A PATTERN IDENTIFICATION APPROACH TO
CARTOGRAPHIC VISUALIZATION

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ABSTRACT Mental visualization and tools that foster it have recently been acknowledged as significant factors in scientific creativity. Cartography occupies a critical position in the growing array of scientific visualization tools, particularly for geographers, earth scientists and atmospheric scientists. Treating the map as a visualization tool leads to a different perspective on cartography than that generally taken when the map is viewed as a communication device. The goal of cartography and cartographic research shifts from a search for the optimal map to a search for spatial data abstraction methods that prompt pattern identification and lead to insight. A model is proposed for cartographic visualization that stresses the role of maps in data exploration. Emphasis is on the potential for maps to stimulate scientific insight by facilitating the discovery of patterns and relationships in spatial data. Following from this pattern identification model for cartographic visualization some perspectives are offered on the design of cartographic visualization tools to facilitate pattern identification. Attention to visualization quality is considered as a key component in the successful development of such tools. In conclusion, the relationship between visualization tools used to foster scientific insight and those developed for other applications such as urban planning or navigation is considered.

Scientists in virtually all disciplines have begun to recognize that mathematical/analytic methods are insufficient to deal with the staggering volumes of data we are now able to generate through remote sensing and other digital data collection methods. At scales from the sub-atomic to the astronomic, there has been a dramatic renewal of interest in visualization as a tool of science. This renewed interest follows decades of disdain for visual depiction of data in favor of more ‘objective’ analytical approaches. The power of human vision is, once again, valued as an important tool in advancement of science.

Computing technology has led to both an abundance of data and the development of visualization tools to cope with it. Formal recognition of visualization as a unique method for problem exploration is largely due to advances in computer graphic systems that aid in, or enhance, the mental visualization abilities of scientists.

Cartographic abstractions form the basis for many of the visualization efforts in the earth sciences. In addition, cartographic depictions have been mimicked in such diverse fields as diagnostic medicine (e.g., Livingstone and Hubel 1984; Schwartz 1990) and chemistry (Maceachren, 1990). Cartography has much to offer toward advances in scientific visualization from our long history of developing visualization tools and our efforts over the past three decades to understand the perceptual and cognitive issues involved in using them. Cartography will be left behind, however, unless it can quickly adapt to the changing role of maps and related graphics in science, and the implications of this change for the theoretical foundations of the field.

The ‘cartography as communication science’ paradigm (at least as generally conceived) does not apply to cartographic visualization. The communication perspective focuses on the map as ‘geographic illustration’ rather than as ‘geog-
raphic thinking' (Muehrcke 1990). The distinction is between tools that allow us to depict or communicate what we know (i.e., communication tools) and tools that prompt questions about what is as yet unknown (i.e., visualization tools). If adhered to, the communication view will inhibit development of successful cartographic visualization tools.

The most basic tenet of the cartographic communication model is that the goal of cartography is to effectively communicate a particular message. There is an assumption not only that the message is known, but that there is an optimal map for each message, and that our objective as cartographers is to identify it. For cartographic visualization the message is unknown and, therefore, there is no optimal map! The goal is to assist an analyst in discovering patterns and relationships in the data.

Our approach to cartographic visualization, therefore, is based on the following tenets:

1. Visualization is a mental process. As such, it has existed for centuries. This fact seems to have been overlooked in the recent excitement about computer 'visualization';
2. Computer graphics can facilitate visualization. Recent emphasis, however, has been solely on how to generate images, rather than on how images may generate new ideas;
3. The goal of cartographic visualization (as with any form of scientific visualization) is to produce scientific insights by facilitating the identification of patterns, relationships, and anomalies in data;
4. Restructuring of problems (looking at them from new perspectives) is a key to insight;
5. Graphics designed simply to 'communicate' what we know are unlikely to foster the necessary new perspectives required to achieve insight about what is unknown.

In this discussion we propose a model* for cartographic visualization that addresses the interplay between the cognitive processes of scientific inquiry and the visual displays created to facilitate those processes. We follow this with some thoughts on the implications of this model for design of cartographic visualization tools and for transformations from reality to representation to display.

