NEW THEORETICAL RESEARCH TRENDS IN CARTOGRAPHY

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ABSTRACT

Cartography has been defined as the art, science, and technology of map-making. Until the middle of the 20th Century, cartography was more an art than a science. Beginning in the 1950's, cartographic researchers began to take a more scientific approach to map-making with Robinson's *The Look of Maps.* In the 1970's, many researchers adopted a communications paradigm for cartography, understanding maps as tools for the communication of information from cartographer to map user. Under this paradigm, cartographers attempted to find the "optimal" map that would communicate known information to the map-reader with as little "noise" as possible. With the rapid progress in computer technology afforded by the ubiquitous personal computer, in the last decade a number of cartographic researchers, led by Alan MacEachren, have suggested a new way of understanding how maps work No longer seen as simply tools for communicating known information, maps can be employed to discover the unknown patterns in any phenomenon that possesses a spatial dimension. Rather than attempting to construct the "best" map, modern computer technology can allow for the construction of a multitude of representations of a phenomenon that can be used to answer different questions posed by individual researchers and reveal hitherto unrealized patterns in the data (data exploration). This new approach is termed "cartographic visualization". Based upon research in other fields, including computer graphics, the neurophysiology of the eye-brain system, cognitive science, and semiotics (the science of symbol systems), this newest thrust in cartographic theory has opened up broad new horizons for cartographic research. This has energized the discipline and promises to lead to new insights which will enable us to make better maps. This paper outlines these new approaches to cartographic research.

Key words: cartography, visualization, visual cognition, semiotics, visual perception.

1. INTRODUCTION

Cartography has been defined as the art, science, and technology of map-making. Prior to the 20th Century, cartography was more art than science. Since the 1950's, cartographic researchers have been trying to reverse that order and began to take a more scientific approach to map-making with Robinson's *The Look of Maps* (1952).

Beginning in the 1970's, many researchers adopted a communications paradigm for cartography, understanding maps as tools for the communication of information from cartographer to map user. Under this paradigm, cartographers attempted to find the "optimal" map that would communicate known information to the map-reader with as little "noise" as possible. This communications science approach in cartographic research has been criticized at a number of levels: for ignoring the many other ways that people use maps; for ignoring the contributions of art in the cartographic process; and for being an approach that falsely claimed to be objective and unbiased.

With the rapid progress in computer technology afforded by the ubiquitous personal computer, in the last decade a number of cartographic researchers, led by Alan MacEachren (1991, 1992, 1994, 1995), have suggested a new way of understanding how maps work. No longer seen as simply tools for communicating known information, maps can be employed to discover the unknown patterns in any phenomenon that possesses a spatial dimension. Rather than attempting to construct the "best" map, modern computer technology can allow for the construction of a multitude of representations of a phenomenon that can be used to answer different questions posed by individual researchers and reveal hitherto unrealized patterns in the data (data exploration). This new approach is termed "cartographic visualization".

Based upon research in other fields, including computer graphics, the neurophysiology of the eye-brain system, cognitive science, and semiotics (the science of symbol systems), this newest thrust in cartographic theory has opened up broad new horizons for cartographic research. This has energized the discipline and promises to lead to new insights which will enable us to make better maps. *Cartography and Geographic Information Science*, the premier American scholarly journal devoted to cartography, published a special issue on "Research Challenges in Geovisualization" (edited by MacEachren and Kraak, 2001). The theoretical bases for all of the papers presented in this special issue derive from the new research paradigms outlined below.

2. COMMUNICATIONS PARADIGM

Beginning in the 1970's, many researchers in cartography adopted a communications paradigm for research in the field. Borrowing from communications systems theory, these researchers attempted to find a scientific approach to cartographic theory that would allow for more structure in cartographic research and provide more reproducible results. Seeing maps as communicating known information to map users, this approach understood map-making as a five-step process (Figure 1). First, a phenomenon that is to be studied (such as soil texture, the distribution of tree species in a forest, or human population density) is sampled and a data set is assembled. Then the mapmaker interprets this data set based on various classification and/or interpolation schemes. Employing this analysis, the cartographer then decides on a design for the map, which is then produced employing best-practice design principles in an attempt to create a map which provides an "optimal" representation of the data (and hopefully of the nature of the phenomenon under study). In the last step of this process, the user interprets the phenomenon based upon the cartographer's ability to correctly communicate his or her ideas.

