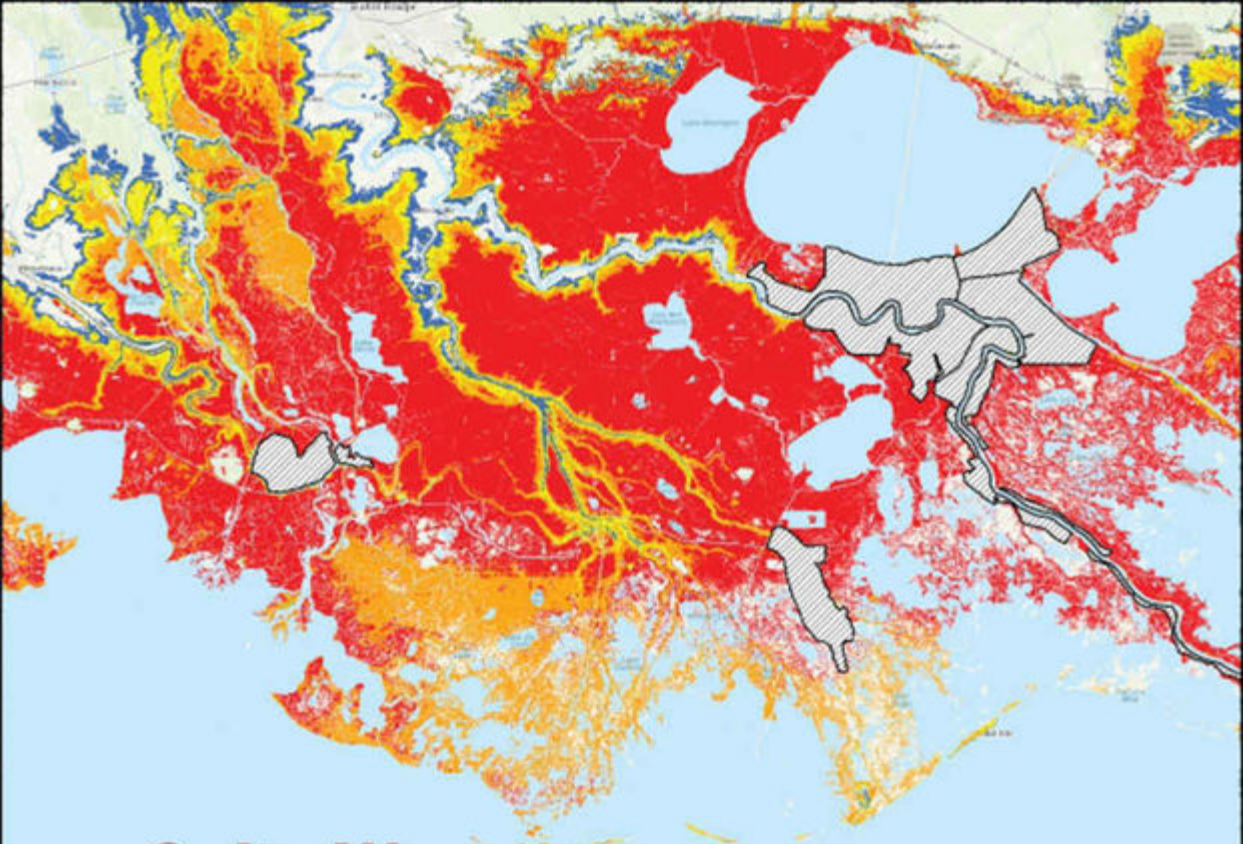




Colin Ware

Information Visualization

Perception for Design

Fourth Edition

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MORGAN KAUFMANN

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PERCEPTION FOR DESIGN

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ELSEVIER

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Preface

Cognitive neuroscience has made rapid progress in the last few years. When this book first appeared in the year 2000, there was no unified model of how we think visually. In the intervening years, the theory of *predictive cognition* has appeared and it provides a new and much more solid foundation for the later chapters of this edition. The brain is now regarded as first and foremost as a prediction engine. For example, theories of how we predict the future and remember the past are now unified. To recall the past we construct a likely scenario for what might have happened using a few recalled fragments together with relevant aspects of our cognitive model of the world, we do not simply pull it out of a memory like a video replay; predicting the future uses the same mechanisms except that we construct a likely future scenario based on a knowledge of the present and the same cognitive model of the world. We remember in order to predict the future and that the neural mechanisms are the same. In addition, the idea that cognition occurs in a distributed fashion, combining brain function with cognitive tools, such as visualizations, is now mainstream. We are all cognitive cyborgs. The later chapters of *Information Visualization: Perception for Design* have been rewritten, reorganized, and extended to reflect this new understanding. [Chapter 10](#) is about interaction, [Chapter 11](#) is about the visual thinking process, and [Chapter 12](#) is about the design of efficient thinking tools.

In addition to these major changes, the book has been revised and updated throughout to take recent research into account. In many cases the changes are small, the replacement of a figure or a brief description of a recent study. In other places, whole sections, such as one on narrative, have undergone major rewrites to take incorporate current thinking on the subject.

Now let me tell you how this book came about. In 1973, after I had completed my master's degree in the psychology of vision, I was frustrated with the overly focused academic way of studying perception. Inspired by the legacy of freedom that seemed to be in the air in the late 1960s and early 1970s, I decided to become an artist and explore perception in a very different way. But after three years with only very small success, I returned, chastened, to the academic fold, though with a broader outlook, a great respect for artists, and a growing interest in the relationship between the way we present information and the way we see. After obtaining a doctorate in the psychology of perception at the University of Toronto, I still did not know what to do next. I moved into computer science, via the University of Waterloo and another degree, and have been working on data visualization, in one way or another, ever since. In a way, this book is a direct result of my ongoing attempt to reconcile the scientific study of perception with the need to convey meaningful information. It is about art in the sense that "form should follow function," and it is about science because the science of perception can tell us what kinds of patterns are most readily perceived.

