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Geobrowsing: creative thinking and knowledge discovery using geographic visualization

Donna J. Peuquet[1]
Menno-Jan Kraak[2]

[1]GeoVista Center and Department of Geography, The Pennsylvania State University, U.S.A.;
[2]Geoinformatics, Cartography and Visualization, International Institute for Aerospace Survey and Earth Sciences (ITC), The Netherlands

Correspondence:
Donna J. Peuquet, Department of Geography, 302 Walker Building, The Pennsylvania State University, University Park, Pennsylvania 16802, U.S.A. Tel: 814-863-0390;
Fax: 814-863-7943; E-mail: peuquet@psu.edu

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Abstract
In the modern computing context, the map is no longer just a final product. Maps are now being used in a fundamentally different way – as a self-directed tool for deriving the desired information from geographic data. This, along with developments in GIScience and computer graphics, have led to the new field of geographic visualization. A central issue is how to design visualization capabilities that, as a process, facilitate creative thinking for discovering previously new information from large databases. The authors propose the term 'geobrowsing' to designate this process. A number of interrelated ways that visualization can be used to spark the imagination in order to derive new insights are discussed and a brief example provided. Based upon the cognitive literature, specific properties of a visual image that promote discovery and insight are discussed. These are known as *preinventive* properties, and include; novelty, incongruence, abstraction, and ambiguity. All of these properties, either individually or in combination, tend to produce features that are unanticipated by the viewer, and often not explicitly created or anticipated by the person generating the visual display. While traditional (i.e. non-computer generated) images can also possess these properties, as shown in the historical examples in this discussion, it is the capability of the viewer to directly and quickly manipulate these properties that provides the real power of 'geobrowsing' for uncovering new insights.
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> '*Most researchers tend to rely on well-worn procedures and paradigms, but creative discoveries, in both art and science, often occur in unusual situations, where one is forced to think unconventionally.*' [p. 31][1]

The changing nature of cartography

Maps have been used for millennia to record and convey geographic information. They also correspond in some fundamental ways to how we cognitively use spatial knowledge.[2–4] The modern mapping environment has been influenced by developments in closely related disciplines such as geographic information sciences and computer graphics. Only recently have developments in scientific visualization[5] and information visualization[6] influenced this area, leading the new field of geographic visualization or geovisualization.[7] Such developments include the use of non-cartographic devices such as the parallel coordinate plot and the exploration of immersive technology. The links and differences between the display of non-spatial and the display of geographic information has been previously discussed by Fabrikant.[8]

Briefly stated, unlike the spatialization of information, which utilizes spatial (i.e., graphic) displays to represent non-spatial data, geographic visualization utilizes spatial displays to present information that is already intrinsically spatial. Geographic visualization is thus not faced with making non-spatial information spatial while also making the information more accessible in the translation. The visualization of geographic data utilizes the same visual system that we use on an everyday basis to directly perceive our environment. Maps are also a frequently used model of our own environment, and are very much an everyday and ordinary tool. As such, we tend to see that we expect to see in maps, and often do so without really thinking about the process. The challenge with maps, then, is how to utilize this common form of spatial display in new ways that encourages exploration and the subsequent discovery of novel insights in geographic databases.

A number of studies have shown that simple maps can be understood and used by children as young as 4 years of age without any previous experience or training.[9–11] Maps have also developed independently in cultures as different and geographically far-flung as Europe and the Middle East, Mesoamerica, and the Marshall Islands in the Pacific. In modern western culture, we use them to see what tomorrow's weather conditions will be, where we are in the mall, which subway train to take, and how to find our way to a friend's party or to Amsterdam. We use them to see where things were in the past, where things might be located in the future, and even the spatial layout of hypothetical worlds.

Much of cartographic representation is also highly conventionalized. Besides a complex and sophisticated system of symbology, the placement of map features within a professionally derived cartographic product is often based upon precise observational measurement of real-world features. Given some specified scale, map projection, etc., the corresponding map features can be measured, thus retrieving (to some level of approximation) the original real-world measurements as data.

Regardless of the mathematics involved, there are also other, less-precise, rules of mapping practice that deal with how to portray a given collection of information in order to convey a specific overall message. The sizes of the symbols used for specific elements, for example, alters their significance overall as well as in relation to other elements in the map. The choice of framing, the orientation of the geographic space in relation to the viewer, as well as the selection of the spatial area portrayed, all similarly affect the overall message.[12]

Mapping is thereby a creative process for the person designing the map. This is something that has been emphasized in the past, within the dominant paradigm of maps as a means of communication. Within this view, the creator of the map designs the map, selecting elements from a known and standardized system of symbology, so that the intended message is accurately conveyed to the map reader who can interpret the meaning contained within the symbology. The map reader is a passive receiver of information through a static medium. By the very nature of this process, the information itself has been pre-interpreted, and in the case of published cartographic products, the creation process is in the hands of trained professionals.

How maps are being created and used has changed with the wide availability of computer mapping facilities as stand-alone programs in GIS and in other software. Mapping has become 'democratized', in that this capability is available to anyone with access to a computer. In this environment, the map reader is an active participant, creating their own map whenever information is desired, using them as a graphical tool for actively exploring vast amounts of digital data. As such, mapping has become a tool for thinking[13] and maps themselves are often ephemeral and transient. Instead of being a data storage medium and communication tool, maps are being used in a fundamentally different way; as an exploratory tool for gaining new information and insight from large, digital databases. The map is not necessarily a final product.

The nature of maps

As with graphics in general, the entire mapping process involves both a complex system of signs and 'rules of grammar' as well as of overall arrangement within which an overall portrayal is shaped through selection, transformation and arrangement. As such, the map has a dual nature.[14] It is a *structure* that is algebraic in nature, as an assemblage of symbols of prescribed meaning ordered according to a system of positional rules of interrelationships. It is also a visual *image* with patterns of light and dark, color, etc. The entire cartographic 'process', including map compilation as well as map interpretation is highly complex as a result. Certainly, the context of the map, the meaning of the individual symbols and the basic 'rules of grammar' must be known for the map to convey the intended meaning to the person viewing it.[15] Thus, the map reader should be able to say: 'Ah – this must be a map of Pennsylvania, and I can see by this particular linear symbol that a railroad runs through here'. Map makers also realize that there are intangible qualities of perceived reality that can only be conveyed cognitively, utilizing the nature of the map as an image. The use of reds and yellows to convey danger in the intensity of thunderstorms in television weather maps (as opposed to shades of green for milder rain) is an example of this. Given all of these characteristics, mapping, as a design skill, inescapably involves art as well as science.

A crucial development in advancing the understanding of how maps work, as well as visualizations of data generally, was the development of *semiotics* as a discipline, and generally defined as the study of symbolic systems.[15] In particular, Bertin[16,17] developed a theory of the nature of map symbology and map sign systems. This was part of the movement emphasizing cartography-as-science.