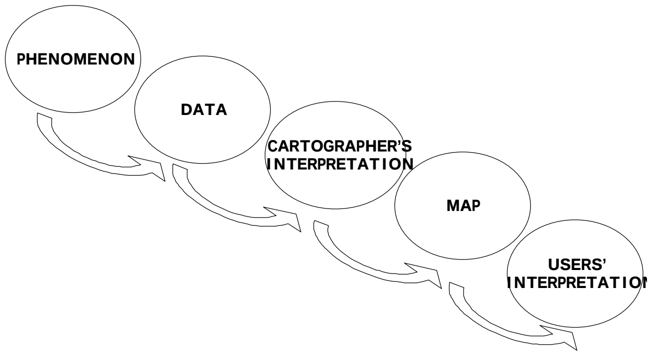

Fig. 1 - The Communications Paradigm for Cartography.

However, there is "noise" in each step of this process (Figure 2). First, the data are but a sample of the reality of the phenomenon under study, and may not be entirely representative of it. Second, the cartographer may misinterpret the data and thus provide an inaccurate view of the phenomenon. Third, the map design may not communicate the cartographer's interpretation fully or accurately. Lastly, the user may not understand the map completely. So, the aim of research in this paradigm was to "reduce the noise level" and to create the one map which optimally represents the phenomenon and successfully communicates this information to the map user.

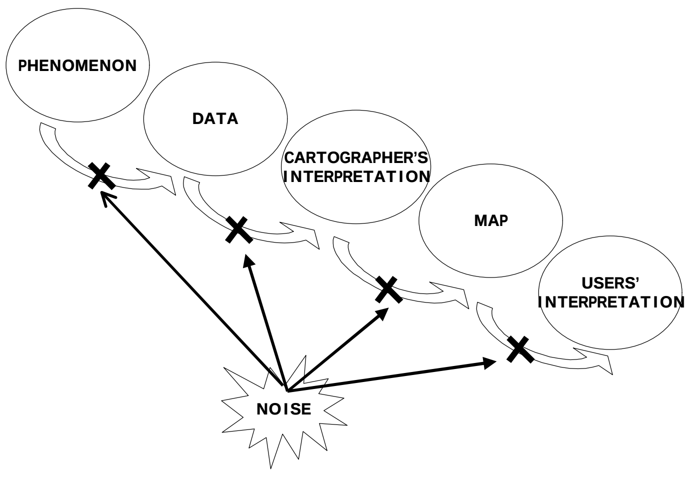

Fig. 2 - Noise in each step of the process.

Almost since its inception, and increasingly over the past decade and a half, this approach to cartographic research has come under criticism. Critiques of the communications paradigm can be lumped under four main topics (MacEachren, 1995):

- Is there one optimal map? Is such a thing possible? Or perhaps for some (or most) phenomena, a series of maps may be more appropriate to aid in understanding.
- People use maps in ways other than to communicate known information - sometimes they can be used to study and to gain understanding of the unknown.
- The communications paradigm ignores the art in cartography.
- And has provided false claims of objectivity and lack of bias.

3. CARTOGRAPHIC REPRESENTATION

Based on these criticisms, a new approach has been proposed by Alan MacEachren (1995). Called "cartographic representation", the goals of this new paradigm in cartographic research are: to create multiple graphic summaries of spatial information (rather than relying on one "optimal" map to represent the phenomenon); to create these multiple graphic summaries in order to explore the data and reveal unknowns as well as to communicate the results of analysis; and thus to create more consistently functional maps.

A key component of this new approach is cartographic visualization. In a 1994 book, MacEachren suggested that we can view the nature of maps in the form of a cubic space with three dimensions or axes (Figure 3). One axis represents the continuum of map *purpose* ranging from presenting known information to revealing the unknown. A second axis representing the continuum of map *use* ranging from the private or individual domain to the public or social domain. And a third axis representing the continuum of map *interaction*, from low human-map interaction to high human-map interaction. The corner of the cube that marks the point of congruence of presenting known information, with low human-map interaction in the public domain defines cartographic communication. The corner of the cube that marks the point of congruence of revealing unknown information, high human-map interaction in the private domain defines cartographic visualization.

