Designing advanced GIS visualisations using cognitive ergonomics theories, models and procedures

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1. Introduction

Much useful and interesting information about the world contains aspects which draw their significance from the spatial distribution of phenomena. Since the earliest days of civilisation such information has been presented in the form of maps and diagrams. The manner of representation has changed exceedingly slowly until recent times. The ability to encode maps digitally has evolved into geographic information systems (GIS) with powerful analysis functionality and display capabilities. Traditional cartographic educational, decision-support and entertainment objectives can now be achieved via a multitude of interactive multimedia products. While this (technology led) revolution has greatly enhanced the potential to fulfil these objectives, it has not eliminated the basic question: what is a good map? Indeed the problem of design has become considerably more complex.

The map designer could be said to be faced with a choice between:

. the easy solution – giving users what you have;
. the popular solution – giving users what they want;
. the complex solution – giving users what they need.

Traditionally, cartographers have often opted for the easy solution, especially in the case of topographic maps. Map design concentrated on the objectives of some well defined specific initial user, usually the one who paid for the survey and map production costs. Subsequent users had to take what was offered. While the cost of manually produced special purpose maps was prohibitive and cartographic products were scarce, users were usually satisfied with this arrangement, if not uniformly content.

As users became less desperate for any map at all, they started voicing increasingly loud demands for products which matched their individual desires. Some cartographers welcomed this unrest as an expression of legitimate user involvement in the cartographic communication process. However, others highlighted the fact that user demands were sometimes made in ignorance - patients don't tell their doctor how to treat them so why shouldn't map users trust cartographers? There was also the real problem of conflicting user demands. Prior to the development of effective digital mapping and GIS technology, one cartographic product frequently had to (inadequately) cover the expectations of a wide range of potential users. This often lead to the informal application of the concept of the 'optimal map' defined, for instance, as that producing the 'least sum of (weighted) user dissatisfaction'. As well as the extreme technical difficulty of achieving such an optimisation in any formal sense, there was the problem of obtaining the required user feedback. Questionnaire surveys, map users forums, user advisory committees, and like mechanisms were often ineffective and short-lived.

The developments in cartographic technology of the late 1970's and the 1980's provided greatly increased potential to satisfy the needs of users. Computer-assisted cartography could provide products designed to meet specific user-requirement specifications. Various approaches to the optimisation of cartographic design could be adopted, including the following:

- Expert Opinion:
  People who are recognised as expert cartographers could be used to design the map;
- Conventions:
  The cartographic design could use accepted conventions or principles of map 'goodness';
- Specifications:
  Some maps (especially those which are part of a series) may be designed by adherence to an explicit set of specifications;
- User Feedback:
  Users may be requested to subjectively rate alternative map designs;
- Utility:
  The map design may be objectively assessed in terms of how well it carries out specific predetermined functions, which may include aesthetic as well as more utilitarian objectives.

Clearly the last alternative is the most scientific, rational and objective. This approach led cartographers to undertake psycho-physical experiments to test specific hypotheses concerning map design parameters. It was at this point in history that the initial development of GIS started to significantly expand the analysis and output capabilities of computerised mapping systems. Increasingly, the expanded display options and use scenarios rendered the psycho-physical experiment approach inadequate. It was simply impossible to adequately define the optimisation parameters, let alone conduct the exponentially increasing number of experiments which would be required. Clearly a new approach to designing GIS visualisations is needed. It must take advantage of the understanding of human-computer interaction developed from other application domains and be soundly based on psychology theory.

2. Developments in GIS Visualisations

GIS are becoming more flexible and powerful and more closely integrated with modelling software. Hence, the communications between users and GIS are increasingly interactive and complex, especially when GIS are configured as spatial decision support systems (SDSS). Developments in GIS visualisation techniques have been driven by these factors, as well as by improvements in analysis and display functionality. Thus GIS visualisations are becoming increasingly sophisticated. They may display relationships between conceptual as well as physical entities and may involve image draping and stereoscopic viewing [1; 2].