**Visual Thinking and Insight**

**Visualization Defined**

The first order of business is to clarify the term visualization. It is in the realm of computer graphics that the greatest advancements are being made in visual portrayal of scientific information. Restricting the concept of visualization to computer use, however, obscures the long history of visualization in scientific advances.

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*The term 'model' is used here in its general sense of being a description or analogy used to help visualize something that cannot be directly observed rather than in the sense of a mathematically precise description of an object or process.
Visualization is, first and foremost, an act of cognition (Miller 1984). It is a human ability to develop mental images, often of relationships that have no visible form. This ability can be facilitated and augmented by use of tools that produce visible representations. These representations allow our visual and cognitive processes to focus on the patterns depicted rather than on mentally generating those patterns. The goal, at least in relation to science, is to create or impose higher abstractions. As Wolff (1988), a space physicist, has noted, "... visualization should not be viewed as the end result of a process of scientific analysis, but rather as the process itself."

**Visualization Tools**

The term visualization has recently been extended to include elements of computer vision/pattern recognition, and to the production of images designed to aid understanding and problem solving. These processes of image generation are perhaps better defined as visualization 'tools.' In the past, a pencil and paper (or a paper map) have been helpful and enabling tools to scientists and engineers, but they are not always necessary in order to visualize a complex object or relationship. A superworkstation is also an enormously helpful tool, but it does not guarantee insight or creativity.

Some of the most creative scientists and engineers of our century seem to have had talents to visualize without graphic tools of any sort. We all probably know the story of Kekule’s insights into the structure of benzene that apparently came to him in a dream. Such insights are probably far less rare than some people think. They often, however, appear only as anecdotes, reflecting a largely private and nonverbal part of creativity (Ferguson 1977).

Francis Rogallo, for example (an aeronautical engineer who developed the first fully flexible wing while working at NASA) recently commented to one of us that he always worked out the design of wings or wing components in his head before committing them to paper. Once an object or concept is conceived in the mind, using a computer to generate the visual representation offers a more efficient pencil and paper to the engineer/designer like Rogallo.

The most important role for computer graphics in scientific visualization, as Muehreke (1990) points out, is not in generating elaborate realistic images of ideas. Maps and other visual representations are valuable to science, not because of their realism, but because they are abstractions. The abstraction process, if successful, helps to distinguish pattern from noise.

The most important role for cartographic visualization, then, is in prompting mental visualization of spatial patterns and relationships with schematic bits and pieces of information. This prompting may allow the earth or social scientist using these cartographic tools to visualize complex phenomena or processes, even if unaided mental visualization does not come easily.

**Roots of Visualization**

Visualization tools precede computer graphics in scientific research by centuries. Maps have been a key visualization tool used by many disciplines to symbolize, to depict patterns, to alter scale and resolution, and thus to generate abstractions.
Maps have been created specifically as tools for facilitating scientific insights for at least two centuries (Robinson 1976). In the earth sciences, examples of the early role of maps as tools for arriving at scientific insight include Halley’s 18th-century use of maps to study magnetic declination and Smith’s early 19th-century mapping of geology in England and Wales and related theories on the relationships between fossils and geologic strata (MacEachren 1979).

In medicine, use of visualization as a hypothesis generating and problem solving tool can be traced at least to Dr. John Snow’s 1854 map of cholera cases in London (Gilbert 1958). Cartographic portrayal of his data allowed Snow to identify the link between cholera incidence and a specific water pump. The graphic portrayal of data in the form of a map allowed Snow to see the relationship without having a priori knowledge that cholera could be related to water sources.

Computerization of statistical mapping in the 1960s offers an early example of a computer-assisted scientific visualization tool (MacEachren 1987). More recent developments in geographic information systems are providing a testing ground for a variety of new cartographic and graphic tools for scientific visualization. One of the strongest links between cartography and geographic information systems is through these cartographic visualization tools and their potential to increase the data synthesis and analysis capabilities of GIS.