In stressing the 'scientific' approach in cartography, the focus has been on the accurate representation of information; portrayal of what is already known. An unfortunate consequence of this approach is that the use of the imagination in finding new information (i.e.

new patterns and relationships) has been ignored, if not actually repressed. With the adoption and extension of Bertin's semiology over the past 30 years, systems of symbology have been codified, so that overall patterns can be most effectively portrayed by the cartographer in getting an intended message across to the map user.

The use of the imagination in published cartographic portrayal has a long tradition, but has in large part been left to the artist in recent decades. The map-as-metaphor is one such 'artistic' form that is also a very powerful communication form, stretching the ability to go beyond the individual elements portrayed even further – beyond the power of the map alone.

It must be noted here that the map-as-metaphor is very different from the use of the map as a metaphor in other contexts, such as the use of the map as a metaphor in computer interfaces to help the user access data.[8,18] Rather, the map-as-metaphor, or the metaphorical map, visually superimposes non-geographic features or elements onto a map that still depicts geographic space.

There are many historical examples that use the map-as-metaphor in making various political statements. One of the most famous historical examples is Leo Belgicus (the Belgic Lion) as shown in Figure 1. This metaphorical map consisted of the superimposition of a lion onto a map of the lowland provinces. This was first conceived around 1579, when the lowland provinces (now The Netherlands and Belgium) were fighting for independence from Spain. The lion appeared on the coat of arms of almost every province, so in addition to implying lion-like strength, independence and dignity, it also served to imply unity. Other examples are the many maps on stamps, which are either just a decorative device or indeed claim territory or emphasize the identity of a country or region.

The combination of modern computing technology and exhaustive digital coverage of the earth at multiple scales is a particular form of cyberspace, blurring the distinction between reality and a representation of it. Of course, small-scale maps have always been an important tool in constructing our perception of geographical space of a scale beyond what we can experience directly through our senses, such as our view on a global scale. Although at one time a main purpose of world-scale maps was to record and present known knowledge of the larger world, they were also of necessity abstractions and simplifications. Both types of maps are now being replaced with what may be described as imitation of experience through exhaustive coverages in cyberspace, complete with realistic images and imagery.

The boundaries between direct and indirect experience of the environment is becoming so blurred that it is becoming difficult in a cyber-world to distinguish between the real and the created; past, present, or future. But is that ever going to replace textual and graphic representations of geographic space? The answer is clearly no, because maps by definition are symbolized abstractions of reality. Part of the power of maps lies in their ability to abstract and provide selections from reality that facilitate an understanding of the selected features. Even though developments in virtual reality in relation to geography are tremendous,[19] one can wonder when using (three-dimensional) maps in such a virtual reality environment up to what level of realism will the maps be effective. Nevertheless, maps need to change, as mapping has already changed. We will always have the need for simplified representations of reality in order to comprehend its complexities. What we need, then, is research into how maps can be best used as visualization tools for exploring digital geographic databases and as interactive aids in experiencing the world, deriving decisions and solving spatial problems.

Computing thus represents both a need and an opportunity. There is a need for development of strategies for appropriately using maps and related displays as tools in the hands of the user for exploring virtual worlds. There is also a major opportunity that the very different medium of the computer provides for cartography in providing these tools. Although digital maps (i.e. 'computer cartography') and GIS have both been around for over 30 years, much of the emphasis during that time has been in replicating paper map displays. It has only been in the last decade that the map has also been seen as a thinking tool to solve problems.

Visually sparking the imagination

In exploring how the map can best be used as a tool for exploring virtual spaces rather than just as an information-receiving device, the basic issue is how to 'spark the imagination' via geographic visualization, and how the user can guide this process. What should the user be able to do with geographic visualization software? What should they be encouraged to do? What should they be discouraged from doing?

We are already instinctively using maps and other forms of graphics to interactively explore geographic databases and solve problems. We pan the map, zoom in and zoom out, and change colors. All of these involve 'playing' with the map to allow latent relationships to emerge. There are other ways of manipulating maps for this purpose that we may not ordinarily do – turning the map upside down or sideways, for example. Other ways of aiding the map maker/user to see emergent features and to allow computer mapping to truly become an exploratory tool need to be investigated.

There have been many examples of scientific breakthroughs made through the use of conceptual metaphors; relating the knowledge domain at issue with a more familiar knowledge domain.[20,21] Even though the use of standardized procedures and models is considered a virtue in science and emphasized in university graduate programs to aspiring researchers in a wide range of fields, this can inhibit creative thinking. Adherence to procedures in script-like fashion serves to facilitate routine tasks, but the unthinking adherence to them