Why should we be interested in visualization? Because the human visual system is a pattern seeker of enormous power and subtlety. The eye and the visual cortex of the brain form a massively parallel processor that provides the highest bandwidth channel into human cognitive centers. At higher levels of processing, perception and cognition are closely interrelated, which is the reason why the words “understanding” and “seeing” are synonymous. However, the visual system has its own rules. We can easily see patterns presented in certain ways, but if they are presented in other ways they become invisible. Thus, for example, the word *goggle*, shown in the accompanying figure, is much more visible in the version shown at the bottom than in the one at the top. This is despite the fact that identical parts of the letters are visible in each case and in the lower figure there is more irrelevant “noise” than in the upper figure. The rule that applies here, apparently, is that when the missing pieces are interpreted as foreground objects then continuity between the background letter fragments is easier to infer. The more general point is that when data is presented in certain ways the patterns can be readily perceived. If we can understand how perception works, our knowledge can be translated into guidelines for displaying information. Following perception-based rules, we can present our data in such a way that the important and informative patterns stand out. If we disobey these rules, our data will be incomprehensible or misleading.

This is a book about what the science of perception can tell us about visualization. There is a gold mine of information about how we see to be found in more than a century of work by vision researchers. The purpose of this book is to extract from that large body of research literature those design principles that apply to displaying information effectively.

Visualization can be approached in many ways. It can be studied in the art school tradition of graphic design. It can be studied within computer graphics as an area concerned with the algorithms needed to display data. It can be studied as part of semiotics, the constructivist approach to symbol systems. These are valid approaches, but a scientific approach based on perception uniquely promises design rules that transcend the vagaries of design fashion, being based on the relatively stable structure of the human visual system.

The study of perception by psychologists and neuroscientists has advanced enormously over the past three decades, and it is possible to say a great deal about how we see that is relevant to data visualization. Unfortunately, much of this information is stored in highly specialized journals and usually couched in language that is accessible only to the research scientist. The research literature concerning human perception is voluminous. Several hundred new papers are published every month, and a surprising number of them have some application in information display. This information can be extremely useful in helping us design better displays, both by avoiding mistakes and by coming up with original solutions. *Information Visualization: Perception for Design* is intended to make this science and its applications available to the nonspecialist. It should be of interest to anyone concerned with displaying data effectively. It is designed with a number of audiences in mind: multimedia designers specializing in visualization, researchers in both industry and academia, and anyone who has a deep

interest in effective information display. The book presents extensive technical information about various visual acuities, thresholds, and other basic properties of human vision. It also contains, where possible, specific guidelines and recommendations.