As well as the trend towards more realistic visualisations, there is increasing use of abstract graphics to represent the distribution of non-visual phenomena and to describe processes [3]. Applications of this type often utilise sequences of graphics/images to provide an animated message, especially to communicate changes in phenomena over time, for example, in global change research [4; 5].

3. Approaches to the Design of Advanced GIS Visualisations

The role of visualisations in advanced, interactive information systems is receiving increasingly scientific assessment. This is essential because of the rapidly increasing representational potential of new systems, especially those employing multimedia or hypermedia approaches. In the GIS application domain the potential for systems to produce enhanced graphics has outstripped the ability of system designers and users to understand which visualisations are most appropriate to particular communication objectives. Visualisations should not be selected merely on the basis of tradition or expediency, but rather, so as to provide the greatest utility for the user in terms of their cognitive work requirements.

If GIS visualisations are to be optimised it is necessary to address rationally the relationship between communication objectives and the nature of the display, within a user-centred, cognitive ergonomics framework [6; 7]. This may be achieved by the use of cognitive task analysis procedures. The means-ends structure of any GIS-based decision process defines the cognitive task requirements and the sets of potential mental strategies which may be used. A cognitive ergonomics analysis enables the identification of representation and interpretation requirements. The interaction of these requirements with the viewers' roles and characteristics may be analysed to infer the visualisation design parameters.

Visualisation design may be undertaken as a formal procedure which implements a user-GIS interaction model through a cognitive task analysis procedure. However, a vast array of interaction models and task analysis procedures exist [8; 9; 10; 11; 12; 13; 14]. A Cognitive Ergonomics in GIS Reference Model may be used as a means of integrating alternative approaches and tailoring procedures to suit specific aspects of GIS design and evaluation, including the design of visualisations [7]. The initial structure of such a reference model is shown in Figure 1.

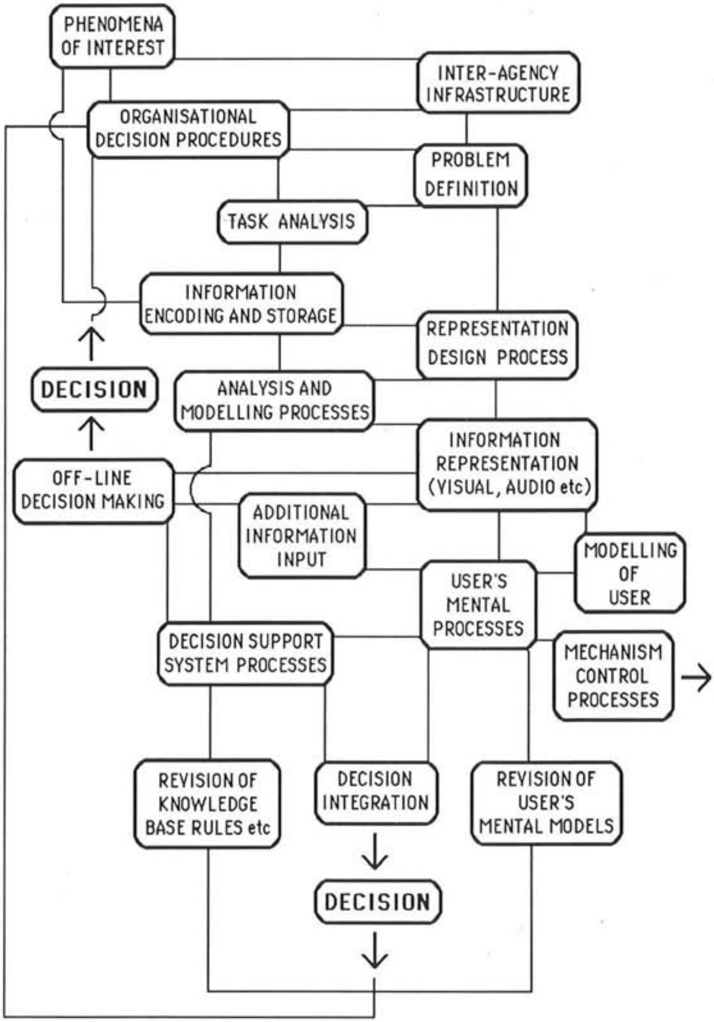

Figure 1 – Initial 'Cognitive Ergonomics in GIS' Reference Model Structure and Components.