**Vision as an Abstraction Process**

A significant barrier to developing systems that enhance visualization is our limited knowledge of how our mind actually uses visual information. The speed of this kind of human visual processing contrasts dramatically without relatively slow and error-prone performance in strictly logical analysis (such as mathematics). If the underlying cognitive process was linear, logical and algorithmic, then our errors on what should be simple problems of logic or perception would be hard to explain, as would our apparently good ability to discern order in noisy data. Although the human mind can arrive at highly accurate conclusions, it does not work in precise, discrete, logical steps (the strengths of digital computers). The mind’s strengths are in simplification, approximation, and abstraction. Arnheim (1969) has argued that vision is efficient because it produces abstractions from the complex input to the system. Perception, according to Arnheim, involves matching of stimuli to simple templates. Scientific insight often comes about when the scientist is able to ‘discover’ good fits that might be hidden by the primary appearance of the evidence.

Friedhoff and Benson (1989) echo Arnheim when he contends that visualization is an effective scientific method because it utilizes 'preconscious' processes to sort out patterns before conscious (i.e., logical) processing of the information is required. This point of view is supported by research indicating that the "retina and optic nerves and visual cortex actively map the world out there, creating pattern, at every instant ..." (Judson, 1987). This neurological 'mapping' appears to result in such similarities in how different humans compare patterns that people not trained in science can be employed by particle-physics laboratories to search the thousands of photographs produced there for specific patterns predicted by theorists.
Judson (1987, p. 24) has argued that "... in science as in life, patterns come even before numbers." Even mathematics, he suggests "is the recognition and pursuit of patterns in numbers." Abilities to abstract, simplify, approximate — to identify pattern — often allow us to arrive at insights without necessarily following a logical progression of thought. Mathematicians, for example, are often able to detect a truth condition before they can write out a formal proof. Other scientists have made huge intuitive leaps (both visual and verbal) which have required many years, or further insight by other scientists, to explore and explain. Watson and Crick, for example, were able to build on the critical recognition by Pauling of a helix pattern for amino acids. They actually beat Pauling to the discovery of the double helix structure of DNA due to use of a visualization tool that stimulated the final leap to this insight. The tool, an X-ray photo of DNA taken by another scientist, allowed Watson to identify the key pattern that led to his dramatic insight (Judson 1987).

An early visual/graphic example of an insight that required considerable further work to explain fully is found in the well known but often misused Mercator map projection. In 1569, Mercator devised this navigational projection, the only projection having the convenience of lines of constant bearing (i.e., rhumb lines) being straight in all directions. Mercator made the intuitive leap to realize that rhumb lines (which are curved on the globe) could be conveniently straightened if the globe's parallels were spread apart at the same rate that the meridians were pulled apart when straightened to produce a cylindrical projection (see Figure 1). A mathematical understanding of what Mercator had accomplished, however, did not appear for thirty years until Edward Wright applied the relatively new idea of logarithms to the problem (Crone 1966).

THE RESEARCH SEQUENCE
Scientific inquiry proceeds in at least three stages: exploration, confirmation, and
presentation (see Tukey 1980; DiBiase 1990). At the exploratory stage, the scientist often is interested in a general category of phenomena, but has no well-defined problem or hypothesis in mind. Identification of the questions to be addressed is quickly becoming a non-trivial task as we must sift through increasing volumes of data generated by satellite remote sensing, global environmental monitoring stations, and national censuses. From a seemingly infinite array of potential problems, the scientist must select a few key leads that show promise for advances to be made. The goal of exploratory analysis, then, is often the identification of problems and hypotheses worthy of further investigation.

Once a hypothesis has been formulated, exploration is followed by a confirmatory stage in which the hypothesis is subjected to intense scrutiny. It seems clear that some of the most significant insights have been achieved when a scientist sticks with a concept identified in exploratory analysis in the face of strong contradictory empirical evidence. In these cases, visualization tools can play a role in trying to identify flaws in the logic of experimental designs that might be concealing a pattern that ‘should’ be visible.

Once a scientist has confirmed a hypothesis to his or her satisfaction (or to that of co-workers) there is an obligation (and strong motivation) to share the work with scientific peers through presentations and publications. This presentational stage of scientific inquiry involves proffering a hypothesis and support for that hypothesis in a form that allows others not privy to all aspects of the study to understand the fundamental issues being explored. Often, the goal is to lead fellow scientists to the same conclusions by allowing them to ‘see’ the patterns and relationships for themselves. Conclusions are much more convincing if the audience discovers the relationships before being told what they are. Even at this stage, then, the goal of cartographic visualization is pattern identification rather than information communication.

