1 Introduction to Human-Centered Visualization Environments

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The title of this book—Human-Centered Visualization Environments (HCVE)—is composed of two key components: "human-centered" and "visualization environments". While the first part refers to the research area of *Human-Computer Interaction* (HCI), the second one refers to the design of *Visualization* systems. Thus, the focus of this textbook is on the intersection of both fields. These two terms can be defined as follows:

Visualization can be defined as: "The use of computer-supported, interactive, visual representation of abstract data to amplify cognition." [145]. The aim of visualization is to aid people in understanding and analyzing data. While other subfields, such as Scientific Visualization (SciVis), involve the presentation of data that has some physical or geometric correspondence, Information Visualization (InfoVis) centers on abstract information without such correspondences, i.e., usually it is not possible to map this information into the physical world. In this textbook, the focus is mainly on InfoVis.

Human-Computer Interaction is "the study of interaction between people (users) and computers. It is an interdisciplinary subject, relating computer science with many other fields of study and research. Interaction between users and computers occurs at the user interface (or simply interface), which includes both software and hardware, for example, general purpose computer peripherals and large-scale mechanical systems such as aircraft and power plants." [895]. The aim of HCI research is to improve the interaction between users and computers in the sense that this interaction should become more user-friendly and better adapted to the needs of the users.

The combination of these two areas is a prerequisite for the development of really "effective" visualizations that benefit from the capabilities and functionalities of the human visual system, e.g., visual perception and other cognitive abilities. Furthermore, this approach merges several additional aspects of different research areas, such as Scientific Visualization, Data Mining, Information Design, Graph Drawing, or Computer Graphics on the one hand as well as Cognition Sciences, Perception Theory, or Psychology on the other hand. All of these issues also depend on the data to be visualized and on the user's background, see Figure 1.1.

The creation of this textbook was motivated by the following reasons: The authors would like to increase the reader's awareness that when designing a new

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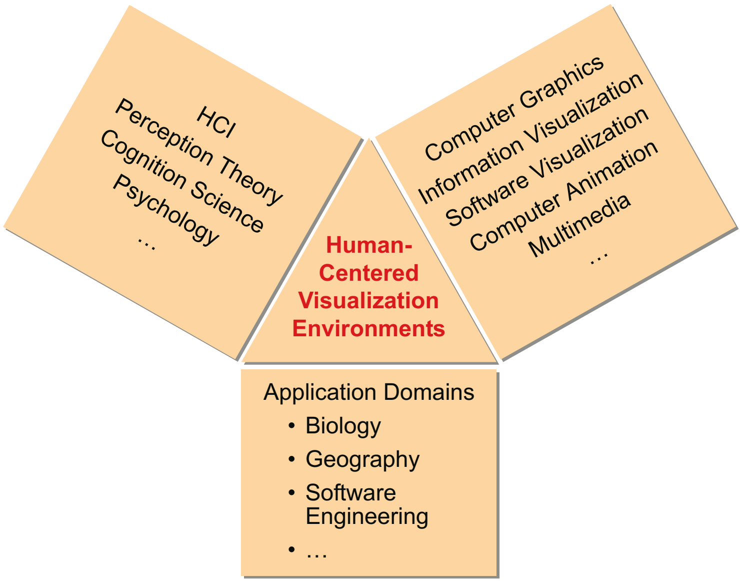

Fig. 1.1. Overview of the most important components of human-centered visualization.

visualization system, research results from the fields of HCI, Cognitive Sciences, Psychology, and others, should be taken into account. Intuitive interaction with a system and human-centered software usability design can increase productivity and efficiency in a work flow. It is the authors' goal that this textbook provides a good overview of popular visualization techniques with respect to both hardware and software. A human-centered point of view is the premier principle for selecting the described techniques. At the beginning of the book, an overview of the most significant human-centered design aspects is given, such as users' aims, users' requirements, and usability, followed by design evaluation methods, such as user studies and performance tests.