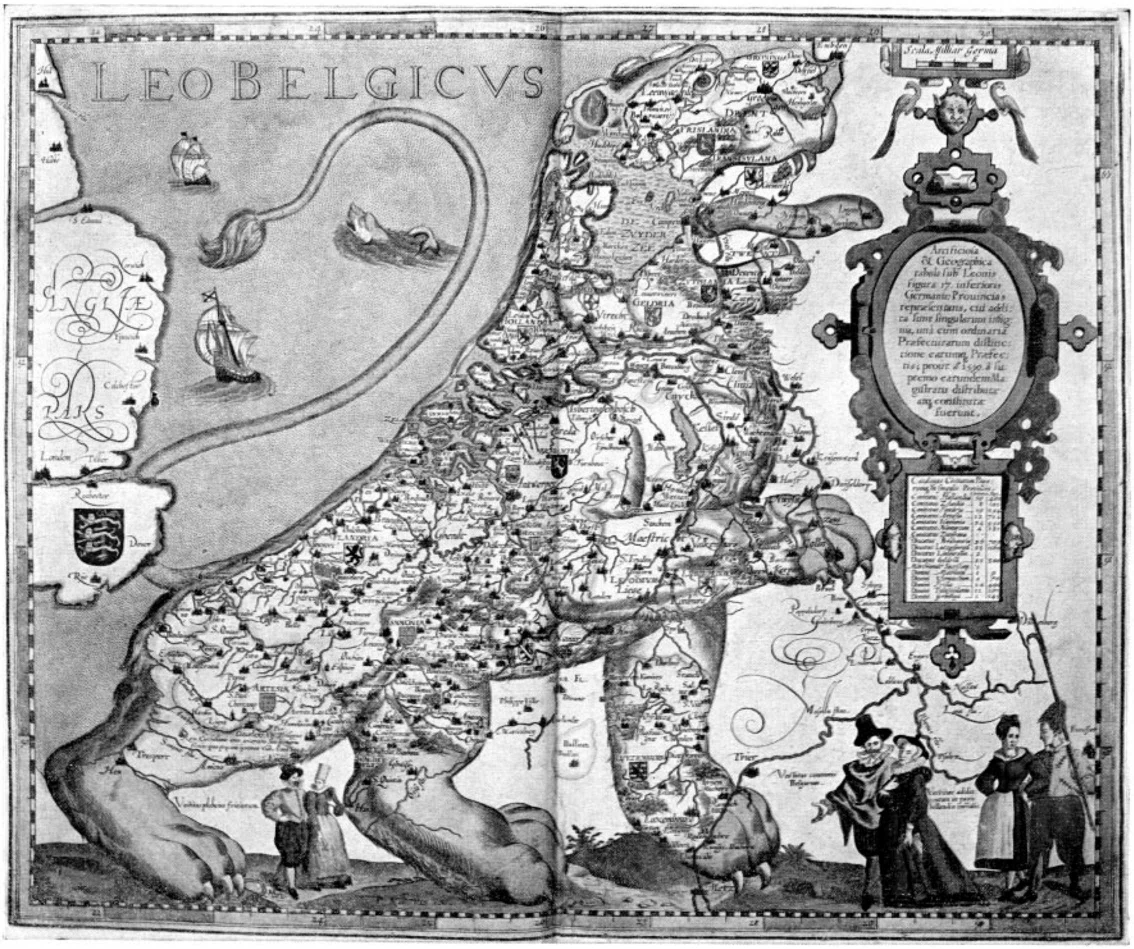

Figure 1 The map as political statement, the Leo Belgicus; from Germania Inferior by Petrus Montanus, engraved and published in Amsterdam in 1617.

can result in a delay in 'breakthroughs' and a continuing acceptance of sub-optimal solutions to problems even where better solutions exist.[1,22] So, the question becomes; how can we promote creativity and insight and avoid the pitfalls of habitual thinking on a more day-to-day level?[23]

An example

To illustrate the above reasoning let's have a look at a well known map and see if and how alternative visual perspectives on the data might reveal new information and change insight. The purpose is to demonstrate the effect on creativity of alternative views on the data, while also trying to distance ourselves from traditional techniques. The map we have in mind is the 'Carte figurative des pertes successives en hommes de l'Armee Française dans la campagne de Russie 1812–1813', or 'Napoleon's March on Moscow' by Charles Minard from 1861. This map, shown in Figure 2, portrays the dramatic losses of Napoleon's army during his Russian campaign. He started with an army of over 400,000 troops and returned with less than 10,000, as is displayed by the width of the path. For the return from Moscow additional information related to temperature is included in a graph below the map. Tufte[24] claims 'it may well be the best statistical graphic ever drawn.' He explains that the map is 'a narrative graphic of time and space which illustrates how multivariate complexity can be subtly integrated ... so gentle and unobtrusively that viewers are hardly aware that they are looking into a world of four or five dimensions.'

Minard indeed did a masterful job if we keep both the tools available and his aim – to prove the senselessness of war – in mind. In telling his story he took some liberty with the data (both geometry as well as attributes), however this is not uncommon among cartographers presenting geospatial data from a particular perspective. For instance compare the detailed representation of rivers with the representation of the path of troop movements. The path used for the retreat westward was the same for long stretches as the advance eastward, but Minard preferred to draw them separately for clarity reasons.[25,26]

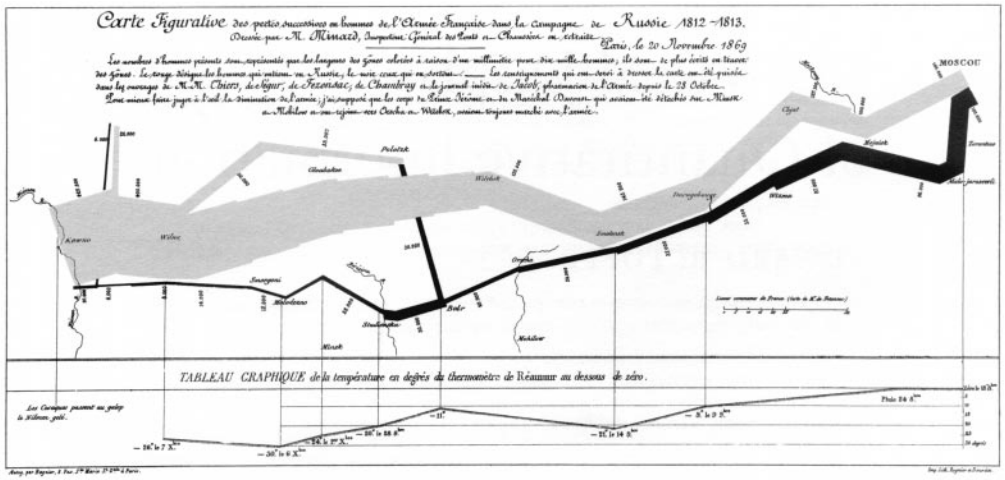

Figure 2 Minards map from 1861 'Carte figurative des pertes successives en hommes de L'Armee Français dans la campagne de Russie 1812–1813.[24]

How has Napoleon's campaign been mapped by others? Many historical atlases portray the campaign as a line or set of lines together with some battlefield locations. However, it is interesting to note that in several recent publications on 'graphic tools', Minard's map has been used to demonstrate how certain visualization techniques can be applied.[27,28] The publication by Roth and his colleagues is of interest because they use the Napoleon data to demonstrate the capabilities of a scientific visualization software tool called SAGE. The maps in Figure 3 (a and b) are linked to diagrams below the maps. In both diagrams, the horizontal axis represents time. The vertical axis in the diagram of Figure 3a represents the longitude, while the vertical axis in the diagram of Figure 3b represents the number of troops. Compared to Minard's original map in Figure 2, the diagram in Figure 3a reveals that at Pollock (located at the northern branch and circled in the diagram) two battles took place instead of one. The diagram in Figure 3b shows that Napoleon stayed for a month in Moscow before returning west, information not seen in the original map.

The above examples show that alternative views can be revealing and clarifying. Environments in which such graphics are presented need to be interactive and should allow for real-time action. In this environment, the views can be dynamically linked. In this way, the selection of an object in one view can cause the same objects in the other views to be highlighted.[29] As such, relationships not directly obvious from any of the single views become apparent.

Let's look at some other examples. Figure 4 presents a three-dimensional view in which the height of the path represents the number of troops. Temperature and battle could be represented in three-dimensions as well. The ability to manipulate the three-dimensional scene in space is a prerequisite, since many interesting facts might be hidden within such multidimensional data. Figure 4 shows a view from the south-west. If this scene were initially seen from the north-east, the blocks representing the way back from Moscow would not be visible. However, a tilting of the display by the user as part of normal interaction – like inspecting a newly discovered real-world object in the hand – would quickly allow the hidden elements to be revealed.

Figure 5 gives a snapshot in time, showing the location of the troops at a particular date – 24 July 1812. The map could be a single frame from an animation. Animations are sell-suited to represent changes over time. However, if the user has no ability to interact (e.g. stop, pause, back up, go forward) much of the exploratory power of this mechanism is lost. By manipulating a slider the viewer can select a moment during the campaign, or perhaps back up to take a closer look at something they think they might have seen.

If we compare this map with Minard's original, his map gives an overview, while the map in Figure 5 offers a better representation of the situation at a particular moment in time. The viewer is not distracted by previous or future moments in time. Alternatively, Minard's original map design could be animated. To focus on a particular moment an option would be to gray-out or make transparent the part of the path that has been traversed.