The book is organized according to bottom-up perceptual principles. The first chapter provides a general conceptual framework and the theoretical context for a vision-science-based approach. The next four chapters discuss what can be considered to be the low-level perceptual elements of vision, color, texture, motion, and elements of form. These primitives of vision tell us about the design of attention-grabbing features and the best ways of coding data so that one object will be distinct from another. The later chapters move on to discussing what it takes to perceive patterns in data: first two-dimensional pattern perception and later three-dimensional space perception. Visualization design, data space navigation, interaction techniques, and visual problem solving are all discussed.

Here is a road map to the book: In general, the pattern for each chapter is first to describe some aspect of human vision and then to apply this information to some problem in visualization. The first chapters provide a foundation of knowledge on which the later chapters are built. Nevertheless, it is perfectly reasonable to randomly access the book to learn about specific topics. When it is needed, missing background information can be obtained by consulting the index.

Chapter 1: Foundations for an Applied Science of Data Visualization A conceptual framework for visualization design is based on human perception. The nature of claims about sensory representations is articulated, with special attention paid to the work of perception theorist J.J. Gibson. This analysis is used to define the differences between a design-based approach and an approach based on the science of perception. A classification of abstract data classes is provided as the basis for mapping data to visual representations.

Chapter 2: The Environment, Optics, Resolution, and the Display This chapter deals with the basic inputs to perception. It begins with the physics of light and the way light interacts with objects in the environment. Central concepts include the structure of light as it arrives at a viewpoint and the information carried by that light array about surfaces and objects available for interaction. This chapter goes on to discuss the basics of visual optics and issues such as how much detail we can resolve. Human acuity measurements are described and applied to display design.

The applications discussed include design of 3D environments, how many pixels are needed for visual display systems and how fast they should be updated, requirements for virtual reality display systems, how much detail can be displayed using graphics and text, and detection of faint targets.

Chapter 3: Lightness, Brightness, Contrast, and Constancy The visual system does not measure the amount of light in the environment; instead, it measures *changes* in light and color. How the brain uses this information to discover properties of the surfaces of objects in the environment is presented. This is related to issues in data coding and setting up display systems.

The applications discussed include integrating the display into a viewing environment, minimal conditions under which targets will be detected, methods for creating gray-scales to code data, and errors that occur because of contrast effects.

Chapter 4: Color This chapter introduces the science of color vision, starting with receptors and trichromacy theory. Color measurement systems and color standards are presented. The standard equations for the CIE standard and the *CIELUV* uniform color space are given. Opponent process theory is introduced and related to the way data should be displayed using luminance and chrominance.

The applications discussed include color measurement and specification, color selection interfaces, color coding symbols, colormapping scientific data, color reproduction, and color for multidimensional discrete data.

Chapter 5: Visual Salience: Finding and Reading Data Glyphs A “searchlight” model of visual attention is introduced to describe the way eye movements are used to sweep for information. The bulk of the chapter is taken up with a description of the massively parallel processes whereby the visual image is broken into elements of color, form, and motion. Preattentive processing theory is applied to critical issues of making one data object distinct from another. Methods for coding data so it can be perceptually integrated or separated are discussed.

The applications discussed include display for rapid comprehension, information coding, the use of texture for data coding, the design of symbology, and multidimensional discrete data display.

Chapter 6: Static and Moving Patterns This chapter looks at the process whereby the brain segments the world into regions and finds links, structure, and prototypical objects. These are converted into a set of design guidelines for information display.

The applications discussed include display of data so that patterns can be perceived, information layout, charts, node-link diagrams, and layered displays.