The authors' wish is that the reader—and thus a potential user or developer of visualization systems and environments—is capable of choosing an appropriate visualization technique that fits a given requirement *and* evaluating the quality and efficiency of the design by means of user studies or performance tests. A comprehensive bibliography at the end of the textbook provides additional reading material for those readers interested in further study of the subject areas.

This textbook was written as a self-contained study book that can be used for self-study or for a graduate-level semester course on human-centered visualization environments.

Structure

The content of this textbook is divided into two parts: The first part covers fundamentals of human-centered design, hardware- and software-related technologies for interaction, and base methods for visual representation. It then leads to a classification of future challenges and unsolved problems in human-centered visualization. The second part addresses the most important methods and common solutions for domain-specific visualizations, especially in geosciences, software design (algorithmic structures), and biomedical information.

Part I: Fundamental Principles and Methods

What makes visualization a human-centered approach? In Chapter 2, possible definitions of the therm "human-centered" are given. One out of the definitions and maybe the most important one—the ISO standard [394]—refers to human-centered design as "an approach to interactive system development that focuses specifically on making systems usable". Without doubt, the most prominent term in this definition is *usable*. The meaning of the term *usability* contains a number of aspects: effectiveness, efficiency, satisfaction, learnability, flexibility, memorability, ease of use, and error tolerance. Some of them can be easily measured in an objective way, others are users' subjective opinions about a tool or functionality.

How can all those usability factors be formalized? A key instrument is user studies which describe how critical information about the user can be obtained, so that the designed system is usable. Therefore, the central questions in interaction and visualization designs are: Who are the users of the systems? What kind of data are they working with? What are the general tasks of the users? These questions form a set of arguments for a good user study before one can start with designing visualization techniques.

What is a good visualization? A user study is helpful in addressing this question, even if the answer is sometimes ambiguous. A good visualization for one user could at the same time proof insufficient or inappropriate for a different user due to the variations in user and task characteristics. Several elements can be defined that help in the development of a suitable visualization system. In some cases, however, compromises are necessary, and it will not be possible to score equally high on all factors.

Visualization design and user interface design are closely related. Therefore, some of the same strategies can be applied to both areas. One such strategy is an iterative process which consists of a four-step analysis of user requirements and tasks, visualization design, implementation, and validation. This iterative approach is known as the *design cycle*.

Interacting with Visualizations (Chapter 3) describes the different aspects of interaction when dealing with virtual environments. Every time when communicating with other humans, speech, multiple gestures, or other ordinary signals are used in order to express ourselves. Multiple forms or modalities of interaction are present in such a conversion which can be summarized in the term

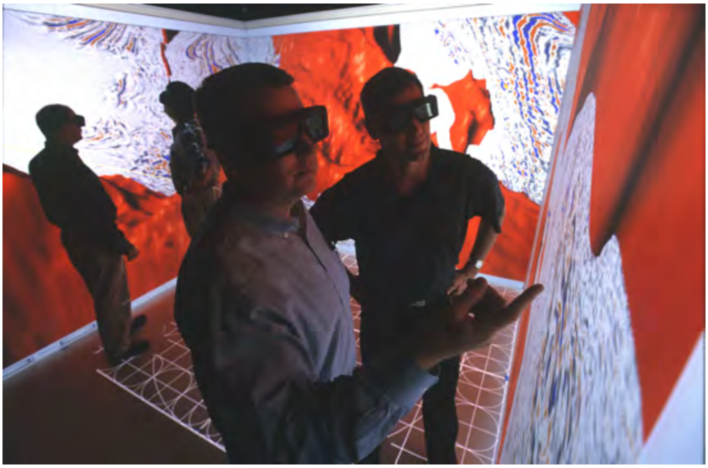

Fig. 1.2. Human-computer interaction in an immersive visualization environment. *Image courtesy of Fakespace Systems.*

multimodal interaction. This consideration is not only limited to inter-human communication, it can easily be transferred to the interaction and visualization paradigms used in a human-centered visualization environment (cp. Figure 1.2).