Individual interaction with visualization tools can occur at each of the three stages of scientific inquiry. At all stages the individual scientist is linked to the reality being studied through representations of that reality. Cartographic visualization involves giving those representations that contain spatial relationships a visible form. The pattern identification model for cartographic visualization described below concentrates on the first two stages of scientific inquiry, exploration and confirmation, the stages at which patterns are initially identified and anomalies to apparent patterns are investigated.

A PATTERN IDENTIFICATION MODEL FOR VISUALIZATION

Insight as Seeing-that, then Reasoning-why

Howard Margolis (1987), in his book Patterns, Thinking, and Cognition, develops an intriguing argument to explain scientific insight (or the lack of it). His argument is based on understanding the patterns or schema that scientists bring to their inquiries. He parallels much of the literature on pattern-recognition when he suggests that we make decisions by matching our present situation, as assessed by all the senses, to a vast collection of patterns from previous experience (it is important to realize here that although ‘pattern’ is a visual metaphor, the mechan-
ism can be completely abstract). There is seldom an exact match, instead we do a sort of curve-fitting to get an approximate answer — very quickly.

Much of Margolis' case builds on underpinnings of evolutionary biology. He convincingly demonstrates that there is great survival value in being able to recognize and react quickly with what is usually, but not always, the same response that a more logical and analytical approach would yield. He observes that, like a slide rule, "[the brain] is a device that usually gets things roughly right, and there is no reason to suppose that the means by which it does so look at all like the manipulations of propositions in logic or like the algorithms that run contemporary computers" (p. 68).

We believe that Margolis' basic premise is applicable to how we interact with graphic and cartographic tools designed to facilitate scientific visualization. He proposes a two-stage model for how information is processed. We have adapted this model to the context of cartographic visualization.

First, the analyst searches, often in a series of steps, for a pattern-match; this is what Margolis calls seeing-that or making a decision that can be the basis for some action (Figure 2). Seeing-that may include simple acts of recognition (e.g., knowing what a drumlin looks like on a contour map, a geomorphologist can easily recognize one when encountered).

Seeing-that is also the basis for insight and discovery. Perkins (1981) has suggested that insight involves more than just 'recognizing' a relationship or solution. He makes a distinction between recognizing, as a process of identifying something that would be expected given the problem context, and 'noticing.' Noticing is described as a 'sudden realization' brought on when an unexpected pattern or arrangement suddenly becomes clear. For example, noticing the similarity in shape of the African and South American coastlines was a key step in Wegener's (1966) development of the theory of continental drift.

Another example of patterns noticed on maps leading to insight involves the depiction of data by the World Health Organization concerning modern incidence of cholera in unexpected places. Epidemiologists at the London School of Hygiene and Tropical Medicine argued that the pattern of disease fits the pattern

![Figure 2. Pattern-matching model of cartographic visualization.](image-url)
of air routes (Judson 1987). Water from handbasins in the planes was allowed to empty directly into the atmosphere and experiments demonstrated that the cholera bacteria could survive the fall to the ground.

A pattern recognized or noticed, and thus the judgment derived, may of course be wrong – it very often is. There follows an immediate feedback mechanism, what Margolis calls reasoning-why. We find errors through mulling, and modify our judgments, creating new patterns. Noticing is also critical in relation to anomalies or errors. If the reasoning-why dictates, we do repeated 'double-takes,' seeking more and more information from the situation presented. Considering the early example of cartographic visualization in medicine again, we find that "some of Snow's most telling evidence [about the relationship between cholera and a water source] came from apparent deviations from the pattern" (Judson 1987, p. 37) A workhouse with 535 inhabitants, in the midst of an area with high cholera death rates, exhibited almost no cholera cases. On investigating this anomaly further, Snow found that the workhouse had its own well, thus confirming the suspicion that avoiding the Broad Street pump was a way to avoid cholera.

Noticing a series of small problems in any analysis may eventually lead to an erosion of confidence in the initial interpretation of what is seen and an interest in exploring other alternatives. In order to rectify and explain, we must use higher abilities that can be cultivated: logic and analysis. Self-critical, careful, reasoning-why is a necessity for rejecting mistaken judgments and identifying obscured patterns.

