On Visual Representations in Instructional and Research Environments: Facilitating and Misleading Effects.

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1. Introduction.

We have visualizations all around us, and young people nowadays seem to receive most information about the surrounding world from visual sources rather than textual sources. As a consequence, one might speculate that they are becoming more visually than textually able. Modern technology capitalizes on this movement by allowing more and more advanced forms of visual representations. From the earliest times people have tried to communicate by visual representations, from the early cave paintings to today's satellite images. Visualizations, pictures or images have become increasingly important for understanding the world surrounding us. Thanks to today's technological advances, they can be deployed in various areas, for different purposes, for better or for worse. Their success can be attributed to their facilitative effects. They allow us to understand an idea or concept at a single glance. In addition, they seem to convey the information in a reliable way, since a picture "proves" the truth of what we see. Or, as Roerdink (2004) in his inaugural address puts it, "zien is geloven" ("seeing is believing"). Visualizations are however manipulated more and more frequently, and this has serious consequences for our perception of the world. The information we retrieve from manipulated images becomes biased and far less factual than they suggest. This ambivalence raises the question how reliable or unreliable visual representations are. This question was discussed at the KNAW Meeting of March 17, 2005, by a psychologue, a publicist, a scientific researcher, and two visual artists. This question is indeed particularly relevant to the media, where images can be abused, to the visual arts, where the ambivalence can be exploited to reach a certain effect on the viewer, and to research and instruction, where it should always be questioned whether the visual representation conveys the right information. This paper focuses on visualizations as used in research and instruction. The specific questions addressed in this paper are as follows:

1) What are the main insights gained so far in the scattered research on visualizations?
2) What are the advantages and what are the misleading effects of visualizations pointed out in the literature?

I will start by explaining what kind of representations are taken as visualizations. Next I will show globally what kinds of visualizations have become objects of research and which disciplines are concerned with them. Examples of various visual representations will be given and discussed. I will indicate why it is important and interesting to examine visualizations in more detail. There are good and bad pictures, and it would be nice to know why this is the case and how we can remedy bad design. In order to get a bit more insight into the problem, I will say something about visual communication in general, and the link between the notational system (graphical domain) and the subject matter depicted (application domain). Facilitating as well as misleading effects as mentioned in the literature will be indicated, and finally some general inferential and expressive properties of visualizations will be presented.

2. What are visualizations?

Visualization is a term that can be used to refer to a broad range of external representations of information in a visuospatial modality. Visualizations are representations of information that exploit spatial lay-out in a meaningful way. Information is transformed into a visual structure that combine spatial substrates, graphic marks and graphical properties of these marks in such a way that ideas are easily communicated and even new ideas are triggered. Other terms used for external visualizations are visual or graphical representations or just pictures. They comprise realistic pictures, photographs, icons, maps, charts, graphs, diagrams and the like, displayed on paper or on a computer screen. External visualizations are opposed to internal ones. The latter are also called mental images. The latter are of particular relevance to psychology, cognitive science, and artificial intelligence. Visualizations may be computer-based and interactive. Animations and Virtual Reality are taken as advanced forms of visualization.

3. Research on visualizations.

Researchers have been interested in visual communication, i.e. communication involving the use of external visual representations, since long. This interest has expanded considerably in recent years. Nowadays it includes a large number of disciplines. One can distinguish different research areas that work on topics related to visual communication according to the type of visual representation focused on:

- research on iconic signs and related graphic devices such as the signs used in traffic, instructions, aerospace and military, and graphical user interfaces (GUI's).
- research on diagrams
- research on computer-supported visualizations

3.1. Studies of icons.

Studies on icons go back to the writings of Charles Peirce (1931-1958), a 19th-century American philosopher, and one of the founders of the field of semiotics. Peirce developed ideas about how signs mediate experience. These ideas are often referred to in current discussions on iconic signs. The key distinctions Peirce made are those between icons, indices and symbols. Icons are signs that share characteristics with the objects to which they refer. An index depends on its associated object in a non-arbitrary way. If its object were removed, the index would lose the character that makes it a sign. A symbol stands in an essentially arbitrary relationship to the thing it signifies. The picture of the paper envelope on a GUI desktop is an icon for a folder in the real world. A piece of mold with a bullet-hole in it is an index of a shot. The word 'folder' is the symbol that stands for a class of folders in the world (Peirce, 1955; Familant & Detweiler, 1993). Studies on icons in the peircean sense and comparable graphic devices focus on developing and testing a range of different methodologies for evaluating iconic signs. Comprehension, recognition and name-generation tests have been developed, as well as learning, ranking and sorting tasks.

The distinction between icons and symbols has often been used to justify the use of icons in GUI's. Because of their representational nature, icons give GUI's an intuitive quality, that makes them easy to understand. Icons are one of the key features of the interface that consists mainly of windows, icons, mouse and pull-down menu. By allowing icons, many windows can be available on the screen at the same time, ready to be expanded to their full size by clicking on the icon. Icons can also be used to represent other aspects of the system, such as a wastebasket for throwing unwanted files into, or various disks, programs or functions that are accessible to the user. Icons can take many forms: they can be realistic representations of the objects they stand for, or they can be highly stylized. They can even be arbitrary symbols, but these can be difficult for users to interpret. In fact computing is following dual paths nowadays. The new visual directions are sometimes scorned by the traditionalists as WIMP interfaces whereas the command-line devotees are seen as inflexible, or even stubborn (Shneiderman, 1998, 207). But different people have different cognitive styles, and it is understandable that individual preferences may vary. Preferences will vary by user and by tasks. Consequently, there will be multiple interface styles. The conflict between text and graphics becomes most heated when the issue of icons is raised. In the computing environment an icon is an image, a picture, a symbol that represents a concept (Rogers, 1989). Icon design is an interesting research area, especially now that computer hardware improves and designers become more creative. When a clever designer can create a visual representation of the world of actions a user wishes to perform with the computer, the user's tasks can be greatly simplified because familiar objects can be manipulated directly. Examples of such systems include the Windows operating system which is based on the desktop metaphor, computer-assisted design tools, airtraffic-control systems, and video games. By pointing at visual representations of objects and actions, users can carry out tasks rapidly and can observe the results immediately (Shneiderman, 1998, 71).

3.2. Studies of diagrams.

Diagram studies focus on diagrammatic representations and on reasoning, problem solving and thinking with them. Diagrams are abstract graphical representations that share their abstractness with words, and their exploitation of space with other pictorial representations. Winn (1987) situates diagrams in the center of a continuum with realistic pictures at one end and written and spoken language at the other. This is a convenient continuum on which a variety of representations of information can be arranged. Reasons usually put forward to justify this continuum are that realistic pictures resemble what they stand for, while words are arbitrary and conventional. "From words, [diagrams] inherit the attribute of abstractness, but like pictures they exploit spatial layout in a meaningful way" (Winn, 1987, 152). This means that neither linguistic nor perceptual theories are sufficient to explain their characteristics and applications (Blackwell, 2001). The issues are not about how sensory information in the visual modality is processed to form percepts; that is the subject of theories of image processing and perception. The issues are neither about language, about how words and texts are used as tools of communication. Rather the issues relate to representations of diagrams and mental images and the functions played by them in reasoning, problem solving and thinking (Chandrasekaran, Glasgow & Narayanan, 1995).

Diagrams are not a well-defined unitary class. There are many different types of diagrams: weather maps, flow charts, cycle diagrams, geometric and Venn diagrams all belong to the class, but differ as to the kind of information they represent, the notational system, and the way the notational system is linked to this information. Probably there are more varieties in diagrammatic representations than there are in linguistic ones.