Figure 6 presents a space-time cube in which the x and y axes represent the geography and the z-axis represents time. Again this solution would greatly benefit from interactive options to manipulate the viewer's perspective into the cube. An additional option would be to have a plane(s) that can be moved through the cube along any of the axes to highlight a time period or location. One could of course also change the type of data represented

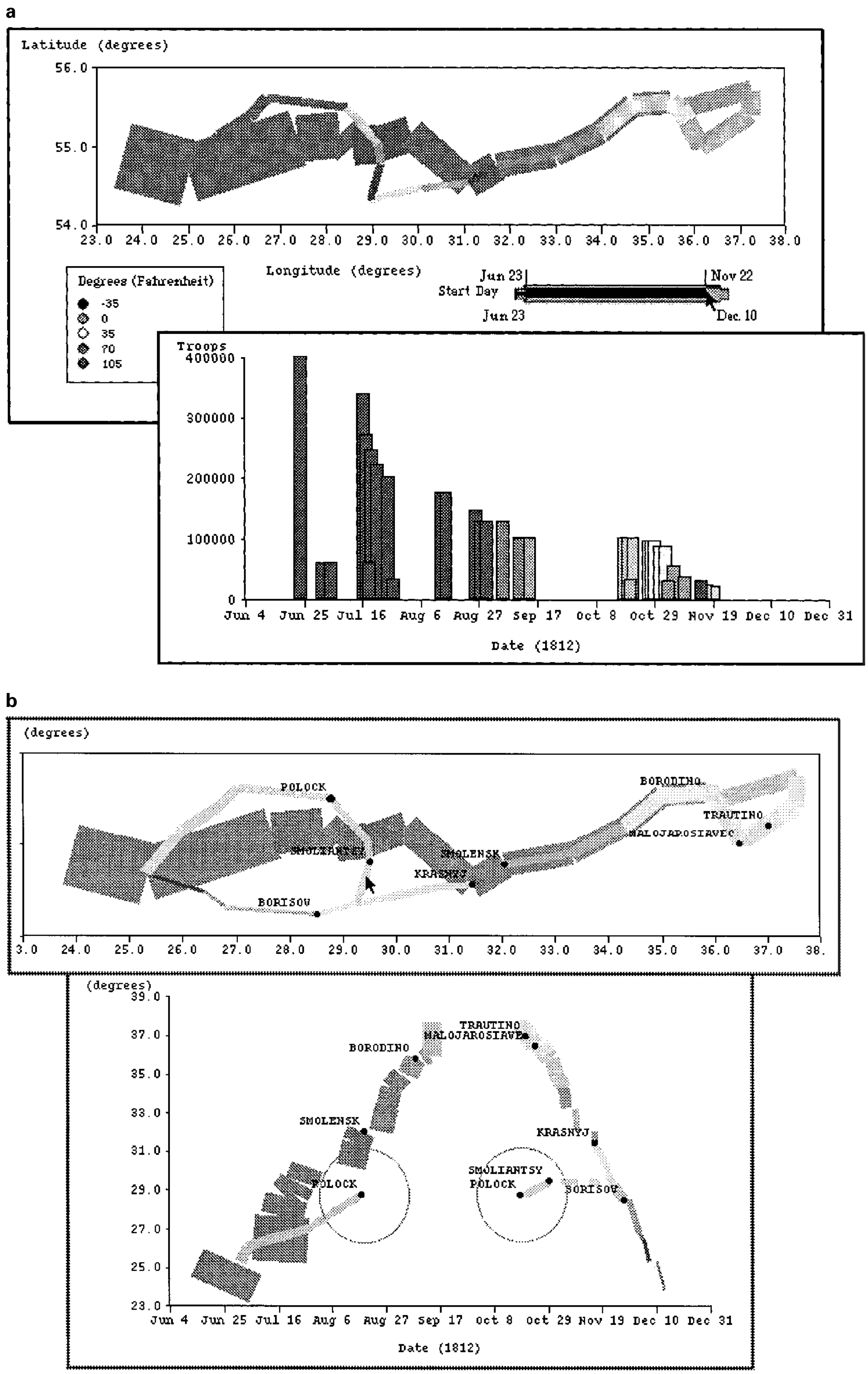

Figure 3 SAGE examples.[26]

along the axes and for instance create temperature *vs* troops *vs* time. In theory, the space-time cube clearly shows the relationships among the data along the three axes. Unfamiliarity with these alternative three-dimensional views might nullify a proper understanding, however.

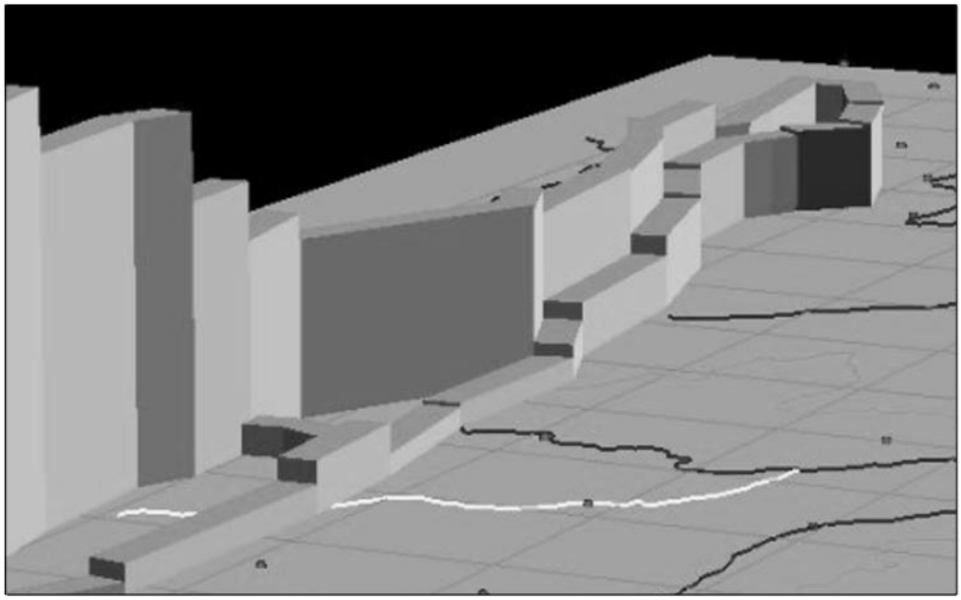

Figure 4 Three-dimensional view on Napoleon's Russian campaign. The crossing of the Berezina River is highlighted (Source: ITC Cartography).

