INTERACTING WITH GIS: FROM PAPER CARTOGRAPHY TO VIRTUAL ENVIRONMENTS

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Summary

Recent geographical information systems (GIS) provide several mechanisms to support the user in the activities of exploring, analyzing, and querying geographical information. The starting point for the development of such mechanisms is the comprehension and modeling of how the human mind perceives and processes spatial data. This article first analyzes issues related with cognitive aspects of GIS and then discusses recent improvements to interaction mechanisms available in GIS which have been made possible by advanced visual techniques, such as 3D, virtual reality, and animation.

1. Introduction

Maps have traditionally been used to explore the Earth and to exploit its resources. GIS technology has enhanced the efficiency and analytic power of traditional mapping, also enriching the set of available visualizations with drawings, images, and animations. In particular, multimedia GIS is the combination of the use of GIS to georeference, structure, and analyze geographical data and the creation of multimedia presentations with links to spatial features. The combination of audio and video along with traditional data types can improve the effectiveness of GIS for the users. Multimedia GIS has the potential to create multiple representations of the same phenomena. This characteristic enables the users to analyze certain information in different contexts and help them in understanding complex geographic phenomena. As an example, the changes in vegetation vigor through a growing season can be animated to determine when drought was most extensive in a particular region. Working with two variables over time will allow researchers to detect regional differences in the lag between a decline in rainfall and its effect on vegetation (see *Advanced Geographic Information Systems)*.

GIS and related technology help greatly in the management and analysis of large volumes of geographically referenced data, allowing for a better understanding of terrestrial processes and better management of human activities to maintain environmental quality and world economic vitality. In order to do this, since GIS have to be used by humans, it is vital that the software and the data be comprehensible to human users. This means that the basic metaphors and conventions used by people in communicating about space and time have to be analyzed and suitably exploited by modern GIS. Since maps are still the primary means of storing, communicating, and analyzing spatially related information, it is fundamental to understand how people perceive and process maps and how they build “cognitive maps.” A cognitive map is the mental representation of the world that allows people to recognize their location, retrace a route they have taken before, derive a new shortcut, and estimate distance and direction between points. This knowledge is usually gained incrementally over time through direct experience navigating in the environment, but, as in the case of the interaction with a GIS, it can also be gained indirectly through appropriate simulated experience (multimedia and 2D/3D interactive representations of space).

In addition to their role as communication and analytical tools, maps are also the primary tools people use for navigation in spatial environments (for instance, the network of roads in a city). Navigating with a map requires several distinct cognitive and perceptual operations. The correct design of navigational maps can greatly simplify the user’s cognitive effort required for navigation. Advanced technology can suitably help in implementing such a design. For instance, widely diffused hypermedia is a dynamic, associative network of nodes and links for organizing, relating, accessing, and sharing information. Given these characteristics, navigating in hypermedia shares many similarities with map navigation. As a consequence, GIS may profit from multimedia and hypermedia extensions to electronic maps without losing their key features. A more realistic navigation can be obtained by exploiting sophisticated visualizations of 3D data and letting the users deeply interact with the modeled 3D scenario through the so-called “virtual reality.” Virtual reality is a tool for providing the users of a computer-based system, dealing with real or realistic data, with a highly vivid interaction with the data.

Such an interaction can be obtained by means of software tools, for instance a VRML browser, or through ad hoc devices, such as head-mounted displays or stereoscopic surround projectors.

High-level interaction answers the need to widen the set of potential users of a computer-based system to include people with no need of technical and specific training. In the case of GIS this issue is crucial while dealing with 3D data. Both the spatial analyst (an expert user aware of the capability of the GIS tool), and the planner, frequently unaware, but interested in performing "what-if" simulations, need to perceive fully the visual impact of different decisions. This is the process known as "visual analysis." The more vivid and direct the interaction is, the more effective visual analysis can be carried out. Thus, in the last 15 years, much effort has been devoted to the integration of 3D GIS and virtual reality. What is somewhat surprising is the independent evolution of virtual reality (developed in pure computer graphics and computer vision environments), that has led to a set of tools immediately available to the realistic vision of 3D spatial data. This has moved the interest of the applied researchers towards the study of the most suitable techniques for feeding a GIS with 3D real data. Although there is still an opportunity for improvement, the current technology already offers appealing solutions that are spreading across the wide GIS users' landscape.