Humans have been curious since ancient times about how they draw inferences that extend their knowledge beyond what they already know, and about how they get new knowledge. Aristotelean logic and Euclidean geometry were major contributions to this question, dealing, respectively, with reasoning in natural or formal language and reasoning with diagrams or other pictorial sources. Linguistic and algebraic representations and diagrammatic representations were commonly used for some time until the invention of analytic geometry by Descartes and symbolic mathematics by Dedekind. These inventions brought about a change in the use of diagrams. As tools for carrying out proofs, even in geometry, they became increasingly unacceptable. Natural language too was not saved. It was judged insufficient for rigorous reasoning in the work of Frege, and of Whitehead and Russell. Rigorous reasoning came to mean reasoning in the formal languages of logic and mathematics (Simon, 1995). The real importance of diagrams lies in the aid they give us in reasoning and reaching conclusions. As shown convincingly by Larkin & Simon (1987, 1995), diagrams can be superior to verbal descriptions for solving problems, because of the following reasons (see Larkin & Simon, 1995, 107):

- Diagrams can group together all information that is used together, thus avoiding large amounts of search for the elements needed to make a problem-solving inference.
- Diagrams typically use location to group information about a single element, avoiding the need to match symbolic labels.
- Diagrams automatically support a large number of perceptual inferences, which are extremely easy for humans.

Verbal and diagrammatic representations may be informationally equivalent without being computationally equivalent: diagrams, when well designed, put less cognitive load on the user than text.

As Simon (1995) points out, research in diagrammatic reasoning has one fundamental goal, viz. understanding the phenomena and processes related to diagrams and reasoning with them. Beyond this goal, he mentions two other goals:

- get a better understanding of ourselves and the ways we are thinking in order to be able to use visual displays effectively in communication, teaching and thinking.
- provide an essential scientific base for constructing representations of diagrammatic information that can be stored and processed by computers, enabling computers to achieve some of the computational efficiencies in their thinking that diagrams now provide to humans.

Many people are still sceptical regarding the status of diagrams, even if diagrams are becoming more and more common in everyday human experience and their advantages have been established in teaching or creative exploration. According to Blackwell (2001), much of this scepticism may be attributable to the fact that diagrams themselves are usually regarded as a tool, rather than an interesting object of study in their own right. It is true, diagrams are not always beneficial; many are badly designed or badly used. But this is also a reason to study diagrams – as a theoretical contribution to the practical questions faced by designers of information in general and of designers of human-computer interfaces in particular.

Philosphers, cognitive psychologists, design theorists, logicians, artificial intelligence researchers are among those studying diagrams and diagrammatic reasoning. Research has been sporadic during the eighties, but since the 1992 AAAI Spring Symposium on Reasoning with Diagrammatic Representations research interest in this area has revived.

3.3. Studies of computer-supported visualizations.

As pointed out by Shneiderman (1998, 522), the success of direct-manipulation interfaces is indicative of the power of using computers in a more visual or graphic manner. Like pictures on paper, which can sometimes be worth ten thousand words, for some tasks, a visual presentation on a computer screen, such as a map or a photograph, is easier to use or comprehend than is a textual description or a spoken report. The bandwidth of information presentation is potentially higher in the visual domain than it is for media reaching any of the other senses.

As we can read in the preface of Card, Mackinlay & Shneiderman (1999), the 15-year foundational period of computer-supported visualization is now ending. Computer power has increased dramatically, and PCs are coming to support real-time, dynamic, interactive visual representations. In the next period, information visualization will get a clearer position in teaching and research. At present, advances in information visualization are scattered throughout the literature. *Readings in Information Visualization. Using Vision to Think*, written and edited by Stuart Card, Jock Mackinlay (at Xerox PARC), and Ben Shneiderman (at the university of Maryland), makes accessible a selection of classic papers and a sampling of current work in information visualization (see Card, Mackinlay & Shneiderman, 1999).

Visual aids for thinking have an ancient history. The evolution of computers is making possible a visual medium with improved rendering, real-time interactivity and lower cost. This medium further allows to make visible large amounts of data that are stored and manipulated by the computer itself. It also allows diagrams to move, react, or initiate. The power of this new medium was first applied to science, resulting in so-called scientific visualizations. Now it is applied more generally to business, to scholarship, and to education. This broader application is called information visualization.

Card, Mackinlay and Shneiderman (1999) propose the following definitions for different forms of computer-supported visualization:

- Visualization: the use of computer-supported, interactive, visual representations of data to amplify cognition

- Scientific visualization: the use of computer-based, interactive visual representations of scientific data, typically physically based, to amplify cognition
- Information visualization: the use of computer-based, interactive visual representations of abstract, nonphysically based data to amplify cognition

It is clear that according to Card et al. the purpose of visualization is to amplify cognition, that is, to acquire more and new knowledge. “The purpose of visualization is insight, not pictures” (Card et al., 1999, 6). Discovery, decision making and explanation are the main goals of this insight. Notice that Card et al. distinguish scientific and information visualization. In scientific visualization the computer is used to render visible some properties of physical data – the human body, the human brains, the world’s oceans, the moon, etc.. The information visualized in scientific visualization is inherently geometrical. In contrast, information rendered visible in information visualization does not have any obvious spatial mapping. There is a great deal of such abstract information in the contemporary world – financial data, business information, collections of documents, research data of all kinds. Two fundamental problems arise: how to render visible properties of the objects of interest, and how to map nonspatial abstractions into effective visual form.

Visualizations in the sense of Card et al. can be thought of as adjustable mappings from data to visual form to the human perceiver. Card et al. (1999, 17) give a clear reference model in the form of a diagram of these mappings. The core of this model is the mapping of a data table to a visual structure. The model allows to organize research around its different parts. Some studies in information visualization focus on how space is used in visualization. There are several possibilities here, ranging from 1D, 2D, 3D to multiple dimensions, trees, and networks. Other studies deal with interaction and focus on the dynamic queries technique, which can be seen as the visual alternative to SQL for querying databases. For simple queries, this technique is faster to use than SQL and requires little training. To handle more complex queries, more elaborate controls such as sliders and magic lenses are required. Another topic in interaction concerns the relation between the information a user would like to focus on and its context. When dealing with large structures, people leave out detail systematically. This idea has been implemented in the “fisheye view”. Still another interesting topic in information visualization is the visualization of text documents and document collections. Emerging technology trends such as the World Wide Web and Digital Libraries imply that document visualization will be an important information visualization application for the future. Document visualizations turn on the success of mapping between raw data and data tables rather than on techniques for transforming data as expressed in data tables into interactive visual forms. In this research subarea, methods are investigated for mapping single documents and document collections in 1D, 2D, 3D, and time-oriented visual structures. The purpose of information visualization, as pointed out above, is to use perception for amplifying cognition, especially for knowledge crystallization, where a person gathers information for some purpose, makes sense of it, and then packages it into some form for communication or action. Information visualization can be used as part of user interfaces for all of these activities. This subject is also investigated in information visualization. Finally, information visualization is considered theoretically and in terms of its potential applications. It seems likely that techniques from information visualization will be important in creating interfaces to large-scale databases and document collections, most notably applications, services, and electronic commerce for the Internet and its successors.

Dix, Finlay, Abowd & Beale (2004) relate information visualization to ubiquitous computing, augmented reality and virtual reality, since all these areas challenge one of the earliest assumptions of Human-Computer Interaction (HCI), viz. the assumption concerning the form factor of the computing device. The traditional computer is a glass box – all you can do is press buttons and see the effect. Ubiquitous computing and augmented reality systems break this glass box by linking the real world with the electronic worlds. Computing devices become so commonplace that we do not distinguish them from the 'normal' physical environment. The defining characteristics of ubiquitous computing is the attempt to break away from the traditional desktop interaction paradigm and move computational power into the environment that surrounds the user. Virtual reality (VR) refers to the computer-generated simulation of a world, or a subset of it, in which the user is immersed. It represents the state of the art in multimedia systems, but concentrates on the visual senses. VR allows the user to experience situations that are too dangerous or expensive to enter 'in the flesh'. Users may explore the real world at a different scale and with hidden features made visisble. The term VR conjures up an image of a user weighed down with a helmet or goggles, grasping, apparently blindly, into empty space. This is fully immersive VR. However, it is only part of the spectrum of VR, which also includes desktop VR, command and control situations, and augmented reality, where virtuality and reality meet. VR and 3D displays can be used to visualize scientific data and other complex information. Whether 3D representations are used or not, animation techniques, especially when under interactive user control, can give a sense of engagement with data, and encourage discovery and pattern formation.