Chapter 7: Space Perception Increasingly, information display is being done in 3D virtual spaces as opposed to 2D screen-based layouts. The different kinds of spatial cues and the ways we perceive them are introduced. The latter half of the chapter is taken up with a set of spatial tasks and the perceptual issues associated with each.

The applications discussed include 3D information displays, stereo displays, the choice of 2D versus 3D visualization, 3D graph viewing, and virtual environments.

Chapter 8: Visual Objects and Data Objects Both image-based and 3D structure-based theories of object perception are reviewed. The concept of the object display is introduced as a method for using visual objects to organize information.

The applications discussed include presenting image data, using 3D structures to organize information, and the object display.

Chapter 9: Images, Narrative, and Gestures for Explanation Visual information and verbal information are processed in different ways and by different parts of the brain. Each has its own strengths and often both should be combined in a presentation. This chapter addresses when visual and verbal presentation should be used and how the

two kinds of information should be linked. Also how visual narratives should be constructed.

The applications discussed include integrating images and words, visual storytelling, visual programming languages, and effective diagrams.

Chapter 10: Interacting with Visualizations Major interaction cycles are defined. Within this framework, low-level data manipulation, dynamic control over data views, and navigation through data spaces are discussed in turn.

The applications discussed include using visualization to discover patterns in data.

Chapter 11: Thinking with Visualizations This chapter begins by outlining the cognitive system involved in thinking with visualizations. These are processes that occur partly in a computer and partly in the visual brain of the user. The output of the computer is a series of visual images that are processed through the visual system of the user. The output of the user is a set of epistemic actions, such as clicking on an object or moving a slider, which result in the visualization being modified in some way by the computer.

The applications discussed include problem solving with visualization, design of interactive systems, and creativity.

Chapter 12: Designing Cognitively Efficient Visualizations A design methodology for producing cognitively efficient visualizations is introduced. The method involves seven steps (1) A high-level cognitive task description; (2) A data inventory; (3) Cognitive task refinement; (4) Identification of appropriate visualization types; (5) Applying visual thinking design patterns (VTDPs); (6) Prototype development; and (7) Evaluation and design refinement. Most of the chapter is devoted to a set of VTDPs. These are descriptions of interactive visualization methods that have demonstrated value, together with a description of perceptual and cognitive issues relating to their use and guidelines for applicability. Design patterns provide a method for taking into account perceptual and cognitive issues in designing interaction especially with respect to key bottlenecks in the visual thinking process, such as limited visual working memory capacity. They also provide a way of reasoning about semiotic issues in perceptual terms via the concept of the visual query.

These are exciting times for visualization design. The computer technology used to produce visualizations has reached a stage at which sophisticated interactive views of data can be produced on laptop and tablet computers and even phones. Newspapers such as *The New York Times* include interactive visualizations in their online editions. The trend toward more and more visual information is accelerating, and there is an explosion of new visualization techniques being invented to help us cope with our need to analyze huge and complex bodies of information. This creative phase will not last for long. With the dawn of a new technology, there is often only a short burst of creative design before the forces of standardization make what is new into what is conventional. Undoubtedly, many of the visualization techniques that are now emerging will become routine tools in the near future. Even badly designed things can become industry standards. Designing for perception and cognition can help us avoid such mistakes. If we can harness the knowledge that has accumulated regarding how we think visually, we can make more efficient cognitive tools for reasoning about data.

I wish to thank the many people who have helped me with this book. The people who most influenced the way I think about perception and visualization are Donald Mitchell, John Kennedy, and William Cowan. I have gained enormously by working with Larry Mayer in developing new tools to map the oceans, as well as with colleagues many, in particular, Kelly Booth, Dave Wells, Scott Mackenzie, Jennifer Dijkstra, John Kelley, and David Wiley. Working with scientists and engineers who have data and interesting visualization problems is what make the discipline of data visualization worthwhile. It has also been my good fortune to work with many talented graduate students and research assistants on visualization-related projects: Daniel Jessome, Richard Guitard, Timothy Lethbridge, Sean Riley, Serge Limoges, David Fowler, Stephen Osborne, Dale Chapman, Pat Cavanaugh, Ravin Balakrishnan, Mark Paton, Monica Sardesai, Cyril Gobrecht, Justine Hickey, Yanchao Li, Kathy Lowther, Li Wang, Greg Parker, Daniel Fleet, Jun Yang, Graham Sweet, Roland Arsenaault, Natalie Webber, Poorang Irani, Jordan Lutes, Irina Padioukova, Glenn Franck, Lyn Bartram, Matthew Plumlee, Pete Mitchell, and Dan Pineo. Many of the ideas presented here have been refined through their efforts.