Finally, multimedia GIS are typically equipped with tools supporting the user in the following basic interaction activities: focusing (highlighting subsets of data), brushing (highlighting specific display objects by pointing them on the display), linking (simultaneous highlighting in multiple views), and querying (spatial queries). Focusing applied to single or multiple map views allows users to adjust a data threshold dynamically. With multiple simultaneous data views, focusing or brushing is usually combined with linking. Spatial queries include conditions on the mutual placements of objects on a map.

The rest of this paper is organized as follows: Section 2 introduces basic notions on how spatial information is processed by humans and on the effects this processing has on the way people perceive and use maps. Section 3 discusses the similarities between maps and hypertexts/ hypermedia and how hypermaps extend GIS functionalities. Section 4 analyzes the role that 3D and virtual reality could play in improving the quality of the user interaction with GIS. Analogously, Section 5 presents visual mechanisms to support spatial querying and Section 6 discusses the role of animation in interactive GIS. Section 7 draws some conclusions.

2. Cognitive Science Aspects of GIS

Maps are the primary means of storing, communicating, and analyzing spatially related information. At a basic level, maps are a visual communication medium, using graphical symbols and the spatial relations between them to encode information. A fundamental aspect of this approach is that symbols have two components: the *content*, which is the conceptual information that is represented; and the *expression*, which is the graphical representation that is perceived. The field of cognitive science studies how the human mind works, drawing from research in anthropology, psychology, linguistics, neuroscience, and artificial intelligence. The following two sections will give a broad overview of two complementary areas of research: relevant results from psychophysical research that characterize aspects of perception; and semiotic and linguistic research that attempts to explain the multiple levels of the communication process. The following sections describe the cognitive aspects of maps for navigation, focusing primarily on the development of cognitive maps, which are the mental representations of geographic space people use to navigate through their environment.

2.1. Perceptual Aspects of Maps

The human perceptual system processes visual information in two ways: controlled and automatic. Controlled processing is a studied decoding of a sign from its external expression to an internal concept in the mind of the reader. For example, reading is a type of controlled processing, requiring recognition of a pattern of symbols into a word that is decoded into a concept. Automatic processing, on the other hand, allows direct perception of a concept from a sign without decoding. For example, finding objects of the same color is automatic. Controlled processing is slow, serial, and requires conscious thought. Automatic processing is fast, parallel, and unconscious. The components of a sign that require controlled processing are called internal, and the components that can be automatically processed are called external. Graphical representations of information, such as maps, diagrams, and charts, are powerful because they support both the "reading" of labeled symbols and the "seeing" of graphical and spatial relationships.

