23 May 2005

Original: English

Eighth United Nations Regional Cartographic Conference for the Americas
New York, 27 June-1 July 2005
Item 8 (b) of the provisional agenda*
Reports on achievements in geographic information in addressing national, regional and global issues, including spatial data infrastructures

Cartography and geo-information science: an integrated approach**

* E/CONF.96/1.

** Prepared by Menno-Jan Kraak, International Institute of Geo-Information Science and Earth Observation (Netherlands).

05-35236 (E)

0535236

Cartography and geo-information science: an integrated approach

Menno-Jan Kraak
ITC - International Institute of Geo-Information Science and Earth Observation
Department of Geo-Information Processing
PO Box 6, 7500 AA Enschede
the Netherlands
kraak@itc.nl

About maps

Maps have the ability to present, to synthesize, to analyze and to explore the real world. Maps do this well because they only present a selection of the complex reality and visualize it in an abstract way. The cartographic discipline has developed a whole set of design guidelines to realize the most suitable map that offers insight in spatial patterns and relations. Many textbooks and papers have been written on this topic (Kraak and Ormeling, 2002, MacEachren, 1994, Robinson et al., 1995, Slocum, 1998, Bertin, 1967). In general professional geographers don't have to be convinced of the unique qualities of maps to express their ideas, to make a point, to obtain new knowledge, and communicate among colleagues, and of course to orientate and navigate. Maps are also appreciated outside our professional community. Ask randomly and the conclusion will be that almost everyone likes them, and has an opinion on their aesthetics and quality, although the last not always based on justifiable arguments.

Despite the above positive remarks the view on maps is often limited to its presentation function. Even the professional geographer might not be fully aware of their possibilities. This view probably partly originates from map descriptions and definitions, and partly from unawareness of the developments in the discipline. Definitions go seldom beyond the presentation function of the map. In the current strategic plan of the International Cartographic Association [url 1] the map is defined as: "A symbolised representation of a geographical reality, representing selected features and characteristics, resulting from the creative effort of its author's execution of choices, and is designed for use when spatial relationships are of primary relevance". This definition mentions use but stresses creation. Of course it is realized that even for exploratory purposes the maps have to be created, but the emphasis is on its use (the exploration). For many other map definitions the website of J.H. Andrews [url 2] is a good source. It lists over 300 definitions. Even though definitions might be limited in scope, maps have been used to solve or highlight problems anyhow. In this respect many cartographic textbooks as well as books outside our geo-disciplines (Tufte, 1983, 1997) demonstrate the strength of maps, while some point to the 'danger' of maps (Pickles, 2003, Wood, 1992, Monmonier, 1991). The classical map examples that are revisited frequently are John Snow's map of London depicting a cholera epidemic [url 3] and Minard's map of Napoleon's campaign into Russia [url 4].

A detail of Snow's map is shown in Figure 1a. It displays the individual cholera deads as well as the water pumps in the area. Snow linked the cause of cholera to the quality of water, and by closing the Broadstreet pump which was located in the vicinity where most victims were found the epidemic was ended. The case can be seen as one of the earlier spatial analysis operations and is referred in both geographic as well as in medical literature (Frerichs, 2001, McLeod, 2000). Tobler [url 5] used the map to demonstrate how problems can be solved using geographic techniques. He created Thiessen polygons to indicate the area of influence of each pump and executed a point-in-polygon operation to determine around which pump most victims where found. Monmonier used the example to demonstrate how the choice of basic geographic units can influence the outcome of a spatial analysis by selecting different combinations of street blocks as basic unit (Monmonier, 1991). Recently Snow's map is thought that the maps has not been used to sparkling his mind leading go the solution, but more as proof that confirmed his approach (Brody et al., 2000). Anyhow, the Snow-case demonstrates the strength of maps and the different roles they can play. Medical geography and maps go hand in hand and have assisted each other in many other cases. See for instance the website of the US National Center of health statistics and its atlas of United States Mortality [url 6] or the Dutch Zorgatlas [url 7].