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Figure P.1 The word *goggle* is easier to read when the overlapping bars are visible. (Redrawn from Nakayama, Shimono, and Silverman (1989).)

About the Author

Colin Ware takes the “visual” in visualization very seriously. He has advanced degrees in both computer science (MMath, Waterloo) and the psychology of perception (Ph.D., Toronto). He has published over 160 articles in scientific and technical journals and at leading conferences, many of which relate to the use of color, texture, motion, and 3D in information visualization. In addition, Professor Ware also builds useful visualization software systems. He has been involved in developing 3D interactive visualization systems for ocean mapping for over 20 years and Fledermaus, a commercial product for visualization of ocean data, came originally from prototypes developed by him and his students. Current projects involve software to interpret data from tagged whales and visualizing ocean currents as well as optimizing colormaps. He is Director of the Data Visualization Research Lab in the Center for Coastal and Ocean Mapping at the University of New Hampshire.

CHAPTER ONE

Foundations for an Applied Science of Data Visualization



In his book *The End of Science*, science writer John Horgan (1997) argued that science is finished except for the mopping up of details. He made a good case where physics is concerned. In that discipline, the remaining deep problems may involve generating so much energy as to require the harnessing of entire stars. Similarly, biology has its foundations in DNA and genetics and is now faced with the infinite but often tedious complexity of mapping genes into proteins through intricate pathways. What Horgan failed to recognize is that cognitive science has fundamental problems that are still to be solved. In particular, the mechanisms of the construction and storage of knowledge remain open questions. He implicitly adopted the physics-centric view of science, which holds that physics is the queen of sciences and in descending order come chemistry, then biology, with psychology barely acknowledged as a science at all. In this pantheon, sociology is regarded as somewhere on a par with astrology. This attitude is shortsighted. Chemistry builds on physics, enabling our understanding of materials; biology builds on chemistry, enabling us to understand the much greater complexity of living organisms; and psychology builds on neurophysiology, enabling us to understand the processes of cognition. At each level is a separate discipline greater in complexity and level of difficulty than those beneath. It is difficult to conceive of a value scale for which the mechanisms of thought are not of fundamentally greater interest and importance than the interaction of subatomic particles. Those who dismiss psychology as a pseudoscience have not been paying attention. Over the past few decades, enormous strides have been made in identifying the brain structures and cognitive mechanisms that have enabled humans to create the huge body of knowledge that now exists. But we need to go one step further and recognize that a person

working with the aid of thinking tools is much more cognitively powerful than that person alone with his or her thoughts. This has been true for a long time. Artifacts such as paper and pens, as well as techniques such as writing and drawing, have been cognitive tools for millennia.

As Hutchins (1995) so effectively pointed out, thinking is not something that goes on entirely, or even mostly, inside people's heads. Little intellectual work is accomplished with our eyes and ears closed. Most cognition is done as a kind of interaction with cognitive tools, pencils and paper, calculators, and, increasingly, computer-based intellectual supports and information systems. Neither is cognition mostly accomplished alone with a computer. It occurs as a process in systems containing many people and many cognitive tools. Since the beginning of science, diagrams, mathematical notations, and writing have been essential tools of the scientist. Now we have powerful interactive analytic tools, such as MATLAB, Tableau, and S-PLUS, together with databases. The entire fields of genomics and proteomics are built on computer storage and analytic tools. The social apparatus of the school system, the university, the academic journal, and the conference are obviously designed to support cognitive activity.