4. Taxonomies for Visualisation Design/Selection Procedures

A formalism (model) linking visualisation objectives and products needs to utilise multi-dimensional, generic task and form taxonomies. Hence, a necessary aspect of the development of effective visualisation design/selection procedures is the development of appropriate taxonomy dimensions and categories. Whether any particular taxonomy dimension is useful will depend upon how it reflects the causal factors which dictate the degree of success of a visualisation sequence. This question partly turns on the nature of the design optimisation procedure being adopted. Hence, any development of visualisation design procedures needs to be embedded within a broader approach to system design methodology and visualisation tasks must form a subset of an overall GIS task taxonomy used to design and evaluate user-GIS interaction [7].

The purpose of visualisations may be formalised in terms of taxonometric dimensions such as the one suggested by Ganter [15]. This dimension classifies visualisation graphics in terms of the following broad categories of use:

1. Exploratory graphics:
   Graphics which portray the information generated from numerical simulations or other modelling, especially where there is a need to simplify the presentation or render it less ambiguous or more convincing. *"These graphics usually mimic the appearance of the object or process being studied, and are often dynamic, showing behavior over time."* [15, p. 234]

2. Design graphics:
   These graphics are *"... an externalization of non-verbal creative thought which permit preliminary testing and comparison of solutions to technological problems"* [15, p. 234-235]. The most common example is CAD graphics.

3. Reference graphics:
   Graphics of this type *"... such as maps, diagrams, and curves are archives of displayed data which can be extracted and put to new uses"* [15, p. 235]. They are frequently prepared for a variety of purposes, possibly some considerable time prior to their use, and their accuracy and completeness may be subject to constraints beyond the control (or even knowledge) of the user.

4. Presentation graphics:
   These are (usually simplified) graphics designed to communicate specific concepts in a particular context. Their general form may be similar to that of reference graphics.

A visualisation designer must determine what phenomena need to be displayed, and the form of the representation, so that the defined communication objectives (cognitive tasks) will be achieved. A taxonomy dimension which may facilitate this process is illustrated by the following list:

A. Phenomena visualisation:
   Depiction of natural or man-made phenomena, recorded in terms of either point, local or global variables;

B. Meta-phenomena visualisation:
   Display of the content/coverage, quality, accuracy, etc., of information sets representing particular phenomena;

C. Phenomena change visualisation:
   Depiction of phenomena change (over some specific time period) or the rate of change of the phenomena or one of its attributes;

D. Visualisations of relationships between phenomena:
   Display of specific, spatially based, relationships (e.g. correlation) between phenomena of interest;

E. Causal visualisation:
   Depiction of cause-effect relationships, known or inferred, involving the phenomena;

F. Meta-causal visualisation:
Displays of the reliability, etc., of inferred causal relationships;

G. Information system (GIS) structure visualisation:
Depiction of the information system's analysis and display functionality;

H. Analysis process visualisation:
Graphic depiction of the processes of analysis used to generate a particular visualisation;

I. Motivational visualisation:
Graphic displays designed to catch and hold the viewer's attention.

The visualisation intent must be implemented through a specific set of graphics. This requires consideration of another taxonomy dimension covering the form of presentation. An example of the sort of classification of form which may be used is the following list:

1. Direct display:
Use of a 'realistic' visual display to depict a phenomenon which is intrinsically visual, or at least a key aspect under study is visual;

2. Indirect display:
Graphics/images used to depict a non-visual phenomenon, where the viewer is consciously or unconsciously aware that the visual display is acting as a surrogate for something real but invisible;

3. Abstract graphics:
Cases where information is rendered in abstract terms;

4. Metaphorical displays:
Where the graphic display is in terms of some (explicit or implicit) metaphor;

5. Aesthetic graphics:
Visualisations designed to produce some emotional response in the viewer.

It is important to note that the visualisation design taxonomy dimensions which are appropriate, in any particular instance, will depend (to some extent) on the nature of the information to be depicted, and on the task analysis procedures adopted. In practice, generic visualisation task and form taxonomy dimensions may need to be supplemented by dimensions which support the design process in terms of the theory of interaction on which it is based. For instance, a mode of engagement dimension may be appropriate for a task analysis procedure which is based on the 'levels of cognitive control' theoretic model [11].