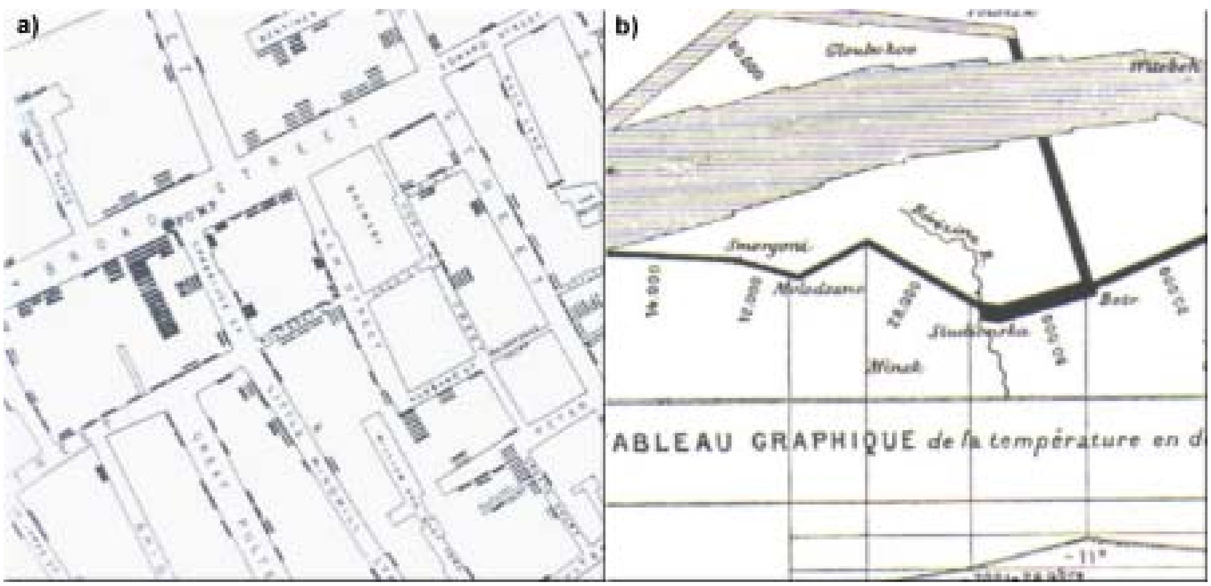

Figure 1. Map classics: a) John Snow's map of London's 1854 cholera epidemic; b) Minard's 1869 map of Napoleon's 1812 campaign into Russia

A detail of Minard's map from 1869, is displayed in Figure 1b and shows Napoleon's dramatic losses during his Russian campaign. The objective of the "Carte figurative des pertes successives en hommes de l'Armee Française dans la campagne de Russie 1812-1813", was to stress the senselessness of war. The map shows two distinct paths, the advance to Moscow (in grey) and the retreat (in black). A diagram indicating temperature is linked to the retreat path, probably making this map one of the first with a linked view. The width of the paths represents the number of troops. The map has been extensively described by several authors is a good example of a narrative of an event displaying time and space(Robinson, 1967, Friendly, 2000). Recently the map has been put in the interactive and dynamic context of today's map making and map use (Kraak, 2003, Roth et al., 1997). These new Minard maps allow the user to interact, query and replay Napoleon's campaign.

The interest in these and other map classics has certainly been stimulated by Tufte's publications which are also widely read outside the geo-community, especially in the scientific and information visualization community (Wilkinson, 1999, Card et al., 1999, Spence, 2001, Chen, 2003). Interestingly these relatively new domains apply cartographic knowledge to realize their objectives, and our discipline should be stimulated by the creative graphics created in these domains.

Although the traditional paper map allowed geographers to use it to synthese, analyse, and explore, it is be obvious that the rise of Geographical Information Systems have stimulated these functions. Maps that used to be elaborative to produce can now be created in many alternatives views by the single click of the mouse. Additionally many more maps are produced and used, a trend multiplied by the development of Internet and especially the WWW (Peterson, 2003). One could argue that these numbers make no difference because of the poor cartographic quality of most of these maps. However, one could also argue if one would need properly designed maps under all circumstances.

When taking these developments into account the map definition given above does not cover all. In the recent book 'Exploring Geovisualization' (Dykes et al., 2004) the traditional role of a map to 'present' is recognized, but the map should also be seen as flexible interface to geospatial data, since they offer interaction with the data behind the representation and additionally maps are instruments that encourage exploration. As such they are used to stimulate (visual) thinking about geospatial patterns, relationships, and trends and are increasingly employed throughout the GIScience process. The context where maps like this operate is the world of Geovisualization (Dykes et al., 2004) and can be described as a loosely bounded domain that addresses the visual exploration, analysis, synthesis and presentation of geospatial data by integrating approaches from disciplines including cartography with those from scientific visualization, image analysis, information visualization, exploratory data analysis and GIScience. The specific relation with GIScience is address in (Kraak and MacEachren, 2005).