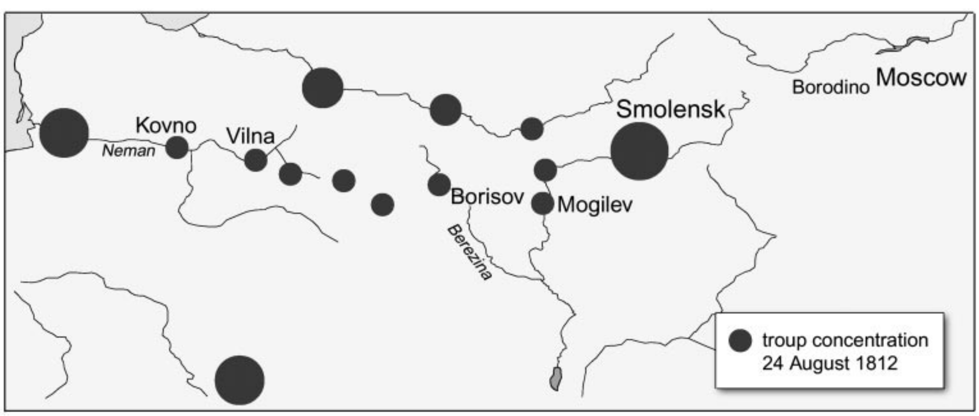

Figure 5 A snapshot in time: Napoleon's position at 24 July 1812 (Source: ITC Cartography).

Graphics and visualization as a means of understanding

What makes graphical images of all sorts particularly effective for (a) portraying and subsequently retrieving that information and (b) gathering new insights? Larkin and Simon[30] investigated this question empirically by comparing individual performance in problem-solving tasks using diagrammatic *vs* non-diagrammatic representations. They found that, first, information retrieval is facilitated by the specific ways that information can be grouped spatially. Second, spatial representation allows the use of recognition mechanisms that are built into the visual perception system and allow very rapid recognition. Detection of spatial patterns and groupings is hardwired into the human visual system. But what is it about some maps, diagrams and paintings and even some realistic visual scenes that sparks the imagination and facilitates the derivation of new ideas while others do not?

Finke asserted that images that spark the imagination seem to possess novelty, incongruity, abstraction, ambiguity, and often some combination of these. He referred to these as preinventive properties.[1] A novel image is one that contains a combination of components that are composed in some unique or unusual way. All or some of the elements could be rotated, be out of scale with the surrounding elements (i.e. be smaller or larger than expected), or portrayed in an unusual color. A simple cartographic example is shown in Figure 7. With the world shown upside down from the way people are

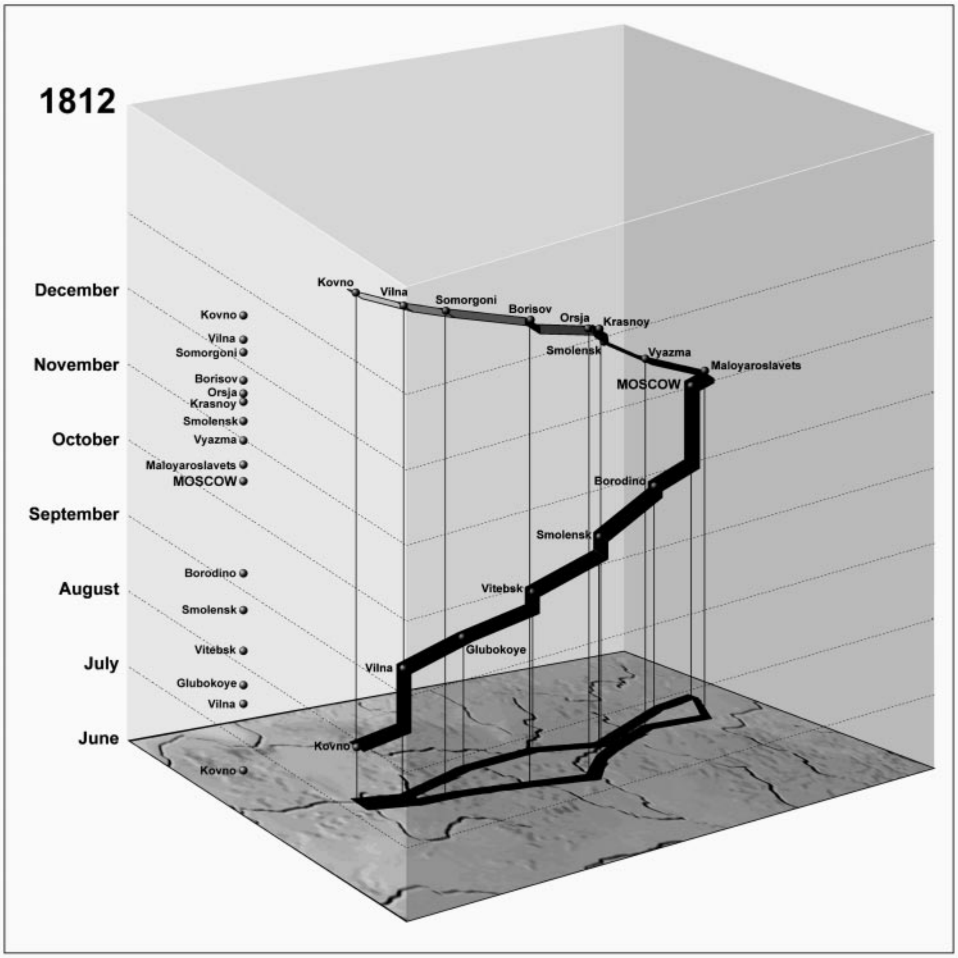

Figure 6 A space-time cube of Napoleon's march in Russia (Source: ITC cartography).

used to viewing it, the viewer is forced to – literally – look at the world in a new way. In so doing, the shapes of the continents is one thing that becomes consciously noticeable. Incongruence in an image is the incorporation of components not normally contained within the same image. The unusual way that space and time have been so seamlessly superimposed in the Minard map (Figure 2) is what gives that particular design its power in conveying the intended message in such an effective way. Ambiguity is the property whereby an image can be interpreted in more than one way because of the interrelationships of its components. There are a number of famous examples of ambiguous images, among them the so-called Nackar cube – a wireframe of a cube positioned such that it is very difficult to determine what is its front or back face. Depending on the design and the particular geography at hand, a map can exhibit a similar effect in determining which areas is the figure and which is the ground.[31] Figure 8 shows an example of this. Abstraction is the property whereby details presented in a normal environmental scene, such as color, shading and the impression of three-dimensionality may be selectively or in large part absent. Diagrammatic images have this property. In the original Minard map, the spatial movement of troops is shown in a greatly simplified fashion, showing the vast majority marching in a single column. The actual movement of troops was much more complex and disjointed.

All of these properties promote what has been called emergence. Emergence happens when features initially unanticipated by the viewer, and often not explicitly created or anticipated by the creator, are detected. In other words, unexpected properties in the image emerge as visual discoveries. There have been a number of studies of this phenomenon and how it works.[32,33] Both drawn images and real-world scenes can have some combination of novelty, incongruence, abstraction and ambiguity that in turn results in emergence. What, then, is special about imagery that makes it seem to be even more powerful in sparking imaginative thought than real and realistic scenes? There are two additional properties of drawn images that make them a particularly powerful tool in reflective learning and understanding; the ease of manipulability, and the freedom from physical constraints.

