reprinted with permission from Cartography and Geographic Information Science, 30(2) p. 108).

through the information space, connecting the landmarks. The third panel, Figure 35.5c, shows thematic regions emerging from the database. These regions, examples of the "aggregate" primitive in Table 35.1, are derived from a point-to-area transformation, based on a Voronoi tessellation. In a first transformation step each node is represented with its own zone of influence (e.g., grey polygon boundaries around every point). Secondly, Voronoi polygon boundaries are merged based on cluster membership derived from a hierarchical clustering solution (Masser and Brown, 1975). Two emerging clusters, "world affairs" and "middle east", are highlighted in Figure 35.5c.

One can transform semantic primitives from one space model (e.g., object/entity view) into another (e.g., field view) and match the geometric primitive accordingly. Utilizing the same discrete, 2D spring embedder configuration from Figure 35.5a, 3D continuous and discrete surface types can be derived, as examples in Figure 35.6 show below. A switch from an object to a field view may be useful (but not necessary) when looking at the space at coarser level of detail (scale change), and to give viewers a general sense of where entities are densest, or how they cluster ("aggregate" primitive).

The four different depictions in Figure 35.6 were generated by means of interpolation, where new data is created to fill the void between the discrete data observations in 2D, and are then depicted in 3D. Which of these representations is more appropriate, and for which particular types of user tasks? Does one of the design solutions convey a detected pattern more effectively than another one? Should we use a particularly compelling method even if it may convey a false sense of the volume and richness of the source data? Is the stepped density surface the most honest depiction, since the underlying 2D geometry was based on an object conceptualization of the high-dimensional space? Do "valleys" carry as much meaning as "ridges" do? These are questions that any of the proposed terrain-like Information Visualization techniques, like Themescapes (Wise et al., 1995) or VxInsight (Davidson et al., 1998) will have to able to confront. Answering these questions is not possible, if the application of any arbitrary interpolation technique is seen as sufficient.

The ability to consider these questions depends on having available both a solid theoretical framework and, arguably, a rich set of cartographic transformation tools. Those tools should be applied in a systematic, justifiable manner, and informed by the theoretical scaffold. A great deal of research in Cartography and geographic information science has focused on understanding the implications of different methods for generating surfaces from information sampled at points in a field (Lam, 1983) and for generating a surface from values representing discrete objects, such as enumeration units (Tobler, 1979a,b).

Scale-related transformations (e.g., to enable zoom operations) are another example for the intersection of GIScience and Information Visualization interests and expertise. The implementation of a scale metaphor through nested cluster hierarchies has recently received attention by geographers and non-geographers alike (Guo et al., 2002; Seo and Shneiderman, 2002; Skupin, 2000, 2002a). Figures 35.7 and 35.8 show an example in which a hierarchical clustering tree (Figure 35.7) drives the creation of scale-dependent, map-like, visualizations (Figure 35.8). A base map consisting of Association

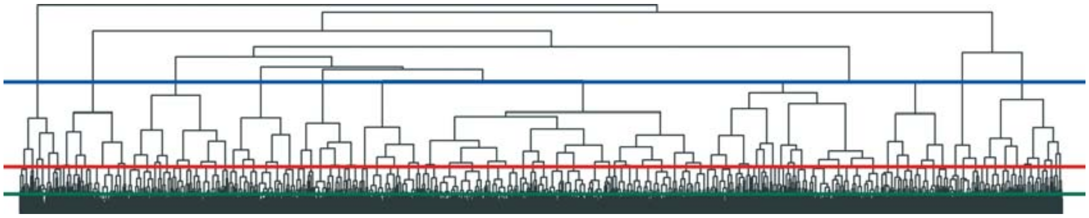


Figure 35.7. Hierarchical clustering tree for a finely grained SOM (4800 neurons). Also shown are three horizontal cuts corresponding to a 10-cluster solution (blue), a 100-cluster solution (red), and an 800-cluster solution (green) (from Skupin, 2002a; ©2002 IEEE).

of American Geographers (AAG) conference abstracts is here generalized by first clustering a fine-resolution SOM, then finding the closest SOM neuron to each abstract, and finally merging neighboring abstracts based on shared cluster membership at defined zoom levels (Skupin, 2002a). The computational extraction of label terms (based on the distribution of author-chosen keywords across the full text of all abstracts) is driven by the desire to express characteristics of a cluster while distinguishing it from other clusters that exist at the same scale level. For example, the cluster labeled "precipitation" – "nino" – "climate" will contain abstracts dealing with the climate aspect of physical Geography, while the cluster labeled "spatial" – "information" – "data" refers to geographic research focusing on GIS and Cartography.