Maps and GIScience

A decade ago the notion of GIScience surfaced. The term was introduced by Goodchild (1992) who described it to deal with the basics of gis-technology, concentrating on those issues that are an impediment to a successful implementation. In a recent book on GIScience (Duckham et al., 2003) it is worded that giscience addresses the fundamental research principles on which geographic information systems are based (e.g. research on gis) or that it refers simply to the use of GIS in scientific applications (e.g. research with gis). Judging the GIScience research agendas discussed by Mark (2003) it can be concluded that visualization is directly or indirectly seen as an important topic.

Ever since the introduction of the term, GIS-related journals and books changed the 'Systems' part of their titles into 'Science'. The International Journal of Geographical Information Science used to be The International Journal of Geographical Information

Systems, and the American Cartographer changed from Cartography and Geographic Information Systems into Cartography and Geographic Information Science. The 'new' version of the two volume Geographic Information Systems by (Longley et al., 1999) is followed by a volume titled Geographic Information Systems and Science (Longley et al., 2001).

The above developments have also influenced the International Cartographic Association. In their recent strategic plan [url 1] they express the ambition "…that the International Cartographic Association should be qualified with the sub-title *The International Society for Cartography and Geographic Information Science*." In their plan GIScience is defined as: The scientific context of spatial information processing and management, including associated technology as well as commercial, social and environmental implications. Information processing and management include data analysis and transformations, data management and information visualisation. Associated methodology includes both hardware and software. Commercial, social and environmental implications refer to the wide scope of applications of GI and GISystems as well as the analysis of their implications locally and globally".

Since geovisualization studies and promotes all kind of (map) graphics that stimulate visual thinking, the approach to GIScierise as research on GIS would fit best. One tries to develop the visual methods and techniques (tools) to present, analyse, synthesise and explore geospatial data, but one is also interested it their effect on the problem solving (efficiency, effectiveness). In his book chapter titled 'Beyond tools: visual support for the entire process of GIScience' Gahegan (2004) addresses this particular problem. He described the GIScience process and projected the possible maps and graphics as well as computational methods on each of the process' steps. He writes: "To better support the entire science process, we must provide mechanisms that can visualize the connections between the various stages of analysis, and show how concepts relate to data, how models relate to concepts, and so forth".

Figure 2, based on Gahagan's ideas, is a simplified version of the process illustrated with the data behind Minard's map. The process contains the steps Exploration, Synthesis, Analysis, Evaluation and Presentation, however not necessarily in a sequential order. Let's look at Napoleon's campaign and follow the process. In this example the objective is to understand what happened during the campaign. The data available consist of statistics and maps derived from all kind of sources such as official French army document, diaries of individuals, Russian reports, and other references (Austin, 2000). In the figure this is summarized by a few tables. To get insight in these data one will have to explore the data, for instance via a parallel coordinate plot in which all variables, such as number of troops, temperature, battles, deaths, wounded are given. The geographic locations for which these facts are known are represented by 'horizontal' lines. At such a stage one might formulate a hypothesis like: 'Since Napoleon lost the campaign he probably lost most battles'. This could be checked via an iconic display, with for instance Chernoff faces to show who won the battles. Additional variable like number of troops involved, wounded, death etc could be expressed in the faces as well. Since he won most battle one will wonder why he lost the campaign and might interested to view the relation between the loss of troops and factors such as weather and geography over time. Interactive visualization tools, such as SAGE (Roth et al., 1994) could reveal interesting patterns. Alternatively one could create time-cartograms to better understand the influence of geography on time. As a result of the analysis one can create time series to compare individual events or create a visual overlay of the data available. A three-dimensional model with different layers of information can display the relations between the different thematic layers. Before the final maps are drawn one should evaluate the result via a uncertainty visualization. This graphic could indicate the accuracy of both location of the campaign path as well as of the numbers of troops. In a last phase the finding are put in well design maps and diagrams. Minard's map could be an example, but it could also be an interactive space time cube.