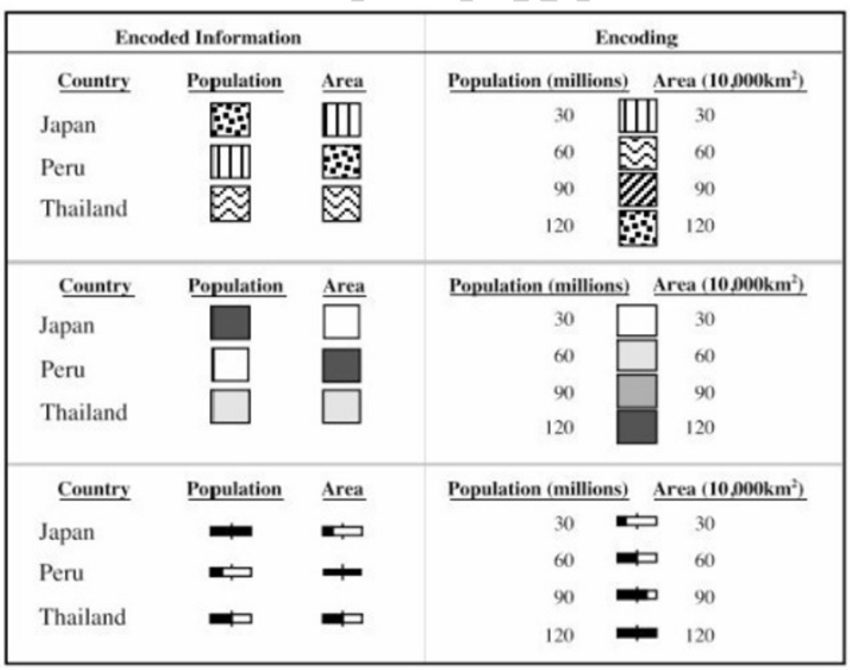

Figure 1. Population and area (ratio information) of three countries encoded with texture (nominal), grayscale (ordinal), and position (ratio). When the dimensionality of information does not match the dimensionality of the visual encoding, the missing dimensions must be stored internally.

Data domains and visual features both have an intrinsic dimensionality or scale. Nominal information allows distinction between elements, such as the set ("orange," "pear," and "apple") and the colors ("red," "green," "blue"). Ordinal information has an intrinsic order, such as the set ("cold," "warm," "hot") and a grayscale from white to black. Interval information allows addition and subtraction, such as the set ("Monday," "Tuesday," and "Wednesday") and the orientation of hands on a clock. Ratio information has an origin, and allows multiplication and division, such as the set ("100m," "700m," "10m") and position along an axis.

An encoding scheme that matches the dimensionality of the data with the dimensionality of the visual feature will be more effective at communicating information (i.e., will allow automatic perceptual processing). When a visual feature represents data with greater dimensionality, then it requires controlled processing to decode. On the other hand, a visual feature that represents data with lower dimensionality may lead to misperception. For example, encoding the set ("Japan," "Peru," "Thailand") with areas as (*v*,o, =) suggests an order ("Japan," "Thailand," "Peru"), which may be misleading.