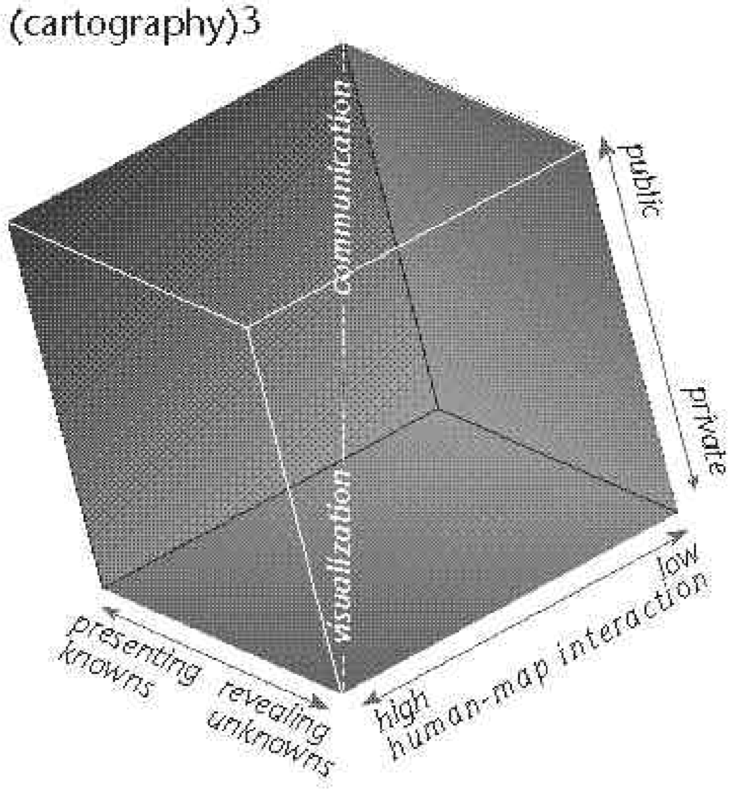

Fig. 3 - Cartographic Visualization.
Source: MacEachren 1994

But any researcher will move from visualization to communication in the course of a research project (DiBiase 1990) (Figure 4). In the beginning, he or she will operate in the private domain and will be concerned with exploring the data set and then confirming his or her findings. This DiBiase calls *visual thinking* and requires multiple maps that are highly interactive. Later in the project, the researcher may want to share

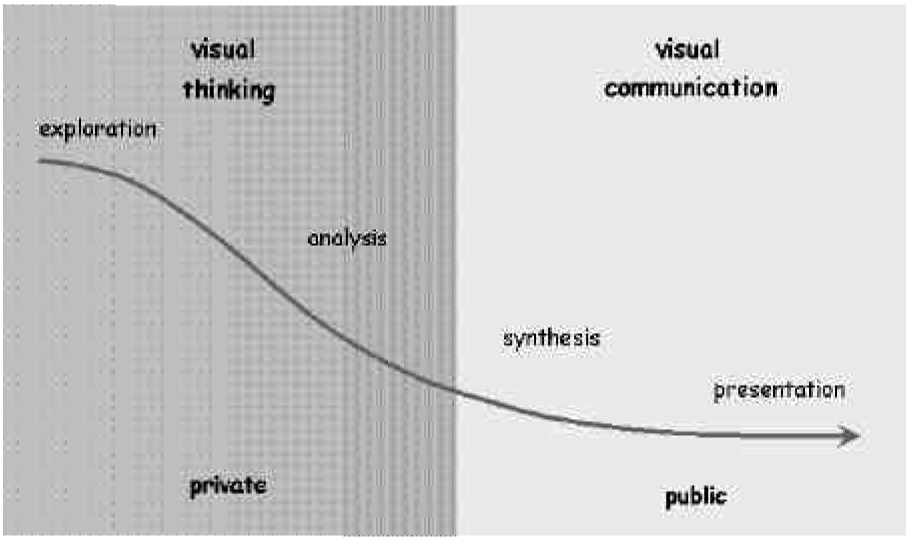

Fig. 4 - Visualization and Communication.
Source: DiBiase 1990

his or her findings with colleagues (synthesis) and then present these findings to a more general audience. This stage takes place in the public domain and may or may not require high human-map interaction or even multiple representations of the phenomenon. DiBiase calls this *visual communication*.

Table 1 represents an example of what topics currently occupy the minds of many researchers in cartography (note that the topics are presented in order of the numbers of papers presented in each field). Visualization was among the top research topics and was the theme of many of the papers to be presented under the other topics. Based on this and other national and international cartographic conferences, it appears that the "hot" topics in cartographic research are presently:

- Visualization
- Automatic generalization
- Cartography on the Internet and World Wide Web
- Electronic atlases
- Maps in Geographic Information Systems and remote sensing
- 3-D and Virtual Reality.

All of this research is taking place in a digital environment and: has been driven by technology (by what is possible with modern computer technology); is very practical in nature; has been conducted with little user testing; and is atheoretical (that is, these research efforts have been conducted with little regard for good theory).