For each of the individual steps particular visualization tools exist, often created with a specific domain dependent task in mind. However, there is no single software environment that can handle all. In a full fledged geovisualization environment easy access to all required functionality should be available. Research in that direction is executed (MacEachren and Kraak, 2001). The approach described based on figure 2 is just one possible view on the GIScience process and as Gahagan (2004) writes : "The more we understand about how the researcher is trying to think and what they are attempting to produce, the better we can design suitable visualization tools that support their tasks".

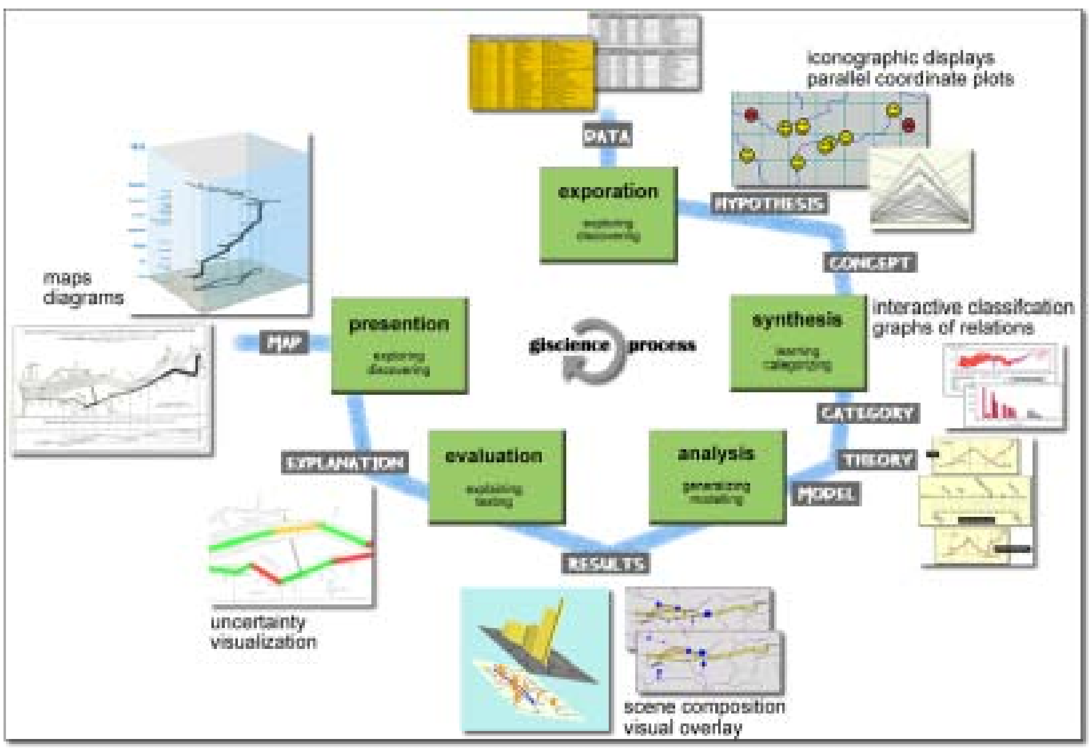

Figure 2. Maps and the GIScience process (based on Gahagan (2004)) and illustrated with Minard's map data

It should also be clear by now that the notion map should be taken very liberal, as was already mentioned at the end of the first section. Although location is involved when solving geo-problems in a GIScience context, maps seem indispensable, but the non-map view might be just as revealing or helpful. Sometimes maps will not be involved at all. If one for instance considers driving from A to B a geo-problem some solutions (particular car navigation systems) work without a maps and instruct the driver by voice where to go left or right. However, personally I cannot imagine that geographers would, in addition need a map to put the trip in the geographic context. It is the strength of the combined graphics that will support finding a (potential) solution.

In the next section some trends are sketched which have a tremendous impact on the cartographic discipline. Figure 3 distinguished between developments that are mainly related to the working environment and those that influence the map appearance. Work environment related developments include the on-screen multiple dynamically linked view, the geodata infrastructure and data portals (clearinghouses), the possibility for visual collaboration and the location based services. Map appearance related developments include the dimensionality of the map content, the design approach, the alternative views and the realistic maps views (virtual and augmented reality).