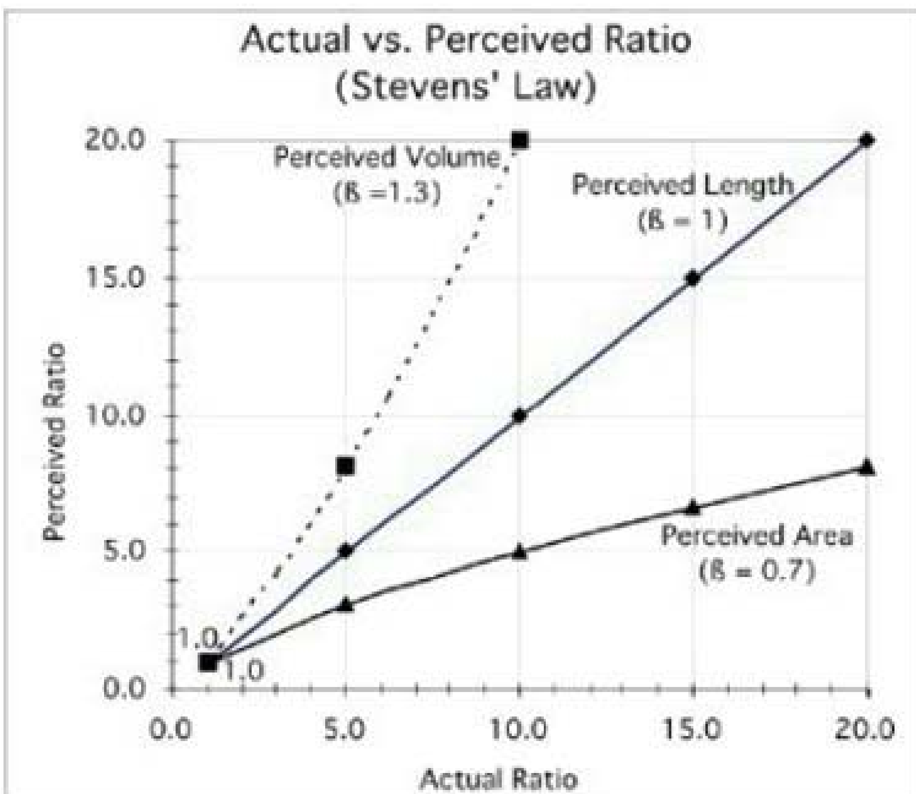

Figure 2. Stevens' Law. The graph shows the actual ratio versus the perceived ratio between measurements for volume, length and area.

As an example, Figure 1 shows the population and area (ratio information) of three countries using three different visual encodings: texture (nominal), grayscale (ordinal), and position along a common scale (ratio). The first encoding allows the reader to perceive patterns (for example, the population/area ratio of Japan and Peru are inversely related), but all higher-dimensional information must be calculated internally. The second encoding allows the reader to perceive ordinal information (for instance, the population of Peru is less than Thailand's), and the third encoding allows the reader to perceive ratio information (for example, Peru is four times larger than Japan but with one fourth the population).

There are several fundamental laws of human perception that help explain the effective dimensionality of a visual feature. For example, Stevens' Law, also called Stevens' Power Law, characterizes the difference between perceived magnitude and physical magnitude of a visual feature (as well as other sensory stimuli). Stevens' Law predicts that the perceived scale is the actual physical scale to a power, ß, where the value ß varies for different visual attributes and from person to person.

Figure 2 shows graphically the actual versus perceived ratio for area, length, and volume, assuming average values for ß of 0.7, 1.0, and 1.3 respectively. Stevens' Law suggests that physical relationships that are *represented accurately* can be grossly misperceived. For example, the relative lengths of road segments will be correctly perceived, but a lake represented on a map with an area graphically 10 times larger than another will be perceived as only 5 times larger. On the other hand, a volume 10 times larger will be perceived as 20 times larger. This suggests that when the purpose of the graphic is to compare *quantitative* information (that is, interval and ratio information), length ratios are more likely to be perceived correctly than area or volume.

Researchers have identified two fundamental perceptual and cognitive tasks required to decode and interpret graphical information: *information retrieval* and *information comparison*. Information retrieval, in this sense, is the process of identifying the value associated with an object along a dimension of interest. This requires a search along a base dimension (the dimension used to encode the information), and identification along a target dimension (for example, the value associated with a specific area or texture). For example, in Figure 1, finding the population of Peru (an information retrieval task) would require finding the symbol representing the population of Peru in the legend, and then identification of the value associated with the symbol.

Information comparison is the process of decoding and comparing values within or between dimensions. Similar to the information retrieval task, comparison tasks have a base dimension and a set of target dimensions. For example (using Figure 1), a within-dimension task would be used to compare the populations of Peru and Thailand, and a between-dimension task for comparing the population and area of Peru.

The perceptual encoding and the match between representing and represented dimensionality affect to what extent these tasks may be completed externally (using automatic processing) versus internally (using controlled processing). The composition of symbols into higher levels of meaning, such as the alignment used to distinguish the rows and columns of the tables in Figure 1, or the lines and scales of the graph in Figure 2, are the subject of the following section.

2.2. Semiotic Aspects of Maps

Semiotics is the study of how symbols are used to communicate information. Linguistics is an area of semiotics that studies languages. Researchers have drawn from these two fields to attempt to understand and formalize the way maps (and graphics in general) are able to communicate information effectively.