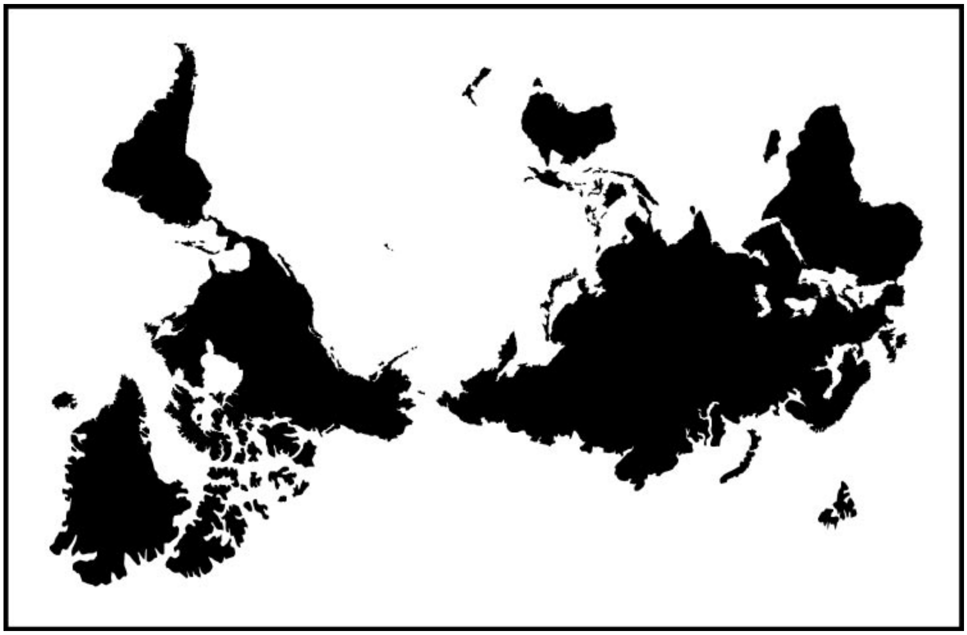

Figure 7 An inverted view of a world map provides a novel perspective.

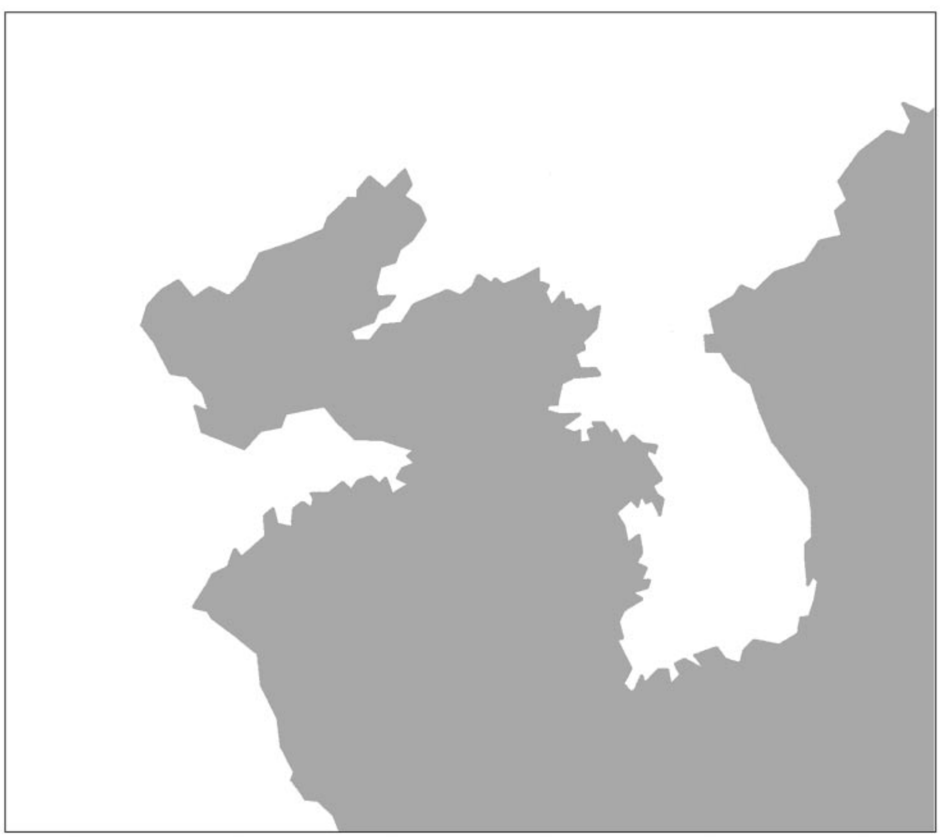

Figure 8 A map where distinction between figure and ground is ambiguous (Derived from Mistrick[31]).

Experimenting with a scene, image or figure is important in making discoveries and deriving new insight. Adding new elements, changing the relative positions of elements or changing the perspective from which it is seen by rotating are all ways of enhancing image properties (novelty, etc.) that enhance the likelihood of emergence. In the field of perception there is much empirical evidence showing that certain patterns can be interpreted as something different after some change or manipulation.

A well-known cartographic example of this is the use of figure-ground relations in a map to emphasize what is important. The visual non-distinction of these is what makes the map in Figure 8 ambiguous. In a conventional world map, the landmasses have a darker tint than the oceans, by design. This causes the landmasses to stand out (as presumably being more important to the map reader). The familiar shape of continents such as Africa will be easily recognized. By reversing this figure-ground relation and making the oceans significantly darker than the land masses, the oceans will stand out. This is a novel image and will result in the viewer perceiving unfamiliar shapes, even in what would otherwise be a familiar image – who knows the shape of the south Atlantic? We, in effect, play around with it to see what emerges.

How we make the connections

Recognition of what properties in images promote discovery is only half of the mechanism involved. The other half is discovery of the cognitive processes at work when we do this. Finke and his colleagues[1] distinguish between two kinds of processes; generative and exploratory. Generative processes are those that create generative structures. Exploratory processes are those that exploit the inherent properties in these structures that promote creative discovery in order to provide meaningful interpretations.

If there is no satisfactory result from one's explorations of an initially generated preinventive structure, the generative phase is returned to again in order to modify and manipulate that structure. The exploratory stage subsequently begins again. This cycle continues until a satisfactory result or insight is achieved, or the initial preinventive structure is abandoned. This kind of iterative creative process is what would occur in locating a new bike path for a given city. The process may typically include the use of physical maps to aid the memory with the details of such a complex structure. Various alternatives can be visualized for a new bike path relative to existing topography, etc. Then, remembering that there is an abandoned railroad right-of-way that runs through the area and knowing that abandoned railway right-of-ways have characteristic desirable for bike paths (i.e. are of necessity flat, cleared of obstructions, of the appropriate width and could be acquired inexpensively) the bike path solution presents itself. Creative discoveries also frequently occur quite rapidly, apparently without repeated generation and exploration. This seems to be related to the complexity of the problem or issue at hand.