In such an environment, the display type has the largest effect on the design of the system, because most information in a virtual environment is communicated to the brain using the visual sense. All other interactions must be placed in its context. The display size greatly affects the way humans interact with a system. For example, the interaction potential of a PDA certainly differ from the interaction capabilities and possibilities of a large display system. Small displays are typically embedded in hand-held devices; this leaves only one hand free for interaction. Larger displays, in contrast, leave both hands free but cannot be easily accessed in a single physical movement. This leads to the conclusion that human-centered interaction and human-centered visualization are closely interconnected. Consequently, the interaction is dependent on the visualization and vice versa.

Which interaction modalities are considered feasible and which ones are not? Considering the term *interaction*, the terms *modality* and furthermore *multimodality* must be explored first, before focusing on the huge spectrum of current interaction devices. These devices are trying to rise to the challenge of natural human interaction, based on the current technologies and developments.

Normally, a visualization researcher works in a team and collaborates with experts of other domains. Consider a team member who is not able to participate in a current meeting or presentation, and an important feature has to be examined or presented, or furthermore his advice or help is needed. The team member must also be able to interact with the visualization in order to provide the necessary expertise. This implies the necessity to use a collaborative workspace or collaborative environment. Current applications trying to handle this issue are facing many problems, e.g., user authentication (access management), creation of multiple, personalized views (personalization), and others. Efficient models for multi-user interactions are the key factor to a successful collaboration. The efficiency of these models must be proven by different criteria. Finally, an overview of current collaborative visualization environments is given to provide insight into features of current systems and into their benefits and shortcomings.

Visual Representations (Chapter 4) explains how data models can be expressed using visual metaphors and converted into representations suitable for interaction, as described in Chapter 3. Edward Tufte, one of the leaders in the field of visual data exploration, describes in his illustrated textbooks [835–837] how information can be prepared so that the visual representation depicts both the data and the data context. His suggestions reach far beyond coordinate axes, labels and legends. The human brain collects data and attempts to correlate the information with previously acquired knowledge. The brain is an associative memory that gathers and sorts information based on contextual information. The task of memorizing information can be supported by providing the brain with additional context information. The use of visual metaphors assists the brain in its endeavor to connect new information received through the visual input channels to existing information stored in short- or long-term memory.

For instance, in a weather analysis chart seasonal temperature changes could be presented as a bar graph showing absolute temperature values over time. Such a diagram would provide the necessary information, but it would not be obvious what the bar graph represents if the axes were not labeled. Such an abstract representation contains no context information.

The first, more intuitive alternative would be a time axis depicted as a calendar. The calendar serves as an icon for the abstract concept of time. A clock icon to represent the time would be misleading, because the time frame comprises of not of minutes or hours, but of months or several years.

In addition, the temperature axis could be shown as a thermometer, which by most people will be recognized immediately as an indicator of temperature. However, the temperature scale and the units (Kelvin, Fahrenheit, or Celsius) are not immediately obvious, especially when viewed from a distance. Colors chosen by universal, culturally accepted or experience-based methods can help to identify hot (red) and cold (blue) temperatures, but the assignment of particular hues within a given range to certain temperatures is about as random as the assignment of unitless numbers to those temperatures. The depiction of physics-based phenomena, for example, frozen or evaporating water, next to the temperature scale would make the visual representation universally understandable and recognizable, even without any knowledge of the language of the annotation or national unit systems.

There are many ways to extend the example given above. For instance, if the temperature changes are too small to be seen in a given graph, the visual metaphor could be extended by superimposing a magnifying lens on the thermometer, maximizing the space for the illustration of temperatures and using only a small add-on for the context. Why not use trees and the color and number of their leaves to illustrate seasonal temperature changes? How about a stream of water that is either liquid, steaming or solid? Be creative and think outside the box!

The authors would like to stimulate a new way of thinking regarding visual representations. Rather than just plotting multi-dimensional coordinate systems, the scientist should keep the message in mind that is to be communicated in the visualization. A convincing diagram is one that people immediately recognize and memorize. It should convey sufficient information for someone to make a decision, and it should resonate in the viewers' (associative) minds.