The role of language, mathematics and mental images is stressed by Margolis as a means to verbalize, formalize and re-run our internal musings. We may turn our images over and over in our minds, using these alternative formats to re-construct and re-test our judgments and subsequent reasoning-why.

Cartographic Visualization Tools

It follows from the above, then, that cartographic display of information is a portion of a much larger cognitive system. From the display, information passes through the eye and visual cortex to the sensory register. This temporary buffer holds images briefly, giving the mind's matching engine the time needed for a match to be made with some pattern. If no match at all is made, more information is rapidly acquired by fixating on another aspect of the illustration.

As Arneheim (1969) points out, perceptual recentering of our focus of attention allows us to restructure our problem. We view illustrations with a series of discrete fixations, the location of which is guided by our visual processing capabilities. Skilled topographic map readers, for example, are able to link these fixations together to allow for interpretation of features larger than they can view in a single fixation (Head 1984). Clearly this process of visual image construction must be employed by anyone attempting to interpret a map or other scientific illustration.

What the viewer is able to 'see' from this process of mentally aggregating pieces of an illustration will depend largely upon the patterns or schema that they bring to the interpretation process. Reasoning-why involves using the schema to compare what is seen with multiple internal representations or 'mental models.'

Eventually, certain patterns of patterns become deeply entrenched through
long experience and utility. These would appear to be what Einstein recognized as concepts, the ‘ordering elements’ which occur repeatedly and link perceptions into knowledge (Miller 1984). Of course, these valuable keys may also result in what Crombie (1986) has referred to as ‘Scientific Blindness’: the tendency to overlook what one is not actively searching for, or even to subconsciously reorder or reinterpret what we have seen so that it matches our expectations.

We seem to have great skills at linking disconnected information on the basis of various organizational schema. Bransford and Franks (1977), for example demonstrated that people presented with disjointed bits of information actually ‘remembered’ an overall whole that could be constructed from the information better than they remembered the details actually presented to them. For spatial information presented visually via maps, Olson (1979) has argued that ‘the mental construct is far more important in the development of spatial knowledge than is any particular product from which it develops.’ ‘Mental construct’ here refers to the understanding developed of an object, event, process, or situation.

A typical example of using cartographic visualization to develop mental constructs is found in synoptic climatology. The goal of synoptic climate research is generally the search for ‘types’ (typical climatic situations) which are then related to local weather events. Winkler (1988), for example, presents four synoptic types that lead to different spatial patterns for extreme rainstorms that have flash flood potential. Synoptic types derived from visual analysis have been criticized for their subjectivity and the resulting lack of consistency from one investigator to the next. Yarnal and White (1987), however, point out that recent attempts to develop ‘objective’ mathematical methods for climate classification have not resulted in elimination of subjectivity inherent in visual classification — it has only concealed the subjectivity.

It is clear that cartographic tools vary in the success with which they help us to apply patterns to new situations or develop new patterns for old situations (i.e., develop new mental constructs). This variability in success (e.g., the lack of consistency that climatologists object to in visual approaches to synoptic typing) may be due to what Muehrcke (1990) has termed map ‘stability.’ He suggests that with analytical maps, quality of depiction should be judged on the basis of how susceptible the representation is to small changes in input. An unstable map form for a particular data set is likely to lead to considerable variability in interpretation.

The typical isoline map used for most visual climate typing is much less stable than a perspective fishnet representation. It can be quite difficult to identify pattern similarity between two contour maps of the same terrain if they are based on elevations sampled at different resolutions (Figure 3). Their corresponding fishnet representations, however, retain the basic similarity of pattern and, therefore, are more stable (Figure 4). Perhaps synoptic climatology can benefit from a change in graphic method used to visualize their data.

To summarize this brief sketch of our approach to cartographic visualization, we treat the human cognitive system as an elaborate pattern matching system, with visual and language inputs and outputs. This system has three key aspects: a it almost always produces some pattern match (a judgement), for given cues; b it is workable, but not optimal; thus its speed must be balanced by a powerful reason-
ing-why mechanism; e the patterns which are most accessible, that are most likely to be matched, are those deeply entrenched by frequent use.