These multi-scale representations are best explored as part of a rich interactive interface. Extension of the (static) "optimal" 2D map design paradigm, typically associated with traditional Cartography, towards interactive exploration has been a main research focus of the geovisualization community in the last decade. Exploratory spatial analysis tools, such as Descartes or GeoVISTA *Studio* (Andrienko and Andrienko, 1998; Gahegan et al., 2002a,b), featuring dynamically linked multi-dimensional cartographic and statistical data depictions, allow the interactive exploration of different views of the

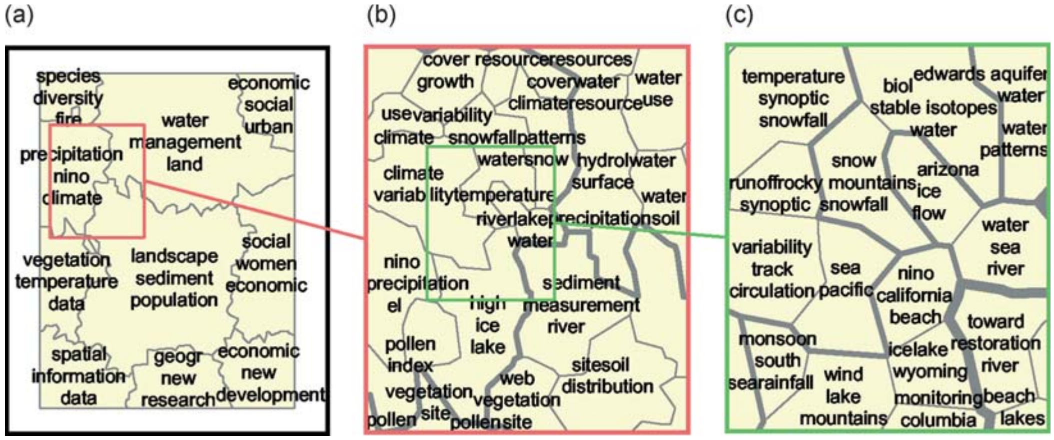


Figure 35.8. Implementing the scale metaphor via nested semantic aggregates: (a) a complete map of conference abstracts shown in a 10-cluster solution; (b) map portion shown for a 100-cluster solution; (c) map portion shown for an 800-cluster solution (from Skupin, 2002a; ©2002 IEEE).

same geographic data set. These methods can also be utilized for spatialized displays. The framework presented here supports this in three ways:

1. semantic primitives can be matched to many possible geographic perspectives (five task-dependent perspectives are shown in Table 35.1);
2. adequate geometric primitives can be matched to the semantic primitives (Figure 35.2);
3. long-standing cartographic transformation methods can be used when transformations between semantic and geometric primitives are necessary

35.4 Conclusions and Outlook

This chapter outlines a theoretical framework for the construction of cognitively plausible semantic information spaces. A cognitively plausible Information Visualization is designed such that it matches human's internal visualization capabilities. The proposed framework focuses on the use of geographic space as a data generalization strategy (ontology), and the use of spatial representations or maps to depict these data abstractions. The building blocks of this spatialization framework are informed by geographic information theory and include principles of ontological modeling, such as semantic generalization (spatial primitives), geometric generalization (visual variables), association (source–target domain mapping through spatial metaphors), and aggregation (hierarchical organization).

A sound spatialization framework enables information designers not only to construct conceptually robust and usable information spaces but also allow information seekers to more efficiently extract knowledge buried in large digital data archives. Such a framework can be substantially supported through two major strands of work, namely: (i) research into the cognitive and ontological foundations and implications of how people interact with non-spatial data on the basis of familiar spatial metaphors; (ii) work on the computational techniques that can produce meaningful spatialized geometries, visualizations, and methods of analysis.