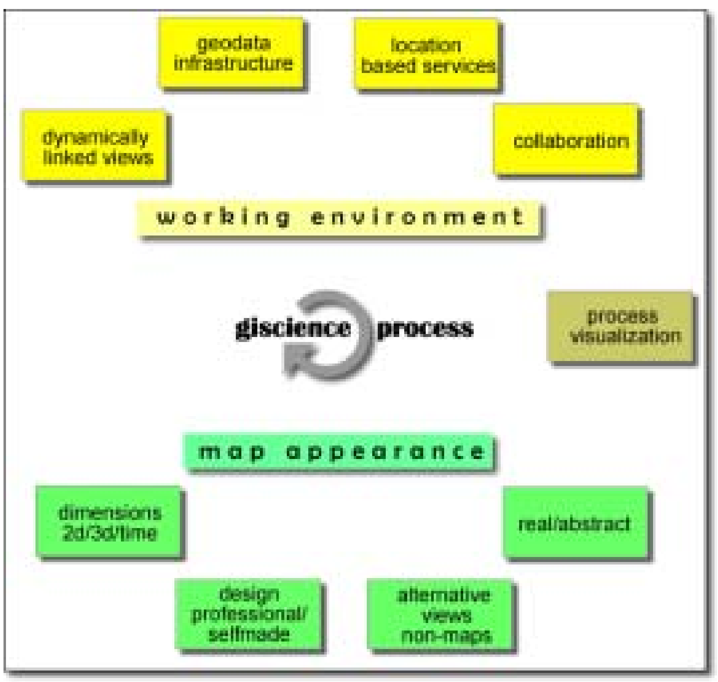

Figure 3. Map, the GISCience process and some developments and trends related to the working environment and the map appearance

Map Appearance: developments and trends

Design and content: professional / self made

Paper maps, and especially topographic maps, are designed and made by professionals. They are very useful under many different circumstances. In the future maps like these will still be produced, but the demand from the user community forced traditional cartographic organizations to change their approach to the market. Users want digital data to process with their own GIS software. One of the consequences to be able to offer the right services national mapping agencies not only have to provide up-to-date digital data, they also have to step away from their century long map sheet thinking. This has a large influence on how the mapping organizations have to arrange their work processes, since revisions are often linked to map sheet number and not to theme such as infrastructure, even though that type of data is in high demand for car navigation systems. For the GIScienst it is important the required data is available on demand, preferably via web mapping services. Based on the problem at hand the scientist can use the data in their own software environment or can compile maps via the web services offered. In this process content (map layers on or off), layout (color and style of symbols) and the area of interest can be defined by the user. A potential disadvantage might be that there is no guarantee that the final map design adheres to cartographic rules because of the many options available. In the professional GIScience environment this might be less problematic then in the consumer environment.

Dimensionality

In the past restrictions in data collection, modelling and display techniques prevented the representation of the three-dimensional world around us as true three dimensional. This resulted in maps with a two-dimensional view of reality, which in most situations is sufficient. However, sometimes the availability of a three-dimensional world which can be queried, analyzed, and viewed would improve insight and is likely to result in better decisions. Examples are the multi use of space in urban areas where complex planning problems have to be solved to avoid conflicts of interest. Three-dimensional displays require an interactive viewing environment that allows one to view the objects from any direction to avoid obstruction and allow query of all objects in the representation. In GISCience the analysis of terrain characteristics, the surface and subsurface features etc requires a true 3d approach and many different viewing options (Döllner and Kersting, 2000). In other situations a three-dimensional view on multiple attribute space can be clarifying as well (Lucieer and Kraak, 2004). The inclusion of a temporal component will complicate the visualizations even further. Animations seem to be a good solution as long as the user has the ability to interact with this type of map representation (Acevedo and Masuoka, 1997).

Alternative views

In understanding spatial patterns and relation the geoscientist has many different map types available, but despite that these follow proven concepts it can be refreshing to view data from a different perspective. However, some of the interesting alternatives require complex computation and data handling and are not available in off-the-self software. Examples of these maps are cartograms, schematic networks, and (3d) models (Avelar, 2002, Keim et al., 2003, Krisp and Ahonen-Rainio, 2003). To be successful these alternatives should be used in conjunction to the familiar map view. It should be remembered that the conceptual ideas behind many of these representations have often been developed during the fifties and sixties of last century, but only today they become operational in our gi-environment. With the tremendous increase in available data the use of maps alone is often no longer sufficient. Graphic techniques to reduce the dimensionality of the data, as they are common in information visualization are needed (Keim et al.). These graphics such parallel coordinate plots, scatter plots or even self organizing maps should also be linked to the map view. The self organizing map was originally designed as spatialization of non-geographic data but can also be used as view on attribute space in our GIScience environment (Skupin and Fabrikant, 2003).