DESIGNING VISUALIZATION TOOLS TO FACILITATE PATTERN IDENTIFICATION

Based on the outline of the scientific research sequence together with the proposed pattern identification model for cartographic visualization, certain fundamental goals of cartographic visualization can be derived. These goals can, in turn, suggest the system design process by which they can be achieved.
Tools to Prompt New Perspectives

Computer visualization tools create discrete stopping points in what might normally be a continuous cycle. They give the users greater opportunity to make drastic changes in the perspective that is brought to a problem. A report commissioned by the National Science Foundation (McCormick, Defanti and Brown 1987) has predicted that visualization tools have the potential to fundamentally restructure the way science is carried out. There are exciting possibilities for methods designed to stimulate insight into complex problems.

For cartographic visualization tools to succeed, interaction is paramount; the system should permit the user to do a wide variety of things to the data (e.g., new viewpoints, displays of behavior under a variety of conditions, etc.) that permit a comparison to many internal patterns which may initially be quite vague or seem independent from or unrelated to one another (Ganter 1988). These multiple episodes also combine to form new patterns, which are then rehearsed, mulled and reasoned. This process is a cyclical one. Moving back and forth through a series of maps is often necessary and systems should be designed to facilitate such movement (Carter 1988).

The system should permit, indeed perhaps demand, that the user experience data in a variety of modes. It is only through this compare/contrast process that mismatches can be rejected by the workings of the reasoning-why process. We iteratively search for, and look closer at, pieces of information mainly on the basis of how they appear to fit in. Consistency across modes is a key to detecting a valid pattern match; if some assessment is true, then it should follow from examination in verbal, visual and mathematical realms. A conclusion can only be arrived at through a single avenue of inquiry is probably of limited usefulness, and is quite likely to simply be wrong, a principle stressed by Kosslyn (1988) in relation to results of research in cognitive psychology.

Initial efforts toward interactive visualization tools that allow investigators to do more than simply change the viewpoint on the data have been developed in the realm of statistical graphics (Becker, Cleveland and Wilks 1988). A technique termed 'scatterplot brushing' is a particularly good example of an exploratory graphic visualization tool (Becker and Cleveland 1987). This technique allows the investigator to uncover relationships among multiple variables by identifying subsets of observations on one scatterplot that depicts two of the variables. These observations are immediately highlighted on adjacent scatterplots that depict the relationships among all other pairs of variables under investigation.

The brushing technique has been extended to spatial data by linking scatterplots of data collected by enumeration unit (e.g., states in the US) with maps depicting related variables (Monmonier 1989). For spatial-temporal data, Monmonier (1990) suggests adding a 'temporal brush.' This would allow the user to manipulate the date for which graphs and maps are depicted by moving a temporal scroll bar.

As we develop new techniques for data exploration, however, we must not lose sight of how scientists reason and what has proven to be effective. Established methods have often evolved to meet subtle characteristics and needs of individuals and the problems that they solve. Woods and Roth (1988) offer a similar caution to
those designing computer tools to assist in task performance (e.g., a computer system designed to assist in monitoring nuclear power plants actually decreased operator responsiveness because it did not match the strategy that the operators brought to dealing with emergencies).

As Woods and Roth (1988) contend, cognitive tools are most useful in enhancing our 'conceptualization power.' They suggest that successful support systems: 1 enhance abilities to consider alternative perspectives; 2 facilitate making abstract ideas concrete and restructuring one's view of the problem as a result; and 3 improve the ability to detect errors. The importance of the latter is evidenced by the choice of the National Center for Geographic Information and Analysis to include 'Visualization of the quality of spatial information' as one of the twelve initiatives to be pursued by the center during their first three years of operation (NCGIA 1988).

We are not suggesting that an emphasis on visualization over communication will change the appearance of maps substantially or make guidelines about text size, line weights, color, etc. derived from perceptual research irrelevant. The computer systems we develop to facilitate cartographic visualization, however, must be dramatically different than those designed in response to the communication paradigm. Rather than developing expert systems that help find a single optimal map for representing a set of information, we need to develop systems that encourage exploration of multiple perspectives on the same data.