For such a dimension, the viewer's mental engagement with the visualisation may be considered to be at one of the following levels:

Level I. Theory/knowledge based:
Decision-making by the application of theories and mental models relevant to the visualisation sequence;

Level II. Principles/rules based:
Decision-making through the use of sets of principles and rules, triggered by appropriate codes or visual cues;

Level III. Automated/skill based:
Decision-making through automated (skilled) responses to familiar tasks represented in the visualisation.

5. Visualisation Design Within an Integrated Methodology

A useful step in the refining of design procedures for GIS visualisations is the development of taxonomies, such as that detailed above, so that the study of the cognitive aspects of visualisation may be approached in a logical manner. Whether any particular taxonomy dimension is useful will depend upon how well it reflects the causal factors which dictate the degree of success of a visualisation sequence. This question partly turns on the nature of the design optimisation procedure being adopted. Hence, any development of visualisation design procedures needs to be embedded within a broader approach to system design methodology.

Where such a design methodology implements models and procedures to ensure the cognitive effectiveness of the GIS and its outputs, it may be termed a 'Cognitive Ergonomics Analysis Methodology' (CEAM) [7]. The cognitive aspects of such analysis procedures must be based on a set of theoretical constructs operationalised through human-computer interaction models. It is also important that the integrated system development methodology incorporates organisational design procedures.

A generic CEAM could include models and procedures which address the following stages of GIS design and evaluation, in an integrated (and possibly iterative) manner:

1. Problem definition and decomposition (including defining causal relationships);
2. Analysis of decision environment and design of decision support processes;
3. Determination of required outputs and outcomes;
4. Preparation of quality management specifications;
5. Definition of goals, tasks and required information transformations;
6. Design of information processing procedures;
7. Assessment of data requirements and database design;
8. Definition of software and hardware functionality requirements;
9. Cognitive task allocation between users and software;
10. Assessment of organisational structure and personnel requirements and user characteristics;
11. User interface design or customisation;
12. Design of decision support visualisations;
13. Design of user instruction and help facilities;
14. Usability evaluation of the system and its products;
15. Audit of efficiency and effectiveness of overall system design process.

The selection of an appropriate sequence of system design and evaluation procedures from the vast array of available models and techniques is a daunting task. However, the definition of a suitable CEAM will be easier once the initial version of the proposed reference model for cognitive ergonomics in GIS is available. In the meantime, GIS design and evaluation studies utilising specific models and task analysis procedures can be used to identify the virtues and problems of different approaches.

6. Limited Case Study - Dam Surveillance SDSS Graphics

The Melbourne Water Corporation (MWC) is a corporatised government agency responsible for the building and management of water storage structures (dams) in the Australian State of Victoria. The principal responsibilities of the Corporation's Structural Surveillance Section are the analysis of stress and deformation measurement information to determine any requirements for urgent action, the development of structure management action proposals with engineers from other sections, and the provision of risk management advice.

There could be said to exist a 'corporate' model of the stress and deformation behaviour of any of these dams: 'corporate' in that it is both a shared model and because it constitutes the official position of the organisation. This model is constituted of various explicit documents and data sets summarising the current best understanding of the situation, as well as implicit shared theoretical and practical knowledge embodied in the expertise of the relevant personnel. It is important that this 'corporate' model be as explicit as possible, since it must be used by personnel other than structural and civil engineers (e.g. for risk management), and so that MWC management are able to understand these matters and balance structure management considerations with financial and other matters.