4. A NEW APPROACH TO CARTOGRAPHIC REPRESENTATION

MacEachren (1995) synthesized some theoretical approaches toward understanding how maps work and pointed the way to creating maps that do what we want them to do, but better. His ideas come from computer graphics, past cartographic research, the neurophysiology of the eye brain system, cognitive science, and semiotics (the science of sign systems). He proposed three basic research paradigms. The research paradigms of visual perception and visual cognition in the private/visualization realm of cartographic space and the research paradigm of semiotics in the public/communication realm of cartographic space (see Figure 4). These paradigms promise to allow cartographic researchers to connect theory to good empirical practice, to help us to understand why some cartographic designs work and why some do not, and to form a framework for further cartographic research. These three research paradigms are presented in more detail below.

TABLE 1 - RESEARCH TOPICS

2001 International Cartographic Conference
Beijing
Preliminary Program

373 Papers, 24 Topics

75 % of all papers in the top 12 topics

1	**GIS and Digital Mapping**
2	**Mapping on the Internet and World-Wide Web**
3	**Computer Generalization of Spatial Data**
4	**Cartographic Theory and Methods**
5	**Map Design and Production**
6	**Spatial Data Visualization**
7	**National and Regional Atlases**
8	**Satellite Mapping**
9	**History of Cartography and Historic Maps**
10	**Cartography and the Environment**
11	**Education and Training in Cartography**
12	**Cartography and Children/Gender in Cartography**

Visual Perception

Visual perception is a research paradigm that is focused on how humans perceive maps, that is, how images that come through the eye are formed in the brain. Research in this paradigm springs from studies in human neurophysiology and the eye-brain visual system. Topics within this paradigm include:

- How the eye forms images and how they are transferred to the brain.
- How the eye sees color, and what map design principles follow from human color perception.
- The visual acuity of the eye with implications in regard to symbol size and visual discrimination.
- Simultaneous contrast or how colors will appear different based upon differences in the colors of surrounding areas on a map.
- Gestalt grouping principles or how map users group symbols on a map. That is, how map users form different groups of symbols and how they understand the distribution of the phenomenon depicted on the map.
- Scanning. How people use their eyes to scan a map scene and what implication this has for how they understand the information represented.
- Figure-ground. How map users separate figure from ground, that is, what information they pay attention to and what they see as background information.
- Discrimination/Selectivity. How map users discriminate one symbol from another.
- Bottom-up versus top-down processing.

Bottom-up versus top-down processing plays an important role in map design since it deals with pre-attentive processes. Most of the topics outlined above can, to a greater or lesser extent, result in pre-attentive processing in that patterns in the information represented in a map can influence mental images before the viewer's knowledge, past experiences and reason can come into play, before viewers can even think about it. These pre-attentive or bottom-up processes can, if not taken into consideration during the design phase of map-making, mislead the map user or result in conflicts with pre-existing understandings of the phenomenon being mapped, and thus interfere with, or reduce, map functionality.

Visual Cognition

The second research paradigm that MacEachren outlined is visual cognition, where existing knowledge in the mind of the map user is employed to interpret visual scenes through *knowledge schemata* that act as an interface between what is seen by the eye and what is understood in the brain. There are three kinds of knowledge schemata that most adult humans possess. The first are *propositional schemata*, which can be seen in geographical terms as declarative knowledge, knowledge about geographical objects, attributes of those objects, and attributes of places. The second are *image schemata*, which represent the organization of configural knowledge about space, knowledge of spatial relationships among entities in space. The third are *event schemata*, procedural knowledge of the sequence of steps needed to get from one place to another. They are all applicable to the understanding of maps, but image schemata and event schemata are the most important in relationship to creating maps that work well.

Image schemata are the most important of the three in the understanding of the majority of map types. Based on current psychological research, humans do not actually see "pictures in the head". But evidence suggests that we understand and store the meaningful parts of a visual scene using the same geometrical, symbolic and minimal vocabulary found in maps.