Biocca & Levy (1995) have edited a book on communication in the age of virtual reality. They point out that VR is a tantalizing communication medium, as it offers us the opportunity to surf through information-rich cyberspace and to manipulate for better or worse virtual environments, ranging from the smallest chemical compound to the entire surface of a distant planet. They believe that VR may become too important and too powerful a medium to permit ignorance and passivity toward what may become the next dominant medium (Biocca & Levy, 1995, vii). In their book they introduce VR as a communication medium, explore the emerging issues in the creation of VR communication applications and experiences, and examine social and cultural issues impelled by the age of VR.

3.4. Concluding remarks.

All these visual objects - icons, diagrams, computer visualizations - are studied from various perspectives, and by different disciplines. These studies together yield a large amount of literature that is very disparate. Some observations can however be made. There are very few theoretical approaches, empirical studies abound, and a variety of visualization applications are developed and/or tested, implying each different users, different tasks and different environments. Advances in graphical technology have made it possible to interact with information in innovative ways, most notably by exploring multimedia environments and by manipulating 3D virtual worlds.

It is generally assumed that these modern kinds of interactivity have many benefits, and that they are better than the good old fashioned representations. Commonly held assumptions and fallacies are mentioned by Scaife & Rogers (1996, 186). They include ideas that:

- static pictures and diagrams are better than sentential representations
- 3D representations are better than 2D ones
- solid modelling is better than wire-frame modelling
- colour is better than black and white images
- animated diagrams are more effective than static images
- interactive graphics are better than non-interactive graphics
- virtual reality is better than animation

Scaife and Rogers (1996) point out, however, that little is known about the cognitive value of any visualization, be they good old fashioned (e.g. diagrams) or more advanced (e.g. animations, multimedia, virtual reality). There is no clear evidence whatsoever of the claimed benefits of advanced graphical technologies. Given this incertainty, how can researchers and designers decide to take on board the immense cost and effort to develop a VR application, for example, when a static diagram might be more effective for the task in hand? What is needed, in their view, is a more systematic approach for evaluating the merits of different kinds of visualizations, one that is theoretically driven. Without such an approach there is no principled way of either making sense of the vast empirical literature on the benefits of visual representations or of making predictions about the value of new forms, such as animation and VR.

Scaife and Rogers (1996) propose a new agenda for visualization research, where the relationship between external representations and internal mental ones is particularly stressed. They outline some of the central properties of this relationship that are necessary for the processing of visual representations. This, in turn, can inform the selection and design of both traditional and advanced forms of visualizations. Cheng, Lowe & Scaife (2001) point out too that current orthodoxies about the intrinsic benefits of visualization of information need to be examined far more critically.

4. Different kinds of visualizations: examples and characteristics.

Figures 1 – 6 below contain various visualizations. Figure 1 shows icons as they occur in graphical user interfaces. Figure 2, 3 and 4 contain different diagrams: a diagram representing a physics problem, viz. collision; an illustration of the carbon cycle through the environment as it could occur in a biology school textbook; a weather map for the United States on the basis of which meteorologists are able to forecast the weather. Figure 5 is an example of a scientific visualization, and figure 6 of an information visualization in the sense of Card, Mackinlay & Shneiderman (1999).

Figure 1

Figure 1 contains icons which we take for granted as part of graphical user interfaces. The Apple Macintosh popularized “icons” as the slightly misnamed term for these visual signs (Marcus, 2003). Above we recognize the folder icon, a variation on the trash icon, a variation on the icon for the specific application ‘paint’, and the close symbol. Today, icons and symbols are pervasive throughout most platforms. For better or for worse, most computer users must master as novices an astonishing number of signs. Familant & Detweiler (1993) point out that objects currently called icons in a computer environment, are far more diverse, and their relationships to the objects and events they are intended to represent far more complicated, than one might suppose from reading the popular press or even research publications. They show the complications involved by analyzing icons from a semiotic point of view. For instance, the trash sign is an example of indirect reference involving a graphic icon that represents a trash can in the real world, but that refers to a program that removes files. Their icon taxonomy should be seen as a beginning effort to clarify important distinctions that may be useful in addressing issues related to how easy or hard icons are to detect, discriminate, recognize, interpret, learn, and remember.

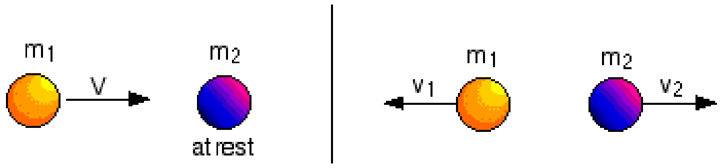


Figure 2

Figure 2 contains pictures of a physics problem. They represent the situations before and after a single collision of two bodies. These are the pictures that are generally used for solving problems concerning the calculation of the value of some property of a body, e.g. v, v1, v2 (velocities of the bodies) or m1, m2 (masses of the bodies). Larkin & Simon (1987) have shown convincingly that, for this kind of problem solving, pictures are often more efficacious than words, even when they are informationally equivalent. Pictures just put less cognitive load on the user than text.

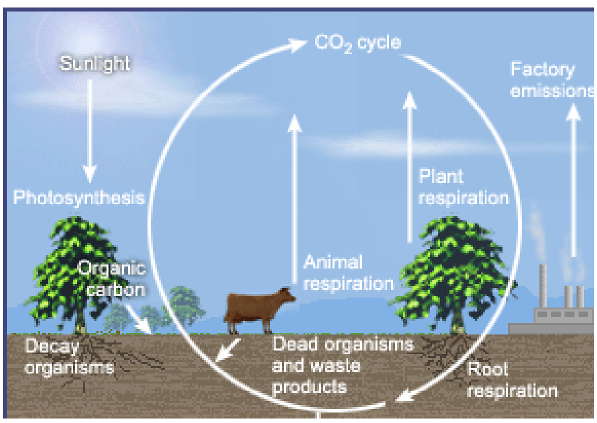


Figure 3

Figure 3 contains a visual representation of the carbon cycle. This is the kind of picture you might find in a biology school textbook. Notice that it involves icons, text and a set of conventional notations such as arrows, lines or boxes. The diagram is not purely "diagrammatic", as it contains text. But even the text parts use spatial properties to encode information. Their position in the diagram conveys meaning as well. The icons stand for the location of CO_2 in different entities and the arrows represent processes transferring CO_2 from one entity to the other. Notice that this kind of picture belongs to the class of canonical cyclical diagrams that make relevant aspects of processes and events more salient when distributed over time and space.