Finke's generative processes include memory retrieval, association, mental synthesis, mental transformation, analogical transfer and categorical reduction. A straightforward retrieval of existing structures from memory, such as a recalled visual scene or phrase, is the most basic generative process. Several scenes or phrases can also be retrieved and then associated in novel ways.

A richer variety of preinventive structures results from the mental synthesis of components from varying memories and elements of one's knowledge, and subsequently transforming the structure by rotating it, rearranging various components, etc. Another form of generative process is called analogical transfer, in which the relationship or set of relationships in one context is transferred into another. Analogical transfer allows properties on one, familiar, knowledge domain to be transferred to another, less familiar domain.

Gick and Holyoak[34,35] demonstrated this phenomenon experimentally using a famous reasoning problem. Called Duncker's[36] radiation problem, this problem involves how to destroy a tumor using radiation without destroying the surrounding healthy tissue. The solution is to use multiple low-intensity rays from various directions so that they converge on the tumor and in sum provide a total high-intensity dosage at the tumor site. In Gick and Holyoak's experiment, the number of subjects who could figure out the solution rose from 10–80% after telling an analogous story about a general successfully attacking a fortress by dividing his troops and having them attack from different directions. It has also been shown that analogical learning is facilitated when people are encouraged to look at things from varying points of view.[37]

The distance between the two knowledge domains also determines how many properties can be mapped. If a metaphor represents a mapping of two closely-related conceptual domains, then the correspondence of properties is high. The greater the cognitive distance, the fewer properties the number of properties that can be mapped, but the greater the novelty (through novel correspondences) and the greater the potential for new insights.

Nevertheless, there are two limiting factors to this process – one is an intrinsic limitation and the other can be overcome through visualization techniques. First, no matter how abstract the concept, new understanding and insight can only be derived by using our accumulated experience and preexisting knowledge. Thus, no matter how gifted and imaginative the individual, he or she will not be able to grasp a concept that is too far unrelated to what they have already known and experienced. Imagine one has to identify a country by its outline only. Would someone from, let us say, South America be familiar with the outline of Iceland? Our knowledge is also set within a specific cultural context. Thus, the idea of a city like New York or London would be very difficult for an Australian aborigine of a hundred years ago to grasp. This is also why myths are invented – to explain the unexplainable in familiar terms. In a cartographic context, this includes the use of mythical figures on the earlier maps of little-known territories.

Second, there is the phenomenon of mental fixation or mental blocking. Mental fixation is the focusing of one's selection of contexts, categories and elements of preinventive structures to an overly-narrow range. This has the effect of significantly diminishing the level of novelty and the other attributes of preinventive structures that promote insight and new discovery. Overcoming mental fixation has led to the expression of 'thinking outside of the box' in the corporate world to encourage creative thinking. Mental blocking usually occurs when one solution or interpretation is suggested, effectively blocking or interfering with other, alternative, solutions from coming into one's mind. There have been many empirical experiments on word memory and problem solving that demonstrate this phenomenon.[38–40]

It is also the particular lack of this constraint – in drawing from broadly separated knowledge domains during the generative process and avoiding constraints on thought brought on by habitual thinking – that makes for creative genius.[41] This has the effect of maximizing the utility of the knowledge and experience that one does have in making insights and making what are effectively 'leaps' of insight. In a visualization context, presenting the information in novel ways as part of playing with the image is an obvious means of overcoming mental fixation.

Conclusions

The idea of 'geobrowsing' as the authors have defined it – using geographic visualization to aid knowledge discovery in large spatial databases and to aid interactive analysis and complex problem-solving – has been shown in this discussion to be a potentially powerful tool. The cognitive literature provides much guidance as to how tools for geobrowsing should be designed, as well as for other forms of visual knowledge discovery contexts. The current discussion has provided only some brief examples. The authors have shown that there are some very simple techniques in 'playing' with maps that promote emergent properties in visual images; properties that 'spark the imagination'.

These include some things that can easily be incorporated into cartographic software but at the moment are usually not allowed, or are things that are made very difficult to do, as violations of cartographic convention. This includes being able to easily turn the map upside down, and playing with the representation of figure *vs* ground. These are operations that are basic in image editing software, such as Photoshop. Encouraging people to use such capabilities within the cartographic context may be as easy as promoting them. In other words, simply tell the user that they are free to play! What things users should be discouraged from doing is a much more difficult question if the idea is to let the user explore. Certainly, if the user's purpose is to prepare a map for portrayal of a specific message (e.g. results of an analysis for a report), then cartographic convention needs to be adhered-to. This can be accommodated in software as two different mapping modes; one for free-form exploration, and the other where cartographic convention (and restrictions) reign to guide the user toward graphical portrayal of the intended message.

Future research should also certainly reveal some new forms of cartographic representation that are very different from maps that we are currently used to, and should include use of haptics and the other senses. This is where closer linkages between the geographic visualization and (non-geographic) information visualization research communities would help.

Computer displays have some constraints with the technology commonly available at the moment. Projected holographic images are not yet available, so computer graphics are limited to flat screens with limited choice in size, although virtual environments already bring us a long way in that direction. The dynamic and interactive capabilities of computer representation of graphic images greatly enhance the potential capabilities of the map as a tool for creative thinking in ways that before were only possible via mental imagery: They instantaneously create, modify and manipulate images. Images can be set in motion and speeded up or slowed down. And indeed whole worlds can be created that would be physically impossible in the real world.

There are, however, a number of difficult challenges. While specific aspects of creativity have been demonstrated experimentally in various contexts, empirical testing of the overall creative process for geobrowsing has been recognized as a difficult problem.[42,43] Slocum *et al.*[42] assert that addressing this problem requires a two-pronged effort involving both usability studies and cognitive testing. Usability assessment of software utilizes engineering principles. Such assessment can be done in a number of ways, based on specific variables; the expertise of the user, independent or collaborative problem-solving, maturity of the software product, etc. Cognitive testing involves inference from observable phenomena as indicators of what is something that cannot be observed directly. Because of the complexity and time consuming nature of deriving an overall picture from weaving together the multiple threads involved in such observational evidence, they advocate continuing emphasis on theory-driven cognitive research within a geographic context.

The primary challenge in understanding maps as representations of geographic space lies in the inherent melding of data, knowledge, and personal and cultural perspectives. This melding is also intertwined with the dual image/structure nature of maps, and it is certainly more difficult to untangle than in textual descriptions of geographic features of phenomena. Personal impressions and interpretations are usually expressed in more generalized terms than observational facts. Observational facts, on the other hand, are frequently expressed in a more detailed and concrete manner. This reflects how people cognitively store knowledge. The dual nature of maps and the complex web of symbolic devices from which they are constituted offers the capacity to intertwine objective data with subjective, cognitive impressions in ways that at times may frustrate the experimentor's attempts to control interactions between such elements.

While empirical testing of geovisualization and what the authors have termed 'geobrowsing' remains at an early stage, research into effective testing tools for geovisualization and 'geobrowsing' continues.