Abstract or real

An important characteristic of maps is the fact that they represent selections from reality in an abstract way. Especially for presentation purposes maps that look 'empty' might even work better than maps with an overloaded view. In an exploratory mode a overloaded map could be very representative for the topic being studied, and via interactive selection and filtering techniques the user can 'drill-down' to the information thought relevant. The 'selection/abstraction' characteristic is not only challenged by exploration but also by new viewing environments such as virtual and augmented reality (VR and AR) (Dykes et al., 1999a, Sherman and Craig, 2002, Unwin and Fisher, 2001). These allow a different view on reality, and in addition one can become completely absorbed in this 'reality'. VR and AR require realism in the imagery used. Again a combination of both the map world and the VR/AR world seem to be the best solution with the option to emphasize one of the two depending on the task at hand (Verbree et al., 1999). For a navigation task the map view might be more helpful, and to judge if the newly design building fits the building style of the old city centre a realistic view will give a better impression.

Working environment: developments and trends

Dynamically multiple linked views

The argument that different views on the data will sparkle the mind and stimulate visual thinking (Peuquet and Kraak, 2002) should be supported by a suitable working environment. This leads to an environment with multiple views with different maps, diagrams, tables etc of the same and/or related data that are linked to each other. The strength of this combination of maps and other graphics is that user action in any of the views will result in highlighting the relevant objects in all the other views. Several of these more or less experimental exploratory environments exist. With roots in statistics (Haslett et al., 1991) map based examples also exist like CommonGIS (Andrienko and Andrienko, 1999) and CDV (Dykes, 1997). Recently a conference series with contributions of different perspectives has been established [url 8].

Geodata infrastrucuture

A geospatial data infrastructure (GDI) offers a set of institutional, technical and economical arrangement to enhance the availability (access and use) for correct up-to-date, fit-for-purpose and integrated geo-information, timely and at an affordable price to support decision making processes (Groot and McLaughlin, 2000). The GIScientist can access the GDI via a clearinghouse or web portal. Such portals are often a collection of metadata describing the geodata available based on which the user will decide the data's fitness for use. Metadata can be visualized in maps, diagrams or browse graphics to give the user additional information on content and quality (Ahonen-Rainio and Kraak, 2004). Maps will also play a role as part of the search mechanisms in the portals. Not only can it be used to indicate the area of interest, but it role extended by linking the atlas concept to the portal use its structured approach to create easy access (Aditya and Kraak, 2004).

Location based services
Human mobility has increased the demand for (geo)services (Gartner and Uhrliz, 2002). Although the paper map can be considered mobile, its content is not. The technology push of tablet pc's, and pda's and mobile phones and wireless networks has stimulated the demand. It is the opportunity to get fresh and up-to-date information anywhere at anytime that introduced the world of the so-called location based services, using the web services of geospatial infrastructures and web portals. Examples could be information to get to the nearest bookshop or museum. A geoscientist is likely to by more interested to downloaded data from the office while in the field to compare findings with the information already in the database (Dykes et al., 1999b).

Collaboration
The magnitude of geo-problems to be solved, like is in disaster management, as well as the large amount of data available requires a multi- and interdisciplinary approach. This obviously means collaboration of one kind of the other. Via the Internet and wireless networks it is possible to work on the same project with colleagues who are based on different continents. Experiments are conducted to realize this type of work(MacEachren, 2000, Wood et al., 1997, MacEachren, 2004).

Conclusions

During the GIScience process different maps and graphics have their role to play to assist the researcher in understanding the data and to support problem-solving. The maps and graphics are there to stimulate thinking, to show the unexpected, to point to the outlayers and the demonstrate trends. Maps and graphics cannot do this alone. Different algorithms, models and other methods and techniques are behind the images, for each of the phases in the GIScience process. In this paper the impact of some developments and trends have been discussed without pretending to be complete. For instance the whole field of (visual) data mining has not been discussed but is an important component of the GIScience process. Maps do much more then just present geographic data. Maps cover the range from indeed presentation al the way to exploration in a connected dynamic and interactive environment. Maps do matter.