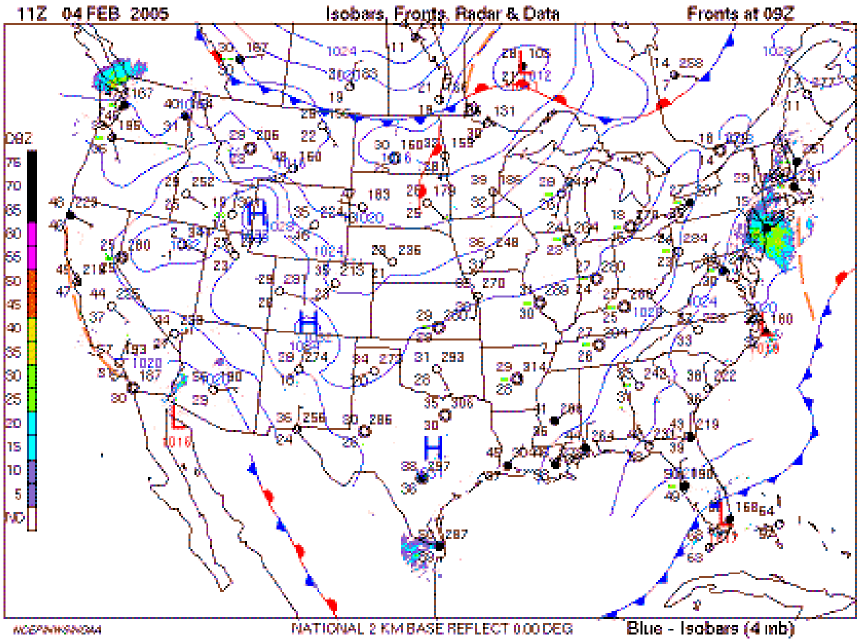


Figure 4

The visualization in Figure 4 is a weather map of data collected by The American Meteorological Society. It shows isobars, fronts and some other data. Specific meteorological symbols are used to represent these data. It is doubtful whether we, as laymen, can read this map, let alone forecast the weather or predict how the area of pressure will change over time. We only understand this map at a superficial level. Lowe (1993) has shown in an experiment involving a weather map for Australia that beginning students of meteorology (novices) distinguish between sets of markings which professional meterologists (experts) configure as a single grouping. The perceptual information that a diagram provides for the user by way of visiospatial cues must be modulated by knowledge about the individual and collective meanings of the graphic elements. It seems that a major factor determining a viewer's capacity to make effective use of a diagram is how much that person already knows about the sort of subject depicted in the diagram and the specific method of depiction.

Figure 5

Figure 5 is an example of a scientific visualization in the sense of Card, Mackinlay and Shneiderman (1999). It is a volume rendering image that illustrates the cerebral atrophy in the advanced Alzheimer's disease brains. The widening of the cortical sulci is indicative of the process of nevronal degeneration and represents anatomically the cognitive impairment associated with the Alzheimer disease.

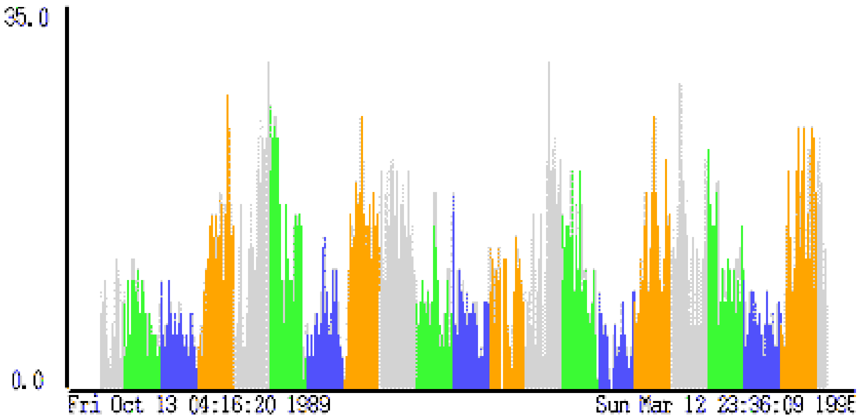


Figure 6

Figure 6 shows the visual representation of data gathered from medical records, viz. the date and number of visits per day for a respiratory disease. The data are visualized in such a way that it might reveal seasonal patterns of the disease. Date is mapped to the X-axis, and number of visits is mapped to the Y-axis. Color is used to represent the season of the year. Green is used for the spring, blue for the summer, orange for the fall and gray for the winter.

When we compare the visual representations given above, we observe that they differ in several respects:

- the phenomena that are depicted: are these objects in the real world, are these physical phenomena that are spatial in nature, or are these more abstract phenomena?
- the application domain: to what domain does the problem visualized belong? For the above visualizations the application areas are human-computer interaction, physics, biology, meteorology, and medecine. Notice that most of these visualizations are currently used in science, and far less in the humanities, which do not have any visual tradition.
- the graphics used, i.e. the particular notational system adopted.
- the extent of abstraction: to what extent does the picture resemble reality?
- the target group: is the visual representation designed for a layman or an expert?
- the environment in which the visualization is used: is it a professional working, communicational, instructional, a problem-solving or a research environment?
- the tasks that are supposed to be accomplished by means of the visualization: should information be recognized, recalled, or learned? Which particular problem should be solved? Should it amplify cognition or just communicate an idea?

It seems then that all these factors play a role in the design of effective visual representation.

5. Good and bad pictures

Although research is done in various fields and from different perspectives, and different factors influence the success of visualizations, it is common knowledge that there are good and bad pictures. Visualizations can lead to great insight but also to the lack of it. Bertin and Tufte have made this point very clearly, witness the points they make. These points can be globally summarized by the following citations:

- Bertin, 1967

  "Combien de dessins admirablement exécutés et richement reproduits […] ne communiquent qu'une information dérisoire et inutile? Que de papier et de couleurs perdus. Tandis que des croquis malhabiles mais correctement construits deviennent les meilleurs instruments de la découverte et de la pédagogie."
- Tufte, 1983

  Graphical excellence

  "consists of complex ideas communicated with clarity, precision, and efficiency."

  "is that which gives the viewer the greatest number of ideas in the shortest time with the least ink in the smallest space."

  "requires telling the truth about the data."

Bertin has often been considered the founder of information visualizations. In his book entitled *Semiologie du système graphique*, he tries to answer the question 'à quoi peut servir un dessin?' ('what purpose can a picture serve?') (Bertin, 1967). The consequences of the answer to this question are shaped into a practical method of use and editing graphical representations. The method he proposes is applied mainly to geographic and demographic data concerning France and her inhabitants, and consequently to graphs and maps, which are evident graphical representations for these kinds of information. Tufte has written two classic books on information display: *The visual display of quantitative information* (Tufte, 1983) and *Envisioning information* (Tufte, 1990). In these books he gives comments on existing complex visualizations of a variety of problems and propagates his ideas on data graphics that emphasize maximizing the density of useful information. His books are interspersed with illustrations which represent the best and the worst examples of visualizations. Napoleon's catastrophic foray into Russia in the 1780's depicted by Charles Joseph Minard is presented as 'perhaps the best chart in history'. On the other hand, Tufte also gives examples of what he calls chartjunk. Chartjunk consists of decorative elements that provide no data and cause confusion. Both Bertin and Tufte give important principles and valuable design guidelines in order to achieve 'graphic excellence'. Their work raises however a number of questions that are not clearly answered. Even after reading Bertin and Tufte, it remains for instance unclear when a picture becomes a tool of discovery and when one of pedagogy, how you communicate with clarity, precision, and efficiency via a picture, or when you tell the truth about the data and when not. Actually these are the topics discussed and investigated in more theory-driven research on visualization. As we have seen above, research is done in different fields, from different perspectives, and by the use of different methods. Research ranges from experiments testing effectiveness of realistic pictures supporting prose comprehension in secondary school textbooks to cognitive theoretic views on the use of diagrams in learning environments. Next to these specific studies, there are studies that attempt to capture more general characteristics of visual representations. In this respect it is good to take a closer and more theoretical look at the transfer of information by visualizations in general, which we will call visual communication.