Jacques Bertin’s *Sémiologie Graphique* in 1967 was the first extensive study on the relationship between data and their graphical representation. He identified three basic types of “graphical marks” (points, lines, and zones), and seven “visual variables” (plan (position), size, value (grayscale), texture, hue (color), orientation, and shape). Bertin classified each of these variables according to the scale of information (that is, nominal, ordinal, and quantitative) that they are most appropriate for encoding. He then explained in detail how each of these variables can be manipulated to enable users perceive the range of data effectively. Table 1 shows a summary of Bertin’s classification of visual variables. All the variables can be used for expressing nominal information; however grayscale and size will perceptually express ordinal and quantitative information that may not be intended. The three extent variables (grayscale, size, and position) are most effective for ordinal and quantitative information. Texture is marginally effective for ordinal information.

Visual scale / Data scale	*Differentiation*				*Extent*		
	Shape	Orientation	Color (Hue)	Texture	Grayscale	Size	Position
	♣ ♦ ♥ ♠	❘ ⁄ — ＼	green, yellow, red, blue			• ● ● ⬤	
Nominal	■	■	■	■	▓	▓	■
Ordinal	□	□	□	░	■	■	■
Quantitative	□	□	□	□	■	■	■

Legend
Least effective
□
░
▓
■
Most effective

Table 1. The perceptual effectiveness of visual variables for communicating different scales of data. Visual variables are grouped by whether they are primarily for differentiating information or indicating extent along a scale. A filled box is more effective at representing a particular type of data.

Bertin’s work is still an essential reference for understanding the process of using graphics to communicate and analyze information. More recent research from semiotics and linguistics has attempted to build a broader theoretical framework of map-based communication of geographical information. First, there is general agreement that the basic unit of communication is the sign, which has a conceptual content and a graphic expression. There is also agreement that signs can be divided (disarticulated) into graphical features that do not have meaning (for example, Bertin's visual variables) and content features that do not have expression (for example, attribute dimensionality). Signs can also be composed (articulated) into units of progressively higher meaning (for instance, clusters of buildings represent villages). However, beyond this there are pronounced differences between semiotic and linguistic approaches. Linguistic approaches assume that, for the composition of signs to be considered a language, the minimum unit and each unit increment must have both content and meaning. Semiotic approaches do not have this requirement.

Second, there is the perceptual and cognitive significance of the communication of *spatial information* in map representations. Unlike linguistic communication, which requires translation, spatial information can be communicated perceptually through the spatial correspondence between the signs on the map and the represented features in the world. At the *sign level*, spatial features of geographical objects (such as location, size, shape, and orientation) may be reflected directly in their representation. For example, the size and shape of the symbol for a city may represent the spatial area and boundaries of the city. At the *map level*, the correspondence between geographical space and map space may be transformed in three ways: projection, reduction, and orientation.

Third, research has focused on the role of the map reader in understanding map symbols, and assembling symbols into higher-order concepts. Researchers have identified and developed a large number of different types of code for representing different aspects of the relationship between content and expression (for example, locational, iconic, temporal, historical, thematic, quantitative). A basic example is the iconic encoding of locational information. A sign that graphically reflects a component of its content is called "motivated," a sign that relies on convention for understanding is called "conventional," and a sign without any visual similarity to what it represents is "arbitrary." For example, the location of a cathedral may be represented by its outline (motivated), by a symbol for a church (conventional), or simply by a triangle (arbitrary).

Semiotics of maps is still an active research domain investigating the variation and composition of visual symbols to represent layers of meaning. Effectively communicating and analyzing spatially related information using maps requires an understanding of these different issues.