References

Weblinks:
url 1 map definitions http://www.usm.maine.edu/~maps/essays/andrews.htm
url 2 ica maps http://www.icaci.org/en/strategic.html
url 3 john snow cholera map of london http://www.ph.ucla.edu/epi/snow.html
url 4 minard's map of napoleon in Russia http://www.itc.nl/personal/kraak/1812
url 5 thiessen polygon and snow's map http://www.ncgia.ucsb.edu/pubs/snow/snow.html
url 6 us mortality atlas http://www.cdc.gov/nchs/products/pubs/pubd/other/atlas/atlas.htm
url 7 zorgatlas the Netherlands http://www.rivm.nl/vtv/data/site_atlas/
url 8 Coordinated & Multiple Views in Exploratory Visualization http://www.cvev.org/

Acevedo, W. and Masuoka, P. (1997) *Computers & Geosciences,* **23,** 423-436.
Aditya, T. and Kraak, M. J. (2004) In *GSDI7*Media Partners / Geospatial Today, Bangalore, India, pp. 83.
Ahonen-Rainio, P. and Kraak, M. J. (2004) In *Exploring geovisualization*(Eds, Dykes, J., MacEachren, A. M. and Kraak, M. J.) Elseviers, Amsterdam, pp. 611-626.
Andrienko, G. L. and Andrienko, N. V. (1999) *International Journal Geographic Information Science,* **13,** 355--374.
Austin, P. B. (2000) *1812,* Greenhill, London.
Avelar, S. (2002) *Schematic maps on demand - design, modeling and visualization - Diss. ETH no. 14700,* ETH, Zuerich.
Bertin, J. (1967) *Semiology Graphique,* Mouton, Den Haag.
Brody, H., Rip, M. R., Vinten-Johansen, P., Paneth, N. and Rachman, R. (2000) *The Lancet***,** 64-68.
Card, S. K., MacKinlay, J. D. and Shneiderman, B. (1999) *Readings in information visualization: using vision to think,* Morgan Kaufmann, San Francisco.
Chen, C. (2003) *Mapping scientific frontiers - the quest for knowledge visualization,* Springer Verlag, London.
Döllner, J. and Kersting, O. (2000) *Proceedings of ACM GIS 2000***,** 115-120.
Duckham, M., Goodchild, M. and Worboys, M. (Eds.) (2003) *Foundations of geographic information science,* Taylor & Francis, London.
Dykes, J., MacEachren, A. M. and Kraak, M. J. (Eds.) (2004) *Exploring geovisualization,* Elseviers., Amsterdam.
Dykes, J., Moore, K. and Fairbairn, D. (1999a) In *VRML '99, Proceedings of the Fourth ACM SIGGRAPH Symposium on the Virtual Reality Modeling Language*Paderborn, Germany, pp. 99-104.
Dykes, J. A. (1997) *Computers & Geosciences,* **23,** 345-370.
Dykes, J. A., Moore, K. E. and Wood, J. D. (1999b) *International Journal of Geographical Information Science,* **13,** 397-416.
Frerichs, R. R. (2001) *The SoC Bulletin,* **34,** 3-7.
Friendly, M. (2000) *Statistical Computing and Graphics Newsletter,* **11**.
Gahegan, M. (2004) In *Exploring geovisualization*(Eds, Dykes, J., MacEachren, A. M. and Kraak, M. J.) Elseviers, Amsterdam, pp. xxx-xxx.
Gartner, G. and Uhrliz, S. (2002) *Geowissenschaftliche Mitteilungen (Technische Universitat Wien),* **60,** 143-150.
Goodchild, M. (1992) *International Journal for Geographic Information Systems,* **6,** 31-45.
Groot, D. and McLaughlin, J. (Eds.) (2000) *Geospatial data infrastructure - concepts, cases, and good practice,* Oxford University Press, Oxford.
Haslett, J., Bradley, R., Craig, P., Unwin, A. and Wills, G. (1991) *The American Statistician,* **45,** 234-242.
Keim, D. A., North, S. C., Panse, C. and Schneidewind, J. (2003) *Information visualization,* **2,** 58-67.
Keim, D. A., Panse, C. and Sips, M. In *Exploring geovisualization*(Eds, Dykes, J., MacEachren, A. M. and Kraak, M. J.) Elsevier, Amsterdam, pp. in print.
Kraak, M. J. (2003) *ISPRS Journal of Photogrammetry and Remote Sensing,* **57,** 1-10.
Kraak, M. J. and MacEachren, A. M. (2005) *Cartography and Geographic Information Systems,* **32**.
Kraak, M. J. and Ormeling, F. J. (2002) *Cartography, visualization of geospatial data,* Prentice Hall, London.
Krisp, J. M. and Ahonen-Rainio, P. (2003) In *Proceedings 21st International Cartographic Conference*Durban South Africa.
Longley, P., Goodchild, M., Maguire, D. M. and Rhind, D. (Eds.) (1999) *Geographical Information Systems: Principles, Techniques, Management, and Applications,* J. Wiley and Sons, New York.
Longley, P. A., Goodchild, M. F., Maguire, D. J. and Rhind, D. W. (2001) *Geographic Information Systems and Science,* Wiley, Chichester.