6. Visual communication and the link between data and visual form.

Visual communication can be interpreted as communication by the use of pictures. Communication should be considered here in a very general sense, implying different kinds of communication, ranging form merely illustration of an idea to computational art. Intuitively, it can be taken to involve three parts (Wang, 1995):

1. a graphical domain, i.e. the picture
2. an application domain, i.e. the subject matter or problem depicted
3. a link that associates the graphical domain with the application domain

Figure 7 visualizes the three parts:

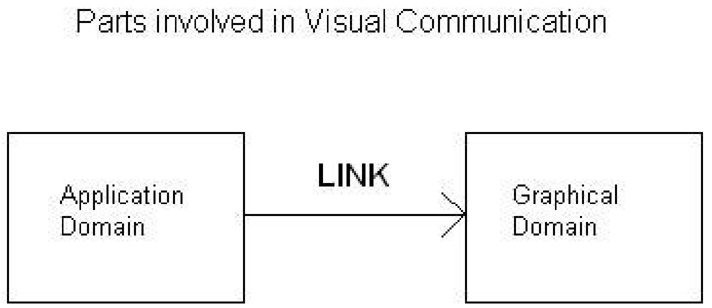


Figure 7

The link plays an important role. Without it, pictures only carry spatial information. The link transfers the spatial information provided by the graphical domain into information about the application domain so that the pictures can be helpful in transferring information. Establishing this link is not trivial. It must satisfy certain conditions. Wang (1995) for instance suggests that it should be natural and not misleading. First, a natural link is one that associates pictures with the subjects matter in the application domain in a way which users view as natural. As an example, Wang puts forward set membership. This concept is more naturally depicted by spatial inclusion between circles (Figure 8), where circles represent sets and circle inclusion represents set membership, than by lines and t-joint lines (Figure 9), where lines represent sets and t-joint lines represent elements. This example illustrates the popularity of Venn diagrams as visual representations of set theory.

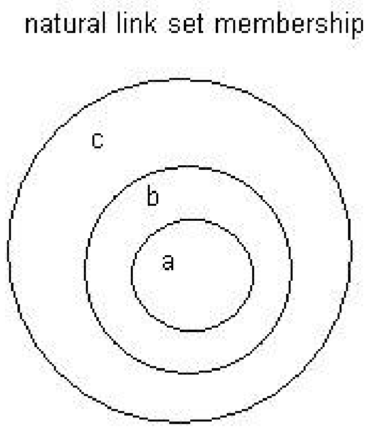


Figure 8

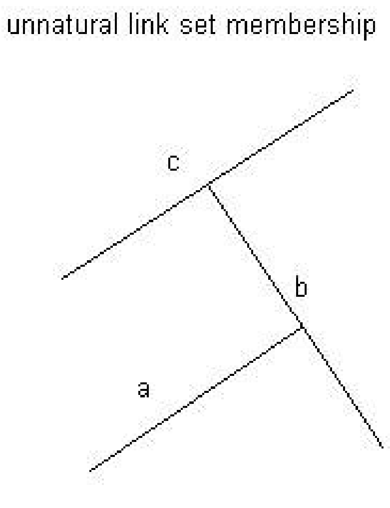


Figure 9

Second, a link is misleading when the picture allows to make correct pictorial inferences that do not correspond however with correct inferences in the application domain.

Imagine for instance that spatial inclusion between circles is used to represent the father-son relation (Figure 10).

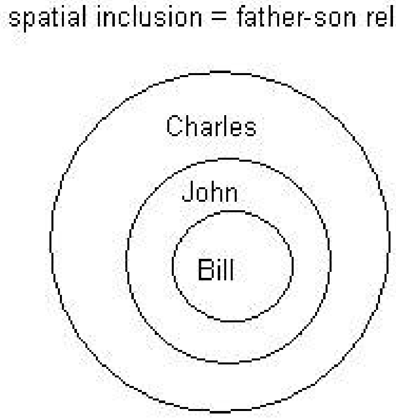


Figure 10

The fact that circle Bill is included in the circle John means that Bill is John's son. That the circle John is included in the circle Charles means that Charles is John's father. Now the picture also shows that that the cirle Charles contains the circle Bill. Consequently, taking this inclusion to mean the father-son relation, allows us to conclude that Charles is Bill's father. But this is clearly not what we want. This inference is not true of to the information in the application domain. In this case the link connecting the graphical domain with the application domain is misleading.

Card, Mackinlay & Shneiderman (1999) also try to model the visual communication process. They focus on abstract information, containing large amounts of in essence numerical data. They are particularly interested into the various transformations and mappings between the components involved in this process. They distinguish raw data, data tables, visual structures and views. In their model (Card, Mackinlay & Shneiderman, 1999, 17), just as in the model of Figure 7, the crucial step is the one from data to visual form. Structured data is mapped onto spatial layout. As they point out, this can be done in multiple ways, but should satisfy the conditions of expressiveness and effectiveness. They call a mapping expressive if all and only the data in the data tables are also represented in the visual structure. Good mappings are thus not a trivial matter, since it is quite easy for unwanted data to appear in the visual structure. They introduce effectiveness as a relative notion. They claim that some mappings are more effective than others, when they are interpreted faster, convey more distinctions, or lead to fewer errors.

Both Wang (1995) and Card, Mackinlay & Shneiderman (1999) emphasize the crucial role played by the link or mapping between the application domain and the graphical domain. Summarizing, in their view, this link should satisfy certain conditions: it should be natural, expressive, effective, and not misleading. Could one say that a good mapping produces good pictures, and a bad one bad pictures? One is inclined to say so. Chartjunk contains graphics that is only there for decoration, and thus does not correspond to data in the application domain, violating thereby expressiveness. Moreover there is a risk that the decorative graphical elements are assigned unwanted meanings, which transforms the picture into a misleading one.

It seems then that good pictures exploit spatial layout and graphics in such a way that they facilitate successful communication. In contrast bad pictures contain elements that interfere with it. As a consequence, visualizations can have facilitating and misleading effects.

7. Facilitating and misleading effects.

7.1. An example: the monk puzzle..

To show the advantages that pictures can have, I refer to the monk puzzle and its solution discussed by Winn (1987) (see also Bosveld, 2004, this reader). Winn (1987, 153) formulates the puzzle as follows:

"A monk went to the temple at the top of a holy mountain to meditate and pray. He started out early one morning along the path that led up to the temple. Because he was an old man, and the way was steep and arduous, he frequently slowed his pace, and even sat and rested a while beside the path. Toward evening, he came to the temple at the top.

After several days of meditation and prayer, it was time for him to leave. Early in the morning, he set off back down the path. Again, he frequently changed his pace and rested by the way. He arrived back at the bottom in the evening.

Show that there is one single point on the path up the mountain where the monk will be at precisely the same time both when he goes up and when he comes down."

To solve this puzzle, people try one of two strategies:

- a mathematical strategy by use of either an algebraic or arithmetic method. Neither method will provide the solution, because pace, distance, time of arrival are all unknown data.
- a graphical strategy by representing the puzzle in graphic form. The successful method will consist in plotting distance along the path against time in a line graph. If the two journeys are superimposed on the same graph, the two lines have to cross (see Figure 11). Where they cross is the unique point that is the solution to the puzzel.

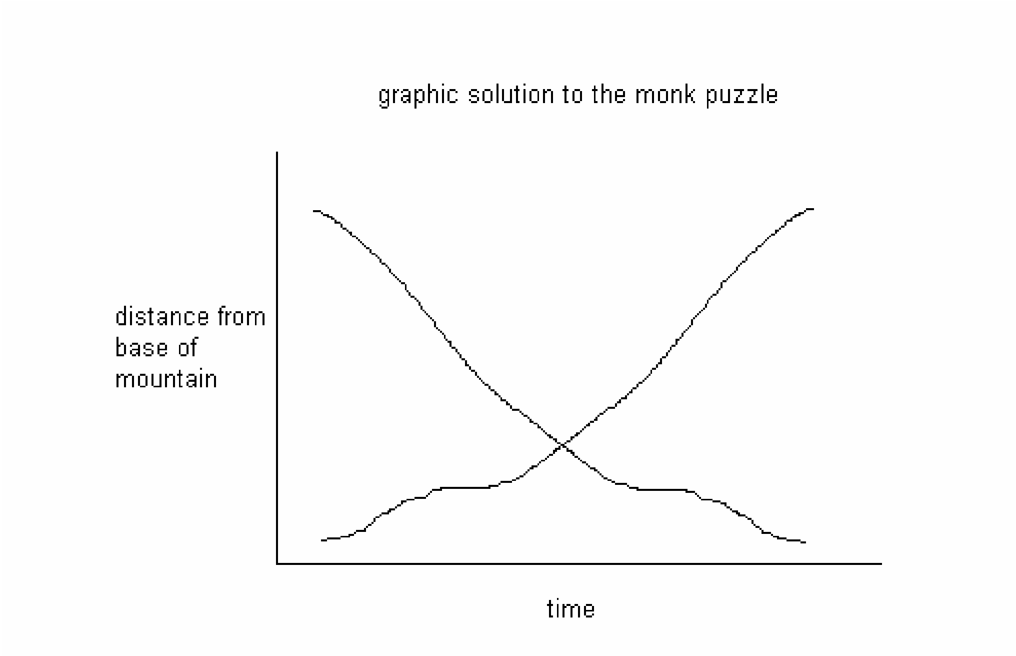


Figure 11

7.2. Facilitating effects.

The transformation of the textual representation of the puzzle into a graph is sufficient to make the solution transparent. This is due to the advantages offered by visual representations. In the literature, several approaches to looking at these advantages are put forward and discussed. Globally one can distinguish the following views:

- the visual ability view: visual representations call on visual abilities and skills humans have next to verbal abilities and skills.
- the physiological view: the human eye is very well suited for processing graphics. Humans can for instance recognize geometric forms and patterns in a picture very easily.
- the cognitive view: pictures put less cognitive load on humans than text, because part of the textual information is directly captured by external spatial properties. Rogers & Scaife (1999) identify at least the following three kinds of 'computational offloading': re-representation (different external representations, that have the same abstract structure, make problem-solving easier or more difficult); graphical constraining (elements in a visual representaion are able to limit the range of inferences that can be made about the represented concept); temporal and spatial constraining (different representations can make relevant aspects of processes and events more salient when distributed over time and space).

The spatial nature of visual representations allows forms of communication that are precluded from purely textual representations. Visualizations can be effective in instruction and research because they allow learners and researchers to use other mental abilities than those needed to understand text. Visual representations have to be understood in terms of how they use space, properties of graphical elements and patterns of these elements. Certain strengths of humans, such as the ability to recognize geometric shapes and patterns as well as 'right-brain' processing can thus be exploited (Winn, 1987; Card, Mackinlay & Shneiderman, 1999). Visual representations also draw upon more cognitive abilities, such as mental model construction (Winn, 1987; Brna, Cox, Good, 2001; Cuevas, Fiore, Oser, 2002), simultaneous processing (scanning quickly in order to discover patterns), and organization of content (Winn, 1987). Levin, Anglin & Carney (1987, 60-61) suggest that different picture types have a positive effect on users' memory. This was noted earlier and can be gleaned from the theoretical literature on basic cognitive processes. Materials presented by pictures, whether representational, organizational, or interpretational, are generally remembered better than their verbal counterparts. The fact is that representational pictures add concreteness to the subject matter, and memory for concrete pictorial materials is superior to memory for their less concrete verbal counterparts. Organizational pictures add coherence to the subject matter, and memory for thematically organized materials exceeds memory for unorganized materials. Interpretational pictures add comprehensibility to the subject matter, and materials that are initially well understood are remembered better than those that are poorly understood.

7.3. Misleading effects.

So visual representations can have beneficial effects, but they can also be misleading. The misleading effects and misuse of visualizations have been pointed out most clearly in the area of scientific visualizations. Bailey's seminal work entitled "Twelve ways to fool the masses when giving performance results on parallel computers" points out the attraction and reliability of pretty colorful pictures, and the possibility to exploit these features of pictures when one wants to avoid illumination of the underlying data (Bailey, 1991). As stated by Bailey himself, "[…]. Audiences love razzle-dazzle color graphics, and this material often helps deflect attention from the substantive technical issues." Bailey gives no guidance in the means and methods to lead the audience astray, but Globus and Raible (1992) do. Below are listed their recommended 13 ways to say nothing with scientific visualization:

1. Never include a color legend.
2. Avoid annotation.
3. Never mention error characteristics.
4. When in doubt, smooth.
5. Avoid providing performance data.
6. Quietly use stop-frame video techniques.
7. Never learn anything about the data or scientific discipline.
8. Never compare your results with other visualization techniques.
9. Avoid visualization systems.
10. Never cite references for the data.
11. Claim generality but show results from a single data set.
12. Use viewing angle to hide blemishes.
13. 'This is easily extended to 3-D'.

The authors of these articles present the issue in a humorous way, but the notes, although amusing, reflect their concerns: the real facts can be hidden by good looking pictures, and scientists who want to present visually their data may unintentionally mislead their audience, and maybe even themselves, by inadvertently employing one of the techniques mentioned above.

Even at a less sensational level, certain tendencies in visual representations of data give rise to concern. Siegrist (1996) for instance draws attention to pie charts and bar charts with a 3-D look, which are easily produced by commercial graphics software. The performance of subjects on these charts with and without 3D was evaluated in an experiment. Subjects were asked to make relative magnitude estimates for different graphs. For pie charts, better performance was observed for 2D than for 3D charts. For the bar charts, performance was dependent on the position, height and dimension of the bars. 3D charts had however the disadvantage that subjects needed more time to evaluate this type of graph.

That one should take care when using visualizations is perhaps not immediately obvious, because communication can be facilitated by them. Large amounts of data can be visualized in one picture and the user gets a lot of information in one single view. In order to show the more subtle dangers inherent to certain visual representations, let's have a look at two examples:

- a choropleth map created by the U.S. Census Bureau on the American FactFinder web site (http://factfinder.census.gov/) and based on age per state data from Census 2000 (with legend represented in Figure 12)
- a cluster map created by Kleiweg (http://www.let.rug.nl/~kleiweg/) and based on the clustering of dialect data from West-Germany. Figure 13 shows the cluster map, in which eight different dialects, as distinguished in the dendrogram of Figure 14, are mapped onto the geographic map of West-Germany.

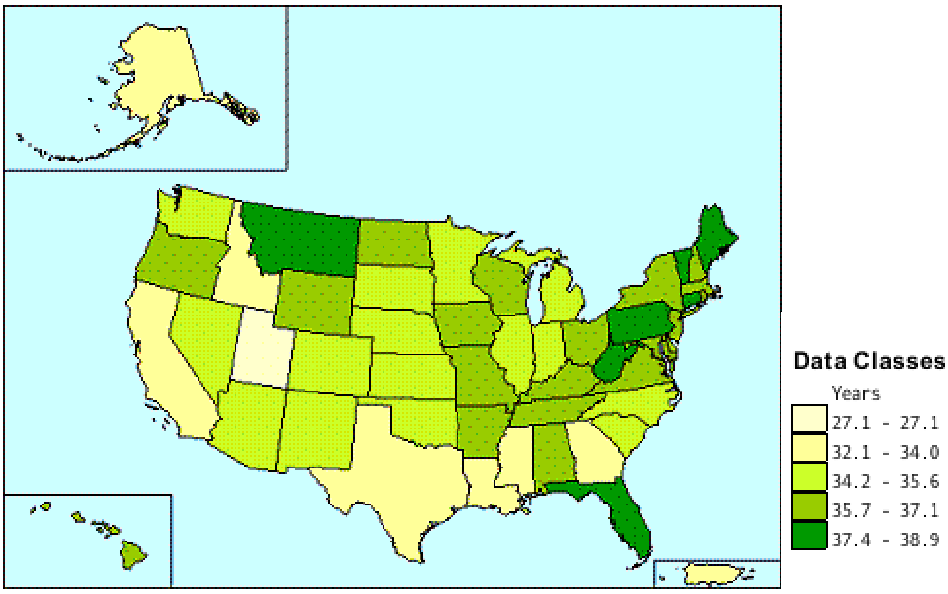
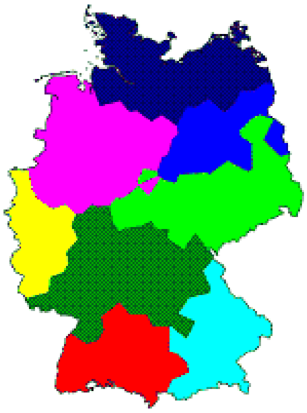