Cognition in engineering, banking, business, and the arts is similarly carried out through distributed cognitive systems. In each case, "thinking" occurs through interaction between individuals, using cognitive tools and operating within social networks. Hence, cognitive systems theory is a much broader discipline than psychology. This is emerging as the most interesting, difficult, and complex, yet fundamentally the most important, of sciences.

Visualizations are an increasingly important part of cognitive systems. Visual displays provide the highest bandwidth channel from the computer to the human. Indeed, we acquire more information through vision than through all of the other senses combined. The 20 billion or so neurons of the brain devoted to analyzing visual information provide a pattern-finding mechanism that is a fundamental component in much of our cognitive activity. Improving cognitive systems often means optimizing the search for data and making it easier to see important patterns. An individual working with a computer-based visual thinking tool is a cognitive system where the critical components are, on one side, the human visual system, a flexible pattern finder coupled with an adaptive decision-making cognitive mechanism, and, on the other side, the computational power and vast information resources of a computer coupled to the World Wide Web. Data analysis programs are themselves the encapsulation, in executable form, of the thinking process of many individuals who have already solved parts of the analytic problem. Interactive visualization is the interface between the two sides. Improving this interface can substantially improve the performance of the entire system.

Until recently, the term *visualization* meant constructing a visual image in the mind (Little, Fowler, & Coulson, 1972). It has now come to mean something more like a graphical representation of data or concepts. Thus, from being an internal construct of the mind, a visualization has become an external artifact supporting decision-making. The way visualizations can function as cognitive tools is the subject of this book.

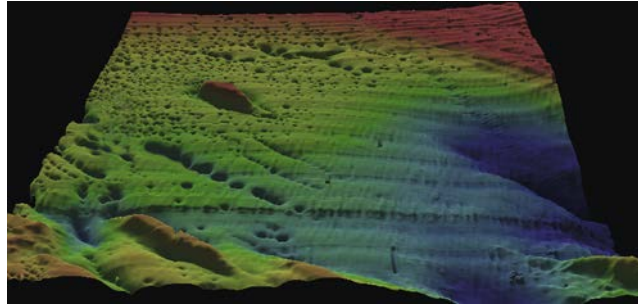


Figure 1.1 Passamaquoddy Bay visualization. (Data courtesy of the Canadian Hydrographic Service.)

One of the greatest benefits of data visualization is the sheer quantity of information that can be rapidly interpreted if it is presented well. Fig. 1.1 shows a visualization derived from a multibeam echo sounder scanning part of Passamaquoddy Bay, between Maine in the United States and New Brunswick in Canada, where the tides are the highest in the world. Approximately one million measurements were made. Traditionally, this kind of data is presented in the form of a nautical chart with contours and spot soundings; however, when the data is converted to a height field and displayed using standard computer graphics techniques, many things become visible that were previously invisible on the chart. A pattern of features called *pockmarks* can immediately be seen, and it is easy to see how they form lines. Also visible are various problems with the data. The linear ripples (not aligned with the pockmarks) are errors in the data because the roll of the ship that took the measurements was not properly taken into account.

The Passamaquoddy Bay image highlights a number of the advantages of visualization:

- Visualization provides an ability to comprehend huge amounts of data. The important information from more than a million measurements is immediately available.
- Visualization allows the perception of emergent properties that were not anticipated. In this visualization, the fact that the pockmarks appear in lines is immediately evident. The perception of a pattern can often be the basis of a new insight. In this case, the pockmarks align with the direction of geological faults, suggesting a cause. They may be due to the release of gas.
- Visualization often enables problems with the data to become immediately apparent. A visualization commonly reveals things not only about the data itself but also about the way it is collected. With an appropriate visualization, errors and artifacts in the data often jump out at you. For this reason, visualizations can be invaluable in quality control.
- Visualization facilitates understanding of both large-scale and small-scale features of the data. It can be especially valuable in allowing the perception of patterns linking local features.