Ongoing work at the University of California Santa Barbara (UCSB) and the University at Buffalo, is concerned with investigating empirically fundamental cognitive and ontological issues in spatialization, as highlighted in this chapter. A research project at the University of New Orleans is underway for building a system for map-like browsing and analysis of conference abstracts. The goal of the project is to develop a proof-of-concept spatialization system, adhering to the cognitively plausible framework discussed in this chapter. All the semantic primitives proposed in this chapter (including the scale metaphor) have been empirically evaluated in a first series of controlled experiments. Initial empirical evidence looks very promising, and are discussed elsewhere (Fabrikant, 2000a, 2001a; Fabrikant et al., 2002). Outcomes of previous experiments have led to revisions of the initial framework. These empirical results also suggest that cartographic design guidelines are applicable and useful for designing non-geographic information spaces (Fabrikant, 2000a). A new series of human subject testing is currently underway at UCSB to replicate and extend initial findings. We believe that spatialization designs will greatly benefit from additional empirical evidence gained from fundamental cognitive evaluations. A sound theoretical scaffold is an important starting point for designing adequate experiments to test the validity of an underlying conceptual model used for depiction. This is what this chapter set out to do. Test outcomes will be used in turn to refine the theory, and derive appropriate spatialization design guidelines.

Recognition of the existence of different space conceptualizations and of the possible range of geometry-based and semantically driven transformations can help shape future Information Visualization efforts. Specifically, such a view should help to move beyond the current engineering-inspired paradigm, in which specific visualization systems are evaluated for usability within the bounds of *ad hoc* choices made by system designers. An incorporation of GIScience-inspired ideas regarding space and its transformation in accordance with the notion of cognitive plausibility may lead to a more systematic understanding of issues of usability and usefulness emphasized elsewhere in this volume.

Acknowledgements

We would like to thank the book editors Jason Dykes, Alan MacEachren and Menno-Jan Kraak for the stimulating ICA Commission meeting in London (UK), in 2002, and for providing this wonderful opportunity for scholarly debate and interdisciplinary exchange. We are grateful for the detailed feedback provided by the book editors, and the anonymous reviewers, which helped improving the presentation of our ideas. Finally, we gratefully acknowledge funding support by the National Imagery and Mapping Agency (NMA-201-00-1-2005: Sara Fabrikant), and by the Louisiana Board of Regents Support Fund, grant # LEQSF(2002-05)-RD-A-34: André Skupin).

References

Andrienko, G. L., and Andrienko, N. V., (1998) “Dynamic categorization for visual study of spatial information”, *Programming and Computer Software*, 24(3), 108-115.

Bertin, J., (1967) *Sémiologie Graphique: Les Diagrammes – les Réseaux – les Cartes*. Paris: Mouton.

Bertin, J., (1998) *Sémiologie Graphique: Les Diagrammes – les Réseaux – les Cartes*. Paris: Éditions de L’École Pratique des Haute Études.

Buckley, A. M., Gahegan, M., and Clarke, K., (2000) Emerging themes in GIScience research: geographic visualization. Online: http://www.ucgis.org/priorities/research/research_white/2000%20Papers/emerging/Geographicvisualization-edit.pdf (23/10/03).

Buttenfield, B. P., Gahegan, M., Miller, H., and Yuan, M., (2000) Emerging themes in GIScience research: geospatial data mining and knowledge discovery. Online: http://www.ucgis.org/priorities/research/research_white/2000%20Papers/emerging/gkd.pdf (23/10/03).

Card, S. K., Mackinlay, J. D., and Shneiderman, B., (eds.), (1999) *Readings in Information Visualization: Using Vision to Think*. San Francisco: Morgan Kaufmann Publishers.

Chen, C., (1999) *Information Visualization and Virtual Environments*. Springer: London, 223 pp.

Chen, C., and Carr, L., (1999) "Visualizing the evolution of a subject domain: a case study", *Proceedings of the Ninth IEEE Visualization '99 Conference*, San Francisco, CA, pp. 449-452, (October 24–29, 1999).

Couclelis, H., (1998) "Worlds of information: the geographic metaphor in the visualization of complex information", *Cartography and Geographic Information Systems*, 25(4), 209-220.

Davidson, G. S., Hendrickson, B., Johnson, D. K., Meyers, C. E., and Wylie, B. N., (1998) "Knowledge mining with VxInsight: discovery through interaction", *Journal of Intelligent Information Systems*, 11(3), 259-285.