Visualization Quality
Cartographic visualization tools can, if properly designed, facilitate our abilities to notice geographic patterns, relationships, etc. and to reason about what initially seems apparent. Due to human tendencies to simplify, approximate, and identify patterns, however, visualization tools have almost as much potential to lead us astray as to lead us to insights. Our visual system allows us to do such things as recognize complex figures in milliseconds, decode scrawled writing, and drive automobiles. It should not surprise us then that a recognition system with such power will, with equal ease, reveal pictures in clouds, canals on Mars, and the planets rotating around us on transparent spheres.

It is particularly critical to recognize that the visual display is not reality, but a depiction of a representation of reality. This depiction will have gone through mathematical, graphic, and cognitive transformations. The chance for misunderstanding will increase in correspondence with the degree of abstraction inherent in both the representation and the display. To elaborate on this caution, we offer a few simple illustrations involving isometric mapping (one of the most common cartographic display methods in the earth and atmospheric sciences).

Transformation between reality and representation as well as the conversion of digital representations into visual form must be done skillfully. As emphasized previously, the seeing-that response is both rapid and prone to errors. These errors can be due to inappropriate decisions in transformation from reality to representation to display and/or to an incorrect pattern match on the part of the user. As a result, we require a powerful checking process in the form of reasoning-why. Our strategy in design of visualization tools must, from the outset, be to assist
in both detecting and confirming proper matches and rejecting those which are incorrect.

The errors that occur can be divided into two categories: seeing what is not really there (seeing-wrong) and not seeing what really is there (not-seeing). These correspond to the Type I and II errors that we associate with formal hypothesis testing. The first reflects our tendency to see shapes in clouds, trends in noise, and order in chaos. The second reflects our blindness in seeing what is new, and sometimes what has been there all along. We must provide tools that prompt the scientist to bring the appropriate concept or pattern to bear on the problem at hand, particularly where the need to consider a pattern may not initially be obvious. While contrasting in results, cognitive errors are obviated through similar means since the underlying problem is the lack of a match between cues and patterns.

For spatial data, particularly at a global scale, map projections can be critical to establishing an appropriate match. A global temperature map offers a typical example of a pervasive problem (Figure 5). The projection that it is plotted on is an equirectangular projection commonly used for plotting global climate data. The projection, of course, introduces severe distortion of area, particularly toward the poles. Even at 60 degrees, a focal point of this map, the projection exaggerates the area of warm temperatures by 200 percent. At 80 degrees, areas are nearly 6 times their proper size. The most serious problem here is that many climatologists and other earth scientists currently exploring global change research have no conception of the amount, kind, or distribution of distortion on this map. Type I errors, seeing a pattern incorrectly, are quite likely as a result.

Similar Type I errors can result in the calculation of the isotherms themselves. As Cort, Rowe, and Philpot (1985) recently pointed out, it is not uncommon for climatologists to use interpolation routines that treat longitude as a unit of con-
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FIGURE 6. The influence of data classification on pattern identification through isometric mapping.

stant length. Their analysis of continental temperature maps indicated a potential for errors of up to 15 degrees C.

When we are designing tools for visualizing scientific data, methods of information categorization are also critical to understanding derived or patterns noticed. Type II errors (not-seeing or discounting a pattern that is really there) are quite possible if we make arbitrary choices on isoline interval just because that is the way everyone else does it. Both maps in this case represent the same hypothetical data values (Figure 6). The map on the right uses the typical equal interval for isolines and as a result nearly hides on obvious pattern.

CONCLUDING PERSPECTIVE

We have presented an argument for developing cartographic visualization systems in a context of the overall process of scientific inquiry. It is only by looking at what scientists do, what information they consider, how they approach problems, and what leads to scientific insight that we can develop computer-based cartographic visualization systems that do more than depict what we already know.

For educational or journalistic purposes, of course, the clear presentation of scientific knowledge is quite important. What must be recognized, however, is that systems best suited to depicting what is already known are not likely to offer the
scientist the tools needed to advance science beyond its present bounds. Too much energy is being put into glamorous presentational systems that do things like simulating flight over an environment, while too little energy is being devoted to development of the less glamorous exploratory tools. The primary use for scientific visualization tools should be in exploring multiple alternative views, and identifying patterns and anomalies that were not necessarily anticipated. The greatest potential may be in generating questions rather than demonstrating conclusions.