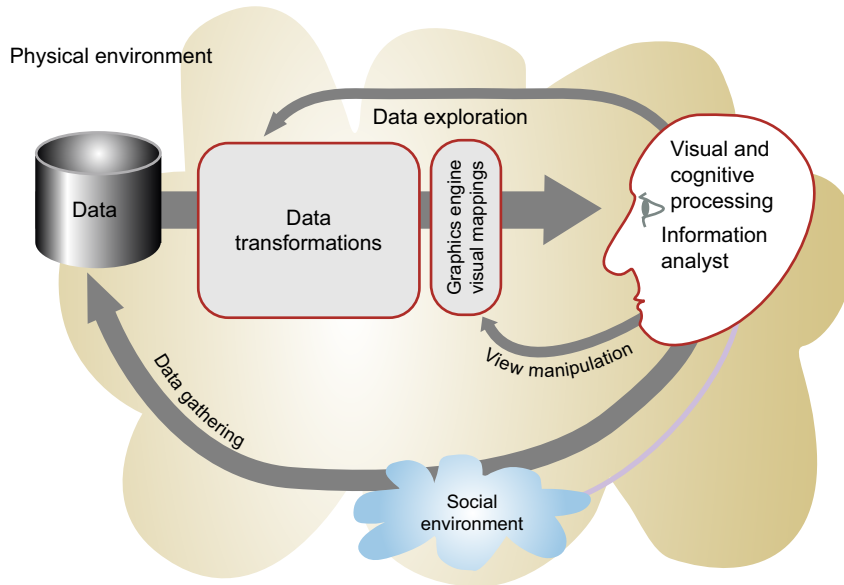


Figure 1.2 The visualization process.

- Visualization facilitates hypothesis formation. For example, the visualization in [Fig. 1.1](#) led to questions about the how the pockmarks might have formed and motivated a research paper concerning the geological significance of the features (Gray, Mayer, & Hughes Clarke, 1997).

Visualization Stages

The process of data visualization includes four basic stages, combined in a number of feedback loops. These are illustrated in [Fig. 1.2](#). The four stages consist of the following:

- The collection and storage of data.
- A preprocessing stage designed to transform the data into something that is easier to manipulate. Usually there is some form of data reduction to reveal selected aspects. Data exploration is the process of changing the subset that is currently being viewed.
- Mapping from the selected data to a visual representation, which is accomplished through computer algorithms that produce an image on the screen. User input can transform the mappings, highlight subsets, or transform the view. Generally this is done on the user's own computer.
- The human perceptual and cognitive system (the perceiver).

The longest feedback loop involves gathering data. A data seeker, such as a scientist or a stock-market analyst, may choose to gather more data to follow up on an interesting lead. Another loop controls the computational preprocessing that takes place prior to

visualization. The analyst may feel that if the data is subjected to a certain transformation prior to visualization, it can be persuaded to give up its meaning. Sometimes the process is a search through a very large volume of data to find an important nugget. Finally, the visualization process itself may be highly interactive; for example, in three-dimensional (3D) data visualization, the scientist may “fly” to a different vantage point to better understand the emerging structures. Alternatively, a computer mouse may be used interactively to select the parameter ranges that are most interesting.

Both the physical environment and the social environment are involved in the data-gathering loop. The physical environment is a source of data, while the social environment determines in subtle and complex ways what is collected and how it is interpreted. In this book, the emphasis is on data, perception, and the various tasks to which visualization may be applied. In general, algorithms are discussed only insofar as they are related to perception. The computer is treated, with some reservations, as a universal tool for producing interactive graphics. This means that once we figure out the best way to visualize data for a particular task, we assume that we can construct algorithms to create the appropriate images.

The critical question is how best to transform the data into something that people can understand for optimal decision-making. Before plunging into a detailed analysis of human perception and how it applies in practice, however, we must establish the conceptual basis for the endeavor. The purpose of this discussion is to stake out a theoretical framework wherein claims about visualizations being “visually efficient” or “natural” can be pinned down in the form of testable predictions.