The chapter on Visual Representations will make the reader familiar with basic visual representations for various types of one- and multi-dimensional data, and it will give some inspiration for the use of visual metaphors. A special section is dedicated to graphs and trees, as these represent a well researched range of visual metaphors.

All technologies and human-centered design methods discussed so far have certain benefits and shortcomings. Most approaches are an intermediate step on the way to solving concrete visualization problems and to building "effective" visualization tools, which aim to incorporate useful knowledge of visual perception into the system. Chapter 5 presents a comprehensive list of top unsolved problems and future challenges in visualization with a main focus on human-centered visualization. This list surveys related literature and classifies future challenges into three different categories: human-centered, technical, and financial.

Each discussed challenge is exemplified with the help of concrete examples and problems. The chapter ends with a careful outlook into the future. Here, the authors try to foresee—with caution and some margin of error—what problems could be solved in 20 years. They recognize that the list of solved problems is shorter than the list of unsolved problems. Thus, the reader of this textbook will realize that research on human-centered visualization environments is a hot and agile one.

Part II: Domain-Specific Visualizations

Geography is one of the best studied and most ancient domains in which visualization can help to understand, explore, and communicate spatial phenomena. Most people are familiar with cartography or so-called thematic maps that display the spatial patterns of climate characteristics, population density, etc. in intuitive and comprehensive ways. There are several definitions of *Geographic Visualization* (abbr. *Geovisualization*): The International Cartographic Association (ICA) Commission on Visualization and Virtual Environments defines: "Geovisualization integrates approaches from visualization in scientific computing (ViSC), cartography, image analysis, information visualization, exploratory data analysis (EDA), and geographic information systems (GISystems) to provide theory, methods and tools for visual exploration, analysis, synthesis, and presentation of geospatial data" [528]. Other authors prefer a more human-centered point of view and describe geovisualization as "the creation and use of

Fig. 1.3. Visualization of world map areas scaled proportional to size of population by country. *Image courtesy of M. Newman.*

visual representations to facilitate thinking, understanding, and knowledge construction about geospatial data" [513] or as "the use of visual geospatial displays to explore data and through that exploration to generate hypotheses, develop problem solutions and construct knowledge" [473]. Chapter 6 surveys the most important geovisualization techniques and methods, shows frequent problems, and in this context also discusses human-centered issues, such as usability and quality assurance by means of user studies.

The first two sections of this chapter discuss aims and driving forces of geovisualization. Because of the historic relevance of cartography, there are several approaches to evaluating the concrete perception of maps and images. The main part of the chapter covers visualization techniques and methods, especially 2D and 3D map-based visualization techniques (see Figure 1.3, for example), animation, interaction, and the integration of multivariate or time-varying data. The challenge for designers of geovisualization tools is to put these methods and techniques together effectively in order to help users solve their respective tasks. To exemplify these processes, five geovisualization systems are briefly described which show how the discussed techniques can be combined and used either individually or jointly.

Cartography has a long-standing history of applying perceptual and cognitive principles to map design. However, the cognitive theory for static maps cannot easily be generalized to apply to modern and interactive geovisualization tools. The last two sections of the chapter present usability issues and evaluation with respect to geovisualization, as well as future trends in the development of geovisualization tools, the impact of new hardware technologies (e.g., large displays or portable devices), and—of course—human-centered aspects.

The next domain discussed in the second part of this textbook (Chapter 7) is *Algorithm Animation* which is a subfield of Software Visualization (SoftVis). Algorithm animation visualizes the behavior of an algorithm by producing an abstraction of both the data and the operations of the algorithm. Initially, it maps the current state of the algorithm into an image which then is animated based on the operations between two succeeding states in the algorithm execution. Animating a visual representation of an algorithm allows for better understanding of the inner workings of the algorithm. Furthermore, it makes apparent its deficiencies and advantages thus allowing for further optimization.