Embodied image schemata are some the most fundamental schemata that people possess. They are schemata that come directly from human experience with the environment. Some of the most common types of embodied image schemata are outlined below:

- Container - like a gallon of milk, or a jar of jelly, things are held within a container. Containers have definite boundaries, and all that is held within is usually homogenous in nature (that is, has little variation in composition, texture, etc.).
- Up-Down - in terms of the human body (head to foot) or a tree (branches at the top with a large trunk in the middle and roots at the base). The up direction tends to indicate higher, greater or more and the down direction tends to indicate lower, smaller or less.
- Front-Back - can be seen in terms of the front or back of the human body, the front or back of a car, or the front or back of a house.
- Part-Whole - in terms of something that is part of a larger thing, which together with its other parts, makes up the whole. For example, a piece of cheese was once part of a whole cheese, or a human leg is part of an entire body.
- Link - Things can be linked together to create a larger structure (like links in a chain).
- Center-Periphery - Some objects grade in attribute quality from the center to the edge. For example, the heartwood of a tree is very different from the bark.
- Source-Path-Goal - In this case, humans travelling in the environment (say walking to school from home) have a source at which the journey begins, a definite path to follow, and a goal in mind.
- Linear order - This image schema is derived from basic linear mathematics in which a lower number is followed by a higher number. Two apples is a lower number than three apples, while four apples follows in the numbering order to get to five apples.

All of these embodied image schemata are believed to be, more or less, the result of pre-attentive mental processing. That is, they elicit mental images before one can bring existing knowledge to bear in understanding a visual scene. For cartography (Table 2), the categories defined in maps are typically understood through container schemata. Hierarchical structure in maps is understood through part-whole and up-down schemata. Foreground (or figure) - background in maps is understood through front-back embodied image schemata, while linear quantity scales on map legends are understood in terms of up-down and linear order schemata.

TABLE 2 - EMBODIED IMAGE SCHEMATA AND MAPS

FOR MAPS

CATEGORIES	→	CONTAINER
HIERARCHICAL STRUCTURE	→	PART-WHOLE, UP-DOWN
FOREGROUND-BACKGROUND	→	FRONT-BACK
LINEAR QUANTITY SCALES	→	UP-DOWN, LINEAR ORDER

Understanding of these different types of map schemata can aid a mapmaker in making good design decisions. For example, when constructing a vertical linear quantity scale in the map legend, one should place the greater or larger quantity at the top of the scale, grading according to the classification scheme to the lowest at the bottom. If the map designer puts the lowest category at the top of the vertical scale, this interferes with most humans' existing schemata (being counter-intuitive), and makes the legend, and thus the map, harder to understand, or even results in the map viewer's complete misunderstanding of the information represented on the map.

The significance of these concepts for cartography is that maps will be more effective when cartographers use these schemata in the design process and the map user employs the same schemata to interpret the maps. The implication here is that the map designer needs to provide the appropriate cues that will aid the map viewer in selecting the correct map schemata to apply in understanding the map. Maps will be more effective when cartographic designs match the schemata held by potential viewers, and are easy to integrate into the general map schemata held by most people. Since all map schemata are learned, user training in new map schemata can result in improvements in the utility and effectiveness of maps.

Semiotics

The third research paradigm outlined by MacEachren (1995) is semiotics. Semiotics is the science of signs, with sign considered to be a relationship between an expression (the sign-vehicle) and its referent (content) or what the expression refers to. Semiotics derives from studies in linguistics, but is broader than spoken or written language and can be seen as an approach to understanding all the ways people communicate with each other.

For cartography, maps can be viewed as tools to communicate meaning primarily through symbols. This implies that there must be a *cartographic language* based on symbols that provides a map with meaning. Semiotics is useful in cartographic research because it provides a conceptual framework for developing a cartographic language that takes advantage of the other approaches discussed above, visual perception and visual cognition.

The most important influence of semiotics in cartography is Bertin's 1967(1983) book *Semiology of Graphics*. He was the first to propose a set of fundamental symbols, called visual variables, that could serve as the building blocks for a cartographic language. The significance for cartography is that a semiotic approach can provide a basis for the "rules" of map symbolization with implications for map design and the creation of expert computer systems that prevent mapping novices from creating misleading maps. Bertin's original formulation of a set of visual variables for map-making appears in Table 3.

TABLE 3 - BERTIN'S VISUAL VARIABLES

	Level of Measurement		
Visual Variable	Numerical	Ordinal	Nominal
Location	X	X	X
Size	X	X	
(Color) Value		X	
Texture		X	
Color (Hue)			X
Orientation		X	
Shape			X

Note: The X marks those variables that are appropriate for each level of measurement.