DiBiase, D., MacEachren, A. M., Krygier, J. B., and Reeves, C., (1992) "Animation and the role of map design in scientific visualization", *Cartography and Geographic Information Systems*, 19(4), 201-214, see also 265–266.

Edwards, G., (2001) "A virtual test bed in support of cognitively-aware geomatics technologies", In: Montello, D. R., (ed.), *Spatial Information Theory. Foundations of Geographic Information Science, Lecture Notes in Computer Science 2205*. Berlin: Springer, pp. 149-155.

Fabrikant, S. I., (2000a) *Spatial Metaphors for Browsing Large Data Archives*, University of Colorado-Boulder, Department of Geography.

Fabrikant, S. I., (2000b) "Spatialized browsing in large data archives", *Transactions in GIS*, 4(1), 65-78.

Fabrikant, S. I., (2001a) "Evaluating the usability of the scale metaphor for querying semantic information spaces", In: Montello, D. R., (ed.), *Spatial Information Theory: Foundations of Geographic Information Science*. Berlin: Springer, pp. 156-171.

Fabrikant, S. I., (2001b) "Visualizing region and scale in semantic spaces", *Proceedings of the 20th International Cartographic Conference, ICC 2001*, Beijing, China, pp. 2522-2529, (August 6–10, 2001).

Fabrikant, S. I., and Buttenfield, B. P., (1997) "Envisioning user access to a large data archive", *Proceedings GIS/LIS '97*, Cincinnati, OH, pp. 686-692, (October 28–30, 1997).

Fabrikant, S. I., and Buttenfield, B. P., (2001) "Formalizing semantic spaces for information access", *Annals of the Association of American Geographers*, 91(2), 263-290.

Fabrikant, S. I., Ruocco, M., Middleton, R., Montello, D. R., and Jörgensen, C., (2002) "The first law of cognitive geography: distance and similarity in semantic space", *Proceedings of GIScience 2002*, Boulder, CO, pp. 31-33.

Gahegan, M., Takatsuka, M., Wheeler, M., and Hardisty, F., (2002a) "GeoVISTA Studio: a geocomputational workbench", *Computers, Environment and Urban Systems*, 26, 267-292.

Gahegan, M., Takatsuka, M., Wheeler, M., and Hardisty, F., (2002b) “Introducing GeoVISTA Studio: an integrated suite of visualization and computational methods for exploration and knowledge construction in geography”, *Computers, Environment and Urban Systems*, 26(4), 267-292.

Gibson, J. J., (1979) *The Ecological Approach to Visual Perception*. Boston, MA: Houghton Miflin.

Guo, D., Peuquet, D., and Gahegan, M., (2002) “Opening the black box: interactive hierarchical clustering for multivariate spatial patterns”, *Proceedings of the Tenth ACM International Symposium on Advances in Geographic Information Systems*, McLean, VA, pp. 131-136, (November 8–9, 2002).

Hake, G., Grünreich, D., and Meng, L., (2002) *Kartographie – Visualisierung raum-zeitlicher Informationen (German)*. Berlin: de Gruyter.

Hegarty, M., (2002) “Mental visualizations and external visualizations”, In: *Proceedings 24th Annual Conference of the Cognitive Science Society (Cog Sci 2002)*, August 7–10, George Mason University, FairFax, VA, p. 40.

Kamada, T., and Kawai, S., (1989) “An algorithm for drawing general undirected graphs”, *Information Processing Letters*, 31(1), 7-15.

Kohonen, T., (1995) *Self-Organizing Maps*. Berlin: Springer.

Kruskal, J. B., and Wish, M., (1978) *Multidimensional Scaling*. Sage University Papers. Series on Quantitative Applications in the Social Sciences, Series Number 07-011, Vol.11. Newbury Park: Sage Publications.

Kuhn, W., and Blumenthal, B., (1996) *Spatialization: Spatial Metaphors for User Interfaces*. Vienna: Technical University of Vienna.

Lakoff, G., (1987) *Women, Fire, And Dangerous Things: What Categories Reveal About The Mind*. Chicago, IL: University of Chicago Press.

Lakoff, G., and Johnson, M., (1987) *Metaphors We Live By*. Chicago, IL: University of Chicago Press.

Lam, N. S.-N., (1983) “Spatial interpolation methods: a review”, *The American Cartographer*, 10, 129-149.