Lucieer, A. and Kraak, M. J. (2004) In *Proceedings of SPIE-IS&T Electronic Imaging, , SPIE and IS&T. Conference: Visualization and Data Analysis 2004*, Vol. 5295 (Eds, Erbacher, R. F., Chen, C. C., Roberts, J. C., Gröhn, M. T. and Börner, K.) SPIE, San Jose, USA, pp. pp. 201-211.
MacEachren, A. M. (1994) *Some truth with maps: a primer on design and symbolization,* Association of American Geographers, Washington, DC.
MacEachren, A. M. (2000) *Progress in Human Geography,* **24,** 445-456.
MacEachren, A. M. (2004) In *Exploring geovisualizatio*(Eds, Dykes, J., MacEachren, A. M. and Kraak, M. J.) Elseviers, Amsterdam, pp. in print.
MacEachren, A. M. and Kraak, M. J. (2001) *Cartography and Geographic Information Systems,* **28,** 3-12.
Mark, D. M. (2003) In *Foundations of geographic information science*(Eds, Duckham, M., Goodchild, M. and Worboys, M.) Taylor & Francis, London, pp. 3-18.
McLeod, K. S. (2000) *Social Science & Medicine (1982),* **50,** 923-935.
Monmonier, M. (1991) *How to lie with maps,* Chicago University Press, Chicago.
Peterson, M. P. (Ed.) (2003) *Maps and the Internet,* Elseviers, Amsterdam.
Peuquet, D. J. and Kraak, M.-J. (2002) *Information visualization,* **1,** 80-91.
Pickles, J. (2003) *A History of Spaces: Cartographic Reason, Mapping, and the Geo-Coded World (Frontiers of Human Geography),* Routledge, London.
Robinson, A. H. (1967) *Imago Mundi,* **21,** 95-108.
Robinson, A. H., Morrison, J. L., Muehrcke, P. C., Kimerling, A. J. and Guptill, S. C. (1995) *Elements of Cartography,* J. Wiley and Sons, New York.
Roth, S. F., Chuah, M. C., Kerpedjiev, S., Kolojejchick, J. A. and Lucas, P. (1997) *Human-Computer Interaction Journal,* **12,** 131-185.
Roth, S. F., Kolojejchick, J., Mattis, J. and Goldstein, J. (1994) In *Proceedings of the Conference on Human Factors in Computing Systems (SIGCHI '94)*Boston, MA,, pp. 112-117.
Sherman, W. B. and Craig, A. B. (2002) *Understanding Virtual Reality - Interface, Application, and Design,* Morgan Kaufmann Publishers, San Francisco.
Skupin, A. and Fabrikant, S. I. (2003) *Cartography and Geographic Information Science,* **30,** 95-119.
Slocum, T. A. (1998) *Thematic Cartography and Visualization,* Prentice Hall, Englewood Cliffs, NJ.
Spence, R. (2001) *Information visualization,* Addison Wesley / ACM Press Books, Harlow.
Tufte, E. R. (1983) *The visual display of quantitative information,* Graphics Press, Cheshire, Conn.
Tufte, E. R. (1997) *Visual Explanations,* Graphics Press, Cheshire, Conn.
Unwin, D. and Fisher, P. F. (Eds.) (2001) *Virtual reality in geography,* Taylor & Francis, London.
Verbree, E., Maren, G. v., Gems, R., Jansen, F. and Kraak, M. J. (1999) *International Journal of Geographical Information Science,* **13,** 385-396.
Wilkinson, L. (1999) *The grammar of graphics,* Springer, New York.
Wood, D. (1992) *The power of maps,* Routledge, London.
Wood, J. D., Wright, H. and Brodlie, K. W. (1997) In *IEEE Visualization 97 Conference*ACM Press, pp. 253-259.