Figure 12



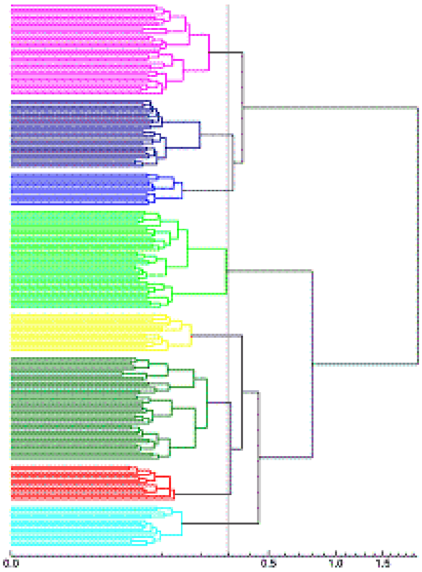


Figure 13

Figure 14

The choropleth map is based on predefined areal units, in the above case, states. It is based on state level data and shows the median age for 50 states and Puerto Rico, as reported in the Census 2000 data. The power of the map is that it might show spatial patterns. But here we must be careful. The map does not tell us exact values for each state but rather it aggregates the states into categories. It employs breaks to aggregate the data into five categories. It is not clear where these breaks are based on. The map is but one view of median age across the U.S. and clearly we cannot extract all information in the census data from this map only. Different maps of the same variable will give different perspectives of the data. How will the map look like when we use other colors (the map in Figure 12 is represented on the web in colors from a green color sequence), or when we break the data into more than five or less than five categories, or when we use other intervals to form the categories? Another way to aggregate data for choropleth maps is to divide the data into quantiles (i.e. putting an equal number of states into each category). All these transformations will probably give maps that are quite different in appearance, while they are based on the same data. Another problem inherent to choropleth maps is that not all areas get equal representation, since geographic areas can vary greatly in size. As a consequence, large areas might get more attention than small ones. Similar remarks can be made with respect to the cluster map in Figure 13. In the dendrogram which represents the progressive clustering process based on dialect difference measures the ruler is set at a position which allows to distinguish eight dialects. Moving the ruler slightly to the right will decrease this number, moving it to the left will increase it. As a result the map will look differently. Another problem with the cluster map is that the arbitrarily chosen different colors used to mark the different dialect areas do not tell us anything about the extent to which the dialects are distinct from each other. For instance, can someone from the south talk with someone from the north, while northern neighbours cannot understand each other? Put otherwise, is there a gradual change in dialect differences? In order to show that there is a clear dialect border between the north and the south, Kleiweg has invented the cluster composite map (see Figure 15), which marks more or less clear borders (see Kleiweg, Nerbonne, Bosveld, 2004).

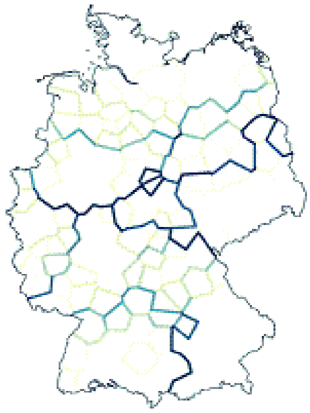


Figure 15

Maps have been a central tool to store and represent information. A map is a convenient graphic tool for classifying, representing and communicating spatial relations. Its misleading effects and misuses reside however in that no map is an objective, neutral artefact. Dodge & Kitchin (2000) point out that many subjective decisions enter its process of creation. Subjective decisions are made about what to include, how the map will look like, and what the map is seeking to communicate. They claim that "maps are never merely descriptive, they are heuristic devices which seek to communicate particular messages" (Dodge & Kitchin, 2000, 2). Subjectivity of maps was has been noted by others as well (MacEachren, 1995; Monmonier, 1995, 1996; Harpold, 1999). A critical reading of maps is important. A user can easily get misinformed when he/she does not expose its ideological messages (called the 'second text' by Dodge & Kitchin), or does not recognize its poverty in terms of cartographic design. Especially maps of the Net turn out to display, with varying degrees of subtlety, the "ideological agendas of cyberboosterism and techno-utopianism of their creators" (Dodge & Kitchin, 2000, 2).

7.4. Concluding remarks.

Correct and effective information extraction and thinking with visual representations thus turns out to be a very complex matter. Research in this field is imperative. As long as there are no uniform theories, principles and guidelines, and maybe there will never be, visual representations need to be actively and reflectively considered by both their creators and their users. The least one can do is to maximize their facilitative properties and minimize their misleading ones.

8. General inferential and expressive capacities of visualizations.

Given the facilitative and misleading effects visual representations can have, it is important to discover concepts that capture the crucial properties of a variety of visualizations. Then we might get even more insight into their functioning. Thanks to recent as well as old theoretical studies, Shimojima (2004) has found four of these concepts. They are free ride properties, auto-consistency, specificity, and meaning derivation properties.

8.1. Free ride properties.

These properties refer to the capacity of visual representations to express visually a certain set of information in such a way that it always results in the expression of another additional set of information that can be deduced from the original set of information. The additional consequential information expressed are called the free rides. This concept relates to the various explanations that have been suggested in the literature of the automaticity of inference provided by visual representations. A visual system with a free-ride property supports deductive inference on an external display, not in the head. That is why one talks here about distributed cognition or external cognition. It should be noted that free rides only guarantee the expression of consequential information, not its recognition by the user. The fact is that there are ‘cheap rides’, easily discovered, but also more expensive ones. For instance, some diagrams, such as meteorological weather maps, require expert knowledge or practice in diagram construction to facilitate the recognition of useful consequences.

8.2. Auto-consistency.

Auto-consistency refers to the fact that certain inconsistencies cannot be expressed by visualizations. This notion explains why consistency inferences are so easy to make with the help of graphical systems.

8.3. Specificity.

Specificity implies the incapacity of a visual system to express certain sets of information without expressing at the same time another set of information which is however not implied by the original set of information to be depicted. It explains the difficulty to express “abstract” information in certain graphical systems. A picture can thus carry too much information or indicate a degree of precision which may be inappropriate.

8.4. Meaning derivation properties.

Meaning derivation properties are related to the capacity of a visual system to express meanings that are not defined in the basic meaning conventions corresponding to the set of information to be depicted, but are only derivable from them. Derived meaning can be made directly visually accessible. This explains the so often famed richness of certain visualizations, such as for instance scatter plots. Meaning not written in basic meaning rules can be derived from the scatter plot, because the shape and the density of the cloud of point symbols can convey important additional information. More generally, representation systems with a meaning derivation property allows the simultaneous presentation of local information and global information implied by the local information. Correctly assessing and recognizing derived meaning may be a major component of expertise in reading graphical representations.

All four concepts are thoroughly explained by means of examples in Bosveld (2004) (see this reader).

9. Conclusion.

This paper has given a global overview of visualizations, as they occur in instructional and research environments. Many disciplines are involved in researches that take visualizations as objects of study. Most research in this field has involved experiments to test the efficacy and efficiency of visual representations. There are quite some guidelines available that help designers to visualize information. More general principles have been discovered. Some theorizing has started. The issue is very complex. On the one hand, more theory-driven research is required to get more insight in the fundamental properties of visualizations, on the other hand it is useful to test theory-based hypotheses by experiments to get a more nuanced view of all factors involved. Inherent basic properties such as the ones proposed by Shimojima (2004) explain some of the effects of visualizations. The meaningfulness of visualizations and the attribution of correct meanings to them is determined by the interpretation link between the graphical domain and the application domain. In addition, there are a number of external elements that have to be taken into account as well. Context is one important external factor that influences design and use of visualizations. An educational setting puts other demands on a visual system than a non-educational one. In instruction a picture plays another role than in a professional environment. Educational settings introduce for instance a tension between 'making things easy' and 'helping students to learn'. The nature of the task to be accomplished with the help of the visualization is another factor to be considered. A picture for remembering content will have another appearance than one for solving a problem, or one for the illustration of facts. Finally the user's prior knowledge, including skills, preferences, experiences, etc. also put particular constraints on the type of visualization to be used, and influences its effects. In this respect, it is useful to repeat here what Cheng, Lowe & Scaife (2001, 90) state about diagrams, but which can be stated for all kinds of visual representations: "[…], a key factor in using a diagram effectively is what the viewer brings to the diagram (rather than what the diagram brings to the user)."