References

1 Finke RA, Ward TB, Smith SM. *Creative Cognition: Theory, Research, and Applications.* The MIT Press: Cambridge, MA, USA, 1992; 205 pp.
2 Board C. Cartographic communication. *Cartographica* 1981; **18:** 42 – 78.
3 Robinson AH, Petchenik BB. *The nature of maps.* University of Chicago Press: Chicago, IL, USA, 1976; 138pp.
4 Stea D, Blaut JM, Stephens J. Mapping as a cultural universal. In: Portugali J (Ed.). *The Construction of Cognitive Maps.* Kluwer Academic Publishers: Dordrecht, 1996; 345 – 360.
5 Sims JS, Hagendorn JG, Ketcham PM, Satterfield SG, Griffin TJ, George WL, Fowler HA, Amende BA, Hung HK, Bohn RB, Koontz JE, Warren JA, Feder DL, Clark CW, Filla BJ. Accelerating Scientific Discovery Through Computation and Visualization. *Journal of Research of the National Institute of Standards and Technology* 2000; **105:** 875 – 894.
6 Card SK, MacKinlay JD, Shneiderman B. *Readings in information visualization: using vision to think.* Morgan Kaufmann: San Francisco, CA, USA, 1999.
7 MacEachren AM, Kraak MJ. Research challenges in geovisualization. *Cartography and Geographic Information Systems* 2001; **28:** 3 – 12.
8 Fabrikant S. Spatialized browsing in large data archives. *Transactions in GIS* 2000; **4:** 65 – 78.
9 Blaut JM, Stea D. Studies of Geographic Learning. *Annals of the Association of American Geographers* 1971; **61:** 387 – 393.
10 Landau B. Early map use as an unlearned ability. *Cognition* 1986; **22:** 201 – 223.
11 Presson C, Hazelrigg M. Building Spatial Representations through Primary and Secondary Learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 1984; **10:** 716 – 772.
12 Cosgrove D. Introduction: Mapping Meaning. In: Cosgrove D (Ed.). *Mappings* Reaktion Books, Ltd: London, UK, 1999; 1 – 23.
13 DiBiase D. Visualization in earth sciences. *Earth & Mineral Sciences, Bulletin of the College of Earth and Mineral Sciences* 1990; **59:** 13 – 18.
14 Peuquet DJ. Representations of Geographic Space: Toward a Conceptual Synthesis. *Annals of the Association of American Geographers* 1988; **78:** 375 – 394.
15 MacEachren AM. *How maps work: representation, visualization, and design.* Guilford Press: New York, USA, 1995.
16 Bertin J. *Graphics and Graphic Information-Processing.* Walter de Gruyter (French edn, 1977): Berlin, Germany, 1981; 267pp.
17 Bertin J. *Semiology of Graphics.* The University of Wisconsin Press (French edn, 1967): Madison, WI, USA, 1983; 415pp.
18 Fabrikant SI, Buttenfield B. *Envisioning user access to a large data archive.* GIS/LIS '97 (Cincinatti, OH, USA, 1997).
19 Unwin D, Fisher PF (Eds). *Virtual reality in geography.* Taylor & Francis: London, UK, 2001; 304pp.
20 Kuhn TS. *The Structure of Scientific Revolutions,* Third edn. University of Chicago Press: Chicago, IL, USA, 1996; 212pp.
21 Miller AI. Metaphors in Creative Scientific Thought. *Creativity Research Journal* 1996; **9:** 113 – 130.
22 Schank RC. *The Creative Attitude: Learning to Ask and Answer the Right Questions.* Macmillan: New York, USA, 1988; 372pp.
23 Keller PR, Keller MM. *Visual cues, practical data visualization.* IEEE Press: Piscataway, USA, 1992; 229pp.
24 Tufte ER. *The visual display of quantitative information.* Graphics Press: Cheshire, CT, USA, 1983; 197pp.
25 Friendly M. Re-Visions of Minard. *Statistical Computing and Graphics Newsletter* 2000; **11:** 13 – 19.
26 Robinson AH. The thematic maps of Charles Joseph Minard. *Imago Mundi* 1967; **21:** 95 – 108.
27 Roth SF, Chuah MC, Kerpedjiev S, Kolojejchick J, Lucas P. Towards an Information Visualization Workspace: Combining Multiple Means of Expression. *Human-Computer Interaction Journal* 1997; **12:** 131 – 185.
28 Spence R. *Information visualization.* Addison Wesley/ACM Press Books: Harlow, 2001; 206pp.
29 Dykes J. Exploring spatial data representation with dynamic graphics. *Computers & Geosciences* 1997; **23:** 345 – 370.
30 Larkin JH, Simon HA. Why a Diagram is (Sometimes) Worth Ten Thousand Words. *Cognitive Science* 1987; **ii:** 65 – 99.
31 Mistrick T. The effects of brightness contrast on figure-ground discrimination for black and white maps. In: *Department of Geography.* The Pennsylvania State University: University Park, PA, USA, 1990.
32 Pinker S, Finke RA. Emergent two-dimensional patterns in images rotated in depth. *Journal of Experimental Psychology: Human Perception and Performance* 1980; **6:** 224 – 264.
33 Finke RA, Pinker S, Farah MJ. Reinterpreting visual patterns in mental imagery. *Cognitive Science* 1989; **13:** 51 – 78.
34 Gick ML, Holyoak KJ. Analogical problem solving. *Cognitive Psychology* 1980; **12:** 306 – 355.
35 Gick ML, Holyoak KJ. Schema induction and analogical transfer. *Cognitive Psychology* 1983; **15:** 1 – 38.
36 Dunker K. On Problem Solving. *Psychological Monographs* 1945 **58(5):** No. 270.
37 Vosniadou S, Ortony A. *Similarity and Analogical Reasoning.* Cambridge University Press: Cambridge, 1989.
38 Luchins AS, Luchins EH. *Rigidity of Behavior.* University of Oregon Press: Eugene, OR, USA, 1959; 281pp.
39 Reason JT, Lucas D. Using cognitive diaries to investigate naturally occurring memory blocks. In: Harris J and Morris PE (Eds). *Everyday Memory, Actions, and Absent Mindedness.* Academic Press: New York, 1984; 53 – 70.
40 Smith SM, Blankenship SE. Incubation and the persistence of fixation in problem solving. *American Journal of Psychology* 1991; **104:** 61 – 87.
41 Way EC. Knowledge Representation and Metaphor. In: Fetzer JH (Ed.). *Studies in Cognitive Systems.* Vol. 7. Boston, MA, USA: Kluwer Academic Publishers, 1991; 271pp.
42 Slocum TA, Blok C, Jiang B, Koussoulakou A, Montello DR, Fuhrmann S, Headley N. Cognitive and usability issues in geovisualization. *Cartography and Geographic Information Science* 2001; **28:** 61 – 75.
43 Haug D, MacEachren AM, Hardisty F. *The challenge of analyzing geovisualization tool use: Taking a visual approach.* 20th International Cartographic Conference (Beijing, China, 2001), ICA.