Longley, P. A., Goodchild, M. F., Maguire, D. J., and Rhind, D. W., (2001) *Geographical Information Systems and Science*. New York: Wiley.

Lynch, K., (1960) *The Image of the City*. Cambridge, MA: MIT Press.

MacEachren, A. M., (1995) *How Maps Work: Representation, Visualization, and Design*. New York: Guildford Press.

Mackinlay, J. D., (1986) “Automating the design of graphical presentations of relational information”, *ACM Transactions on Graphics*, 5(2), 110-141.

Masser, I., and Brown, P. J. B., (1975) “Hierarchical aggregation procedures for interaction data”, *Environment and Planning A*, 7, 509-523.

Merriam-Webster Inc. (2003) Merriam-Webster online language center.
Online: http://www.m-w.com (23/10/03).

National Research Council (1997) *Rediscovering Geography: New Relevance For Science and Society*. Washington, DC: National Academy Press.

Quattrochi, D. A., and Goodchild, M. F., (1997) *Scale in Remote Sensing and GIS*. New York: Lewis Publishers.

Saussure, F., (1993) *Course in General Linguistics*. London, UK: Dockworth.

Schvaneveldt, R. W., (ed.), (1990) *Pathfinder Associative Networks: Studies in Knowledge Organization*. Norwood, NJ: Ablex.

Seo, J., and Shneiderman, B., (2002) "Interactively exploring hierarchical clustering results", *IEEE Computer Graphics and Applications*, 35(7), 80-86.

Skupin, A., (2000) "From metaphor to method: cartographic perspectives on information visualization", In: Roth, S. F., and Keim, D. A., (eds.), *IEEE Symposium on Information Visualization (InfoVis 2000)*, Salt Lake City, UT, pp. 91-97, (October 9–10, 2000).

Skupin, A., (2002a) "A cartographic approach to visualizing conference abstracts", *IEEE Computer Graphics and Applications*, 22(1), 50-58.

Skupin, A., (2002b) "On geometry and transformation in map-like information visualization", In: Börner, K., and Chen, C., (eds.), *Visual Interfaces to Digital Libraries (Lecture Notes in Computer Science 2539*). Berlin: Springer, pp. 161-170.

Skupin, A., and Fabrikant, S. I., (2003) "Spatialization methods: a cartographic research agenda for non-geographic information visualization", *Cartography and Geographic Information Science*, 30(2), 95-119.

Spence, R., (2001) *Information Visualization*. Harlow: Addison Wesley/ACM Press Books, 206 pp.

Tilton, D. W., and Andrews, S. K., (1994) "Space, place and interface", *Cartographica*, 30(4), 61-72.

Tobler, W. R., (1979a) "Smooth pycnophylactic interpolation for geographical regions", *Journal of the American Statistical Association*, 74(367), 519-530.

Tobler, W. R., (1979b) "A transformational view of cartography", *The American Cartographer*, 6, 101-106.

Tufte, E. R., (1983) *The Visual Display of Quantitative Information*. Cheshire, CT: Graphics Press, 197 pp.

van der Waarde, K., and Westendorp, P., (2001) "Theme: Jacques Bertin's theories", *Information Design Journal*, 10(1).

Ware, C., (2000) *Information Visualization: Perception for Design*. San Francisco: Morgan Kaufmann Publishers, 384 pp.

Westerman, S. J., (1998) "A comparison of the cognitive demands of navigating two- vs three-dimensional spatial database layouts", *Ergonomics*, 41, 207-216.

Westerman, S. J., and Cribbin, T., (2000) "Mapping semantic information in virtual space: dimensions, variance, and individual differences", *International Journal of Human–Computer Studies*, 53(5), 765-788.

Wise, T. A., (1999) "The ecological approach to text visualization", *Journal of the American Society of Information Science*, 53(13), 1224-1233.

Wise, T. A., Thomas, J. J., Pennock, K. A., Lantrip, D. B., Pottier, M., Schur, A., and Crow, V., (1995) "Visualizing the non-visual: spatial analysis and interaction with information from text documents", In: *Proceedings of the IEEE Information Visualization (InfoVis, '95*). Los Alamitos, CA: IEEE Computer Press, pp. 51-58, (October 30-31, 1995).