Knowlton's movie [453] about list processing using the programming language L6 was one of the first experiments to visualize program behavior with the help of animation techniques. Other early efforts often focused on aiding teaching [37, 365] including the classic "Sorting Out Sorting" video [38, 39] that described nine different sorting algorithms and illustrated their respective running times. Experiences with algorithm animations made by hand and the wide distribution of personal computers with advanced graphical displays in the 1980's led to the development of complex algorithm animation systems.

After a brief overview of the field, Chapter 7 defines several groups of potential users of algorithm animations. This is important because a later review depends on the aims the users want to follow. Additionally, there are many taxonomies in this field that are presented from a human-centered point of view. The main part of this chapter covers a review of a selection of current algorithm animation tools summarizing the different ways users can interact with them, the methods that have been used to evaluate them, and the results that have been reported.

Biomedical Information Visualization (Chapter 8) addresses the needs of the emerging fields of quantitative biology and medicine on a molecular or genetic level. Large collections of information, such as the Protein Data Bank (PDB) or the Human Genome Project, typically sponsored by large, national and international funding agencies and maintained on supercomputers, have changed the way we look at life.

The tree of life, also known as a phylogenetic tree, represents the evolution of life according to the state of the art in genetic research. Subtrees contain various species, and special phylogenetic trees can be generated for species with related DNA sequences. Due to the complexity of the sequenced material, such trees can become quite complex. They are also subject to change when new research provides evidence for the existence of a new species. Once a new "missing link" is found, an entire tree may have to be restructured. Both their complexity and their subjectivity to change make phylogenetic trees difficult to interpret when plotted on paper. Two- and three-dimensional, interactive visualization software can help to display trees and to interact with their data.

Automated alignment of DNA sequences has enabled great advances in deciphering the human genome. Now we know that the human genome consists of approximately three billion DNA base pairs containing an estimated 20,000–25,000 genes. After collecting all the data, the problem of interpreting these genes and the functions they code for remains. Observation of genetic disorders caused by defects in the DNA is only one way to decode the functions of the proteins transcribed by a particular sequence of DNA. Another method is the observation of the effects of changes in the DNA in other species, such as mice, rats, or fruit flies. These species share an estimated 50% of their genes with humans. Visualization algorithms for sequence alignment aid scientists in the discovery of patterns hidden in the vast amount of data collected in the sequencing.

Understanding the complex biochemical processes within a cell or an organism is another emerging branch in the field of quantitative biology. Rather than looking at a single process, circuit, feedback or control mechanism, a complex system of interdependent, simultaneous processes can be simulated using computational models. Visualization currently helps to organize and understand these complex simulation models. Some illustrative examples are given in this textbook to inspire the reader to drill down deeply into the complex processes that keep an organism alive.

The next part of this chapter deals with a new technology called microarrays. This technique allows scientists to test thousands of gene variations simultaneously in the same experiment, thus speeding up large screening experiments significantly. Visualization of data obtained from such microarrays aids in an analysis of the level of gene expression in each variant. Typical visualization tools include clustering and tree view algorithms.

Medical records can be a useful scientific tool. In 1850, a typhoid epidemic was traced back by Sir John Snow to a sewage contamination of a particular public well. This incident became known as the Broad Street Pump Affair. Since this time it became evident that a systematic analysis of statistical data can reveal patterns in the outbreak, course and spread of a disease. A useful method for obtaining statistical data on pathological conditions is the analysis of patient records. Medical Record Visualization reveals patterns in particular pathological observations and allows clinicians to draw conclusions from comparing an individual patient's record to other patients' data stored in a database. This textbook provides some examples how patient data can be organized and visually presented efficiently.

Summary

The close interconnection between *visualization* and *human-computer interaction* suggests that visualization software design should incorporate human-centered principles of interaction and usability. The assessment of these priciples is primarily done by means of user studies and performance tests. The purpose of this textbook is to provide some inspiration and an overview of existing methods. The authors would like to encourage the reader to experiment with novel interaction techniques to find out which tools are useful and suitable to humans, and what type of interactive visualization helps to gain new insights in information contained in the data. Human-centered visualization environments can be the key to enlightenment!