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Biographical Sketches

Tiziana Catarci received her Ph.D. in Computer Science from the University of Roma, where she is currently a Full Professor. Her main research interests are in theoretical and application-oriented aspects of visual formalisms for databases and database design. Moreover, she has worked on semantic database modeling, cooperative information systems, and statistical databases. She has published more than 100 articles on these topics in leading journals and conferences, and six books. With respect to applications, she has led or participated in various projects on visual query systems and developed methodologies for database design. Particularly relevant are some European projects, including KIM, VENUS, FADIVA, and LAURIN, aiming at investigating different aspects of interface design and human-computer interaction. More information on Dr. Catarci's research activities can be found in: T. Catarci (2000). What happened when database researchers met usability. *Information Systems*, **25**(3), 177–212. Outside of academia, she has been a consultant to large (private and government) organizations. Dr. Catarci is regularly on the programming committees of the main database conferences and is associate editor of IEEE Multimedia. She has been the program co-chair of the Fifth IFIP Working Conference on Visual Database Systems (VDB5) and has been the program co-chair of the International Workshop on Advanced Visual Interfaces (AVI) in 1996, and is in the AVI steering committee. AVI has brought together researchers in Human Computer Interaction and Databases since 1992. She is one of the organizers of the twenty-seventh International Conference on Very Large Databases (VLDB2001) to be held in Roma in September 2001. She has been guest co-editor of two recent special issues of the *Journal of Visual Languages and Computing* (on “Visual Query Languages”) and of *ACM SIGMOD Record* (on “Information Visualization”).

Fabrizio d’Amore, Associate Professor of Computer Science since 1998, is presently affiliated to the University of Rome “La Sapienza,” School of Engineering. He got his Ph.D. in 1993, defending a thesis on algorithms for hyper-rectangles. His research activity, started in 1988, covers several fields of computer science, ranging from algorithm engineering to spatial and temporal databases. Numeric robustness and geometric computing are also central issues in his interests. He has been both editor and author of books, and published more than 40 papers in international journals and conferences; he has also organized several scientific events and co-operates with many international partners. He has taught computer science since 1997.

Paul Janecek is currently a Ph.D. candidate at the Swiss Federal Institute of Technology (EPFL), in Lausanne, Switzerland, where the focus of his research is “semantic fisheye views” and information bisualization. He received the Advanced M.Sc. in Computer Science and Human Computer Interaction from Queen Mary and Westfield College, University of London. Before joining the Human Computer Interaction Group of the database laboratory at the EPFL, Paul began his research on Information Visualization at the Université Paris-Sud, France, and worked as a researcher on an advanced user interface technology project (CPN2000) at Aarhus University, Denmark.

Stefano Spaccapietra is full Professor at the Computer Science Department, Swiss Federal Institute of Technology, in Lausanne, Switzerland, where he chairs the database laboratory. He has been an academic since 1969, when he started teaching database systems at the University of Paris VI. He moved to University of Burgundy, Dijon, in 1983 to occupy a professor position at the Institute of Technology. He left for EPFL in 1988. His Ph.D. is from the University of Paris VI, in 1978. His first interests were in the area of data modelling and distributed database management. Since he joined EPFL, he has developed R&D activities on visual user interfaces, semantic interoperability, spatio-temporal data modeling and multimedia databases. He was chair for five years of the steering committee of Entity-Relationship conferences and currently chairs the steering committee of IFIP Visual Database Systems conferences. He chaired the Database Group of the Swiss Informatics Society (1997-2000), the ISO Working Group “DBMS Coordination,” ISO/TC97/SC5/WG5 (1981-1985), and the ISO Reporter group, ISO/TC97/SC21/WG3 (1985–1986). He was also chair of the “Distributed databases” Working Group, 1975-1980, within AFCET -Informatique (French Computer Society). He is an IEEE fellow, a member of the International Foundation for Cooperative and Interoperable Systems, a member of the EDBT (Extending Database Technology) Foundation and Vice-Chair of the IFIP WG 2.6 “Databases.” He served as Conference Chair or Co-Chair for four international conferences, and Program Chair for six international conferences. He served on the Program Committee for over 50 conferences, including all major ones (VLDB, SIGMOD, ICDE, ER). He has authored, co-authored or edited 10 books, 5 chapters in books, more than 20 papers in international journals (including ACM TODS, IEEE TKDE, IEEE TOSE, and CACM), and about a hundred papers in conferences.