Our perspective is that computer visualization tools offer two key advantages that should be exploited. First, the combined power of computer generated graphics and human visual processing allow us to view many representations and displays of each representation. This gives us repeated chances to see or notice relationships, patterns, or anomalies worth exploring. The availability of repeated interactive visual analysis also facilitates the reasoning-why process necessary to avoid misinterpretation and wasted effort pursuing false-ends.

Together with the advantages that computer visualization provides come a variety of problems due to a lack of understanding of perceptual and cognitive processing of visual information. Even in cartography, where user reaction to symbolization is reasonably well understood we find more examples of computer systems that ignore available guidelines than of those that follow them.

One of the most critical distinctions that must be recognized when developing computer visualization tools is that between images and graphics. Science, at least basic science, tends to concentrate on abstract representations of the world and correspondingly abstract concepts and theories that are generalizable to all situations (Figure 7). Applied science, environmental planning, engineering design, and advertising design offer examples of applications of visualization tools that rely to increasing degrees on mimetic (image based) displays.

The majority of efforts in computer visualization thus far have emphasized images (i.e., the mimetic end of the abstraction continuum), and the public part of the research sequence (the lower portion of the diagram). Recent efforts toward visualization systems to assist science have shifted the emphasis slightly toward the right in the diagram; toward the depiction of more abstract representations. Emphasis remains, however, on the public portion of the cycle with the generation of animated map movies to present what we know about weather patterns or the planets.

Advancement in science, however, begins at the top right of the diagram. Cartographic visualization tools that facilitate scientific advancement must be developed to work in the abstract-exploratory portion of visual thinking at the interface of the display and private/cognitive problem solving processes. To do this, we must allow the scientist to interact with what is displayed in a meaningful way. It is not enough to simply provide a mechanism for allowing scientists to view objects in 3-D, spin them around, look inside of them, etc. They system should permit, indeed perhaps demand, that the user experience data in a variety of modes. The scientist can then iteratively search for, and look closer at, pieces of information mainly on the basis of how they appear to fit in. It is only through this
compare/contrast process that mismatches can be rejected by the workings of the reasoning-why process.

We have come a long way in developing cartographic techniques for depicting spatial variation, but we know relatively little about how these representation tools can be used to prompt mental visualization, or to stimulate insightful discoveries. This should be a research goal for the next decade.

Those developing cartographic visualization systems should explore the growing literature on scientific intuition and creativity. By careful consideration of what has led to discovery and insight in the past, we may find the keys to stimulating scientific insight with visual tools. One step toward this goal is to develop systems that provide cartographic information in a form that allows for, or even insists upon, looking at old problems from new perspectives.

REFERENCES


**RÉSUMÉ**

On a récemment reconnu que la visualisation mentale ainsi que les outils qui la stimulent, étaient des facteurs significatifs pour la créativité scientifique. La cartographie occupe une place critique dans la panoplie croissante d'outils scientifiques de visualisation, particulièrement pour les géographes, scientifiques de la terre et de l'atmosphère. Le fait de traiter la carte comme outil de visualisation conduit à des perspectives sur la cartographie différentes que lorsque l'on considère la carte comme outil de communication. Le but de la cartographie et de la recherche cartographique se déplace: on va de la recherche pour une carte optimale vers la recherche de méthodes d'abstraction de données spatiales qui déclenchent l'identification de motifs et mènent à la perspicacité. On propose un modèle de visualisation cartographique où l'on expose le rôle des cartes dans l'exploration des données. On met l'accent sur le potentiel des cartes à stimuler la perspicacité scientifique en facilitant la découverte de modèles et de relations dans les données spatiales. Pour donner suite à ce modèle d'identification de modes pour la visualisation cartographique, on offre des perspectives de conception d'outils de visualisation cartographique en vue de faciliter l'identification de ces modes. On porte une attention à la qualité de la visualisation comme élément clé dans le développement fructueux de tels outils. En conclusion, l'on considère la relation entre les outils de visualisation utilisés pour stimuler la perspicacité scientifique et ceux qui ont été développés pour d'autres applications telles que la planification urbaine ou la navigation.

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