It is based on the concept of levels of measurement of the data depicted on the map - numerical (referring to interval-ratio data levels), ordinal, and nominal. Varying symbol size, for example, can be useful in depicting variation in the data depicted on the map at numerical and ordinal levels, but is not appropriate for depicting nominal differences in the data. To depict variation in nominal data on a map, it is appropriate to vary only color (color hue) and shape. The use of other symbol types such as color value, texture or orientation would end up misleading or confusing the map viewer. Note also that Bertin considered the viewing of these visual variables to be a pre-attentive process, that is they create a mental image or communicate meaning before any internal image schemata held by the map viewer is brought into play.

Following upon Bertin's original formulation, MacEachren (1995) and others have added to the list of visual variable types that can be treated in this manner and refined their understanding. This includes the addition of symbol crispness, resolution and transparency to depict variations in the certainty of the data represented on a map, and added color saturation and arrangement of symbols to the list of visual variables.

5. COMMENTS AND CONCLUSIONS

The three approaches to cartographic research that I have outlined above promise to energize the discipline, and provide a firm theoretical underpinning to future advances in the field. There remains much to be done, since research in these areas is just beginning. For example, in MacEachren's 1995 book *How Maps Work*, one can find at least five doctoral dissertation topics, 10 to 15 master's theses and 25 to 30 interesting research projects after only a cursory reading.

Beyond adopting a firm theoretical background for future research in cartography, there are several problems that cartographers face which make their work more difficult or reduce the impact of cartographic research in the improvement of the maps people use every day. Most of these problems in research seem to be structural to academic cartography, are based on the nature of cartographic research within the academy, and are often due to time and resource constraints.

The first problem that I have identified in cartographic research is what I call the "honeybee effect". A researcher works on a specific problem to the limits of his or her ability based on resources or individual expertise, publishes an article in a scholarly journal, and then moves on to a completely different topic in his/her next research project. Like a honeybee moving from flower to flower to collect nectar, this trend in research can have a definite pollinating effect, but only if other scholars pick up where the initial researcher left off. This is seldom done, as each researcher has his or her own interests and priorities, and everyone wants to do original research. This results in a lot of articles appearing in scholarly journals that mark the beginnings of good ideas, but these good ideas are seldom followed through, and the knowledge and understanding that result from this research seldom find their way into practical map design.

Another problem that plagues cartographic researchers is the issue of "little science" versus "big science". Cartography seems to be a marginal research effort in most academic institutions, and all the funding seems to go to astrophysicists, nuclear physicists, medical researchers, computer scientists and the like. With all this money, researchers in "big science" can gather into large groups and work on major projects that get tangible results which are relevant to society in relatively short periods of time. Advances in the field come rapidly, and the migration of pure theory into technology happens relatively quickly. Except for a few major centers for cartographic research, most cartographers work alone in their departments. It is difficult to do "big science" and get large research grants, and thus we are limited to doing "little science", working on small projects that get tangible results only in the long term. Advances come slowly and the migration of pure theory into technology happens only occasionally.

One of the solutions to this problem is for cartographers to become more involved in multidisciplinary projects. Working with colleagues within their academic department, or with colleagues in other departments, advances in cartographic research can be made much more rapidly than working alone, and cartographers can participate in "big science" at a higher level than they do at present.

Another problem in cartographic research is the issue of "practical" versus "theoretical" research. Since it is difficult to get funding for pure research, it is often necessary for cartographers to adopt the goal of producing some sort of useful application as the culmination of their research effort. We all want to make maps work better, and are impatient to use the high powered computer technology that is available to us to make that happen quickly. This tendency results in the creation of new types of cartographic applications based upon well established design practices, and in the absence of any strong theoretical underpinnings. As highlighted above, we are just beginning to understand how the human eye-brain system operates to make maps useful. We need to step back from our love affair with technology, and start working out some fundamental theories of map functionality that will allow us to better understand why those new computer applications which do not work well fail, and why those that do work well succeed.

The final problem that I have identified in cartographic research is the absence of useful user testing. In research article after research article, new cartographic techniques are proposed and programmed, and prototype applications or demonstrations are produced, but seldom have I seen these new techniques or applications tested with potential map users. Appropriate user testing should be integrated fully within each and every research project. It is not enough to test the new technique or application informally with a few colleagues or graduate students, because the researcher will not know whether his or her new idea actually works.

In summary, great advances in cartography have been made over the last ten years in terms of new cartographic applications in visualization, 3-D, digital cartography and with new beginnings now in virtual reality. Many of these advances have been made without user testing - we do not know if the maps produced actually work. Many of these advances have been made based on what modern computer technology allows us to do, rather than based upon good theory. The research paradigms outlined above, visual perception, visual cognition, and semiotics promise to fill this theoretical vacuum and will help us to make maps that work better.

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