References

BAILEY, D. (1991), "Twelve ways to fool the masses when giving performance results on parallel computers", *Supercomputer Review*, Aug. 1991, 54-55.

BERTIN J. (1967), *Semiologie Graphique. Les Diagrammes, les Réseaux, les Cartes*, Éditions Gauthier-Villars, Paris; Éditions Mouton & Cie, Paris-La Haye.

BIOCCA, F., LEVY, M.R. (1995) (eds.), *Communication in the Age of Virtual Reality*, Lawrence Erlbaum Associates, Publishers, Hillsdale, New Jersey.

BLACKWELL, A.F. (2001) (ed.), *Thinking with Diagrams*. Kluwer Academic Publishers, Dordrecht, The Netherlands. Reprinted from *Artificial Intelligence Review*, Volume 15, Nos. 1-2, 2001.

BLACKWELL, A.F. (2001), "Introduction. Thinking with diagrams", in Blackwell, A.F. (2001) (ed.), 1-3.

BLACKWELL, A., MARRIOTT, K., SHIMOJIMA, A. (2004) (eds.), *Diagrammatic Representation and Inference. Proceedings of the Third International Conference, Diagrams 2004, Cambridge , Uk, March 2004*, Springer-Verlag, Berlin, etc..

BOSVELD, L.M. (2004), "Visualisatie van Informatie", Ms. University of Groningen.

BRNA, P., COX, R., GOOD, J. (2001), "Learning to Think and Communicate with Diagrams: 14 Questions to Consider", in Blackwell, A.F. (2001) (ed.), 115-134.

CHANDRASEKARAN, B., GLASGOW, J., NARAYANAN, N.H. (1995), "Introduction", in Glasgow, J., Narayanan, N.H., Chandrasekaran, B. (1995) (eds.), xv-xxvii.

CARD, S.K., MACKINLAY, J.D., SHNEIDERMAN, B. (eds.) (1999), *Readings in Information Visualization. Using Vision to Think*, Morgan Kaufmann Publ., San Francisco.

CARD, S.K., MACKINLAY, J.D., SHNEIDERMAN, B. (1999), "Information Visualization", in Card, S.K., Mackinlay, J.D., Shneiderman, B. (eds.) (1999), 1 – 34.

CHENG, C.-H., LOWE, R.K., SCAIFE, M. (2001), "Cognitive science approaches to understanding diagrammatic representations", *Artificial Intelligence Review* 15: 97-94.

CUEVAS, H.M., FIORE, S.M., OSER, R.L. (2002), "Scaffolding cognitive and metacognitive processes in low verbal ability learners: Use of diagrams in computer-based training environments", *Instructional Science* 30, 433-464.

DIX, A., FINLAY, J., ABOWD, G.D., BEALE, R. (2004 (3rd ed.)), *Human-Computer Interaction*, Pearson Educated Limited, Harlow.

DODGE, M., KITCHIN, R. (2000), "Exposing the 'Second Text' of maps on the Net", *Journal of Computer-Mediated Communication* 5 (4), June 2000 [Online].

FAMILANT, M.E., DETWEILER, M.C. (1993), "Iconic reference: evolving perspectives and an organizing framework", *International Journal of Man-Machine Studies* 39, 705-728.

GLASGOW, J., NARAYANAN, N.H., CHANDRASEKARAN, B. (1995) (eds.), *Diagrammatic Reasoning. Cognitive and Computational Perspectives*, AAAI Press, Menlo Park, CA.

GLOBUS, A., RAIBLE, E. (1992), "13 Ways to say nothing with scientific visualization", NASA Report RNR-92-006, 25 Feb. 1992.

HARPOLD, T. (1999), "Dark continents: Critique of Internet metageographies", *Postmodern Culture* 9 (2) [Online].

KLEIWEG P., NERBONNE J., BOSVELD L. (2004), "Geographic Projection of Cluster Composites", in Blackwell, A., Marriott, K., Shimojima, A.(eds.) (2004), 392-394.

LARKIN J.H., SIMON H.A. (1987) "Why a diagram is (sometimes) worth ten thousands words", *Cognitive Science,* 11 (1), 65-99. Reprinted in Glasgow, J., Narayanan, N.H., Chandrasekaran, B. (1995) (eds.), 69-109.

LEVIN J.R., ANGLIN G.J., CARNEY R.N. (1987), "On Empirically Validating Functions of Pictures in Prose", in D.M. Willows & H.A. Houghton (1987) (eds.), 51-85.

LOWE R.K. (1993), "Constructing a mental representation from an abstract technical diagram", *Learning and Instruction*, 3 (3), 157-179.

MACEACHREN, A.M. (1995), *How Maps Work: Representation, Visualization and Design*, Guilford Press, New York.

MARCUS, A. (2003), "Icons, symbols, and signs: visible languages to facilitate communication", *Interactions* May + June 2003, 37-43.

MONMONIER, M. (1995), *Drawing the Line: Tales of Maps and Cartocontroversy*, Henry Holt, New York.

MONMONIER, M. (1996), *How to Lie with Maps*, University of Chicago Press, Chigago.

PEIRCE, C.S. (1955), "Logic as semiotic: the theory of signs", in Buchler, J. (1955) (ed.), *Philosophical Writings of Peirce*, Dover Publications, New York, 98-128.

ROGERS, Y. (1989), "Icons at the interface: their usefulness", *Interacting with Computers* 1, 1, 105-117.

ROGERS, Y., SCAIFE, M. (1999), "How can interactive multimedia facilitate learning?", *Proceedings of the First International Workshop on Intelligence and Multimodality in Multimedia Interfaces*, AAAI Press, Menlo Park, CA.

ROERDINK, J.B.T.M. (2004), *Met het Oog op Inzicht. Visualisatie als Kringloopproces*, Inaugural address, University of Groningen.

SCAIFE M., ROGERS Y. (1996), "External cognition: how do graphical representations work?", *International Journal of Human-Computer Studies* 45, 185-213.

SHIMOJIMA, A. (2004), "Inferential and Expressive Capacities of Graphical Representations; Survey and Some Generalizations", in Blackwell, A., Marriott, K., Shimojima, A. (eds.) (2004), 18 – 21.

SIEGRIST, M. (1996), "The use and misuse of three-dimensional graphs to represent lower-dimensional data", *Behaviour & Information Technology*, vol. 15, no. 2, 96-100.

SIMON, H. (1995), "Foreword", in Glasgow, J., Narayanan, N.H., Chandrasekaran, B. (1995) (eds.), xi-xiii.

SHNEIDERMAN, B. (1998 (3rd ed.)), *Designing the User Interface. Strategied for Effective Human-Computer Interaction*, Addison Wesley Longman, Inc., Reading.

TUFTE E.R. (1983), *The Visual Display of Quantitative Information*, Graphics Press, Cheshire, CN.

TUFTE E.R. (1990), *Envisioning Information*, Graphics Press, Cheshire, CN.

WANG, D. (1995), *Studies in the Formal Semantics of Pictures*. Ph.D Thesis, University of Amsterdam, ILLC-publications.

WILLOWS, D.M., HOUGHTON, H.A. (1987) (eds.), *The Psychology of Illustration. Volume I: Theory*, Springer, New York.

WINN B. (1987), "Charts, Graphs, and Diagrams in Educational Materials", in D.M. Willows & H.A. Houghton (1987) (eds.), 153-198.