Experimental Semiotics Based on Perception

This book is about the applied science of visualization. It is based on the idea that the value of a good visualization is that it lets us see patterns in data and therefore the science of pattern perception can provide a basis for design decisions, but the claim that visualization can be based on science may be disputed. Let us look at the alternative view. Some scholars argue that visualization is best understood as a kind of learned language and not as a science at all. In essence, their argument is the following. Visualization is about diagrams and how they can convey meaning. Diagrams are made up of symbols, and symbols are based on social interaction. The meaning of a symbol is normally understood to be created by convention, which is established in the course of person-to-person communication. Diagrams are arbitrary and are effective in much the same way as the written words on this page are effective—we must learn the conventions of the language, and the better we learn them the clearer that language will be. Thus, one diagram may ultimately be as good as another; it is just a matter of learning the code, and the laws of perception are largely irrelevant. This view has strong philosophical proponents from the classical field of semiotics. Although it is not the position adopted here, the debate can help us define where vision research can assist us in designing better visualizations and where we would be wise to consult a graphic designer trained in an art college.

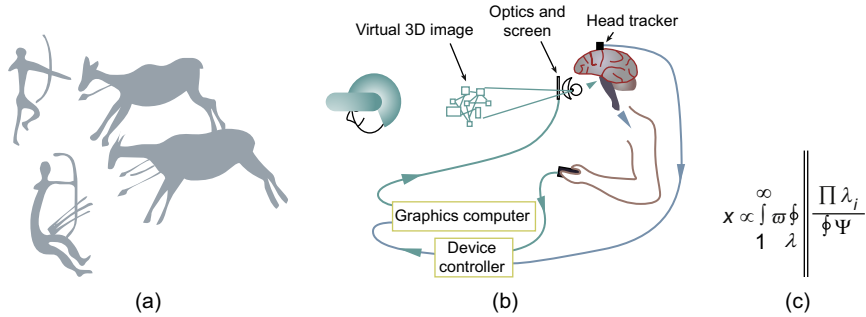


Figure 1.3 Three graphics. Each could be said to be a visualization.

Semiotics of Graphics

The study of symbols and how they convey meaning is called *semiotics*. This discipline was originated in the United States by C. S. Peirce and later developed in Europe by the French philosopher and linguist de Saussure (1959). Semiotics has been dominated mostly by philosophers and by those who construct arguments based on example rather than on formal experiment. In his great masterwork, *Semiology of Graphics*, Bertin (1983) attempted to classify all graphic marks in terms of how they could express data. For the most part, this work is based on his own judgment, although it is a highly trained and sensitive judgment. There are few references to theories of perception or scientific studies.

It is often claimed that visual languages are easy to learn and use, but what do we mean by the term *visual language*? Clearly not the writing on this page. Reading and writing take years of education to master and it can take almost as long to master some diagrams. Fig. 1.3 shows three examples of languages that have some claim to being visual. The first example of visual language is based on a cave painting. We can readily interpret human figures and infer that the people are using bows and arrows to hunt deer. The second example is a schematic diagram showing the interaction between a person and a computer in a virtual environment system; the brain in the diagram is a simplified picture, but it is a part of the anatomy that few have directly perceived. The arrows show data flows and are arbitrary conventions, as are the printed words.

The third example is the expression of a mathematical equation that is utterly obscure to all but the initiated. These examples clearly show that some visual languages are easier to “read” than others. But why? Perhaps it is simply that we have more experience with the kind of pictorial image shown in the cave painting and less with the mathematical notation. Perhaps the concepts expressed in the cave painting are more familiar than those in the equation.

The most profound threat to the idea that there can be a scientific basis for visualization design originates with Saussure. He defined a principle of arbitrariness as applying to the relationship between the symbol and the thing that is signified. Saussure was also a founding member of a group of structuralist philosophers and anthropologists who,

although they disagreed on many fundamental issues, were unified in their general insistence that truth is relative to its social context. Meaning in one culture may be nonsense in another. A trash can as a visual symbol for deletion is meaningful only to those who know how trash cans are used. Thinkers such as Levi-Strauss, Barthes, and Lacan have condemned the cultural imperialism and intellectual arrogance implicit in applying our intellects to characterizing other cultures as “primitive.” As a result, they have developed the theory that all meaning is relative to the culture. Indeed, meaning is created by society. They claim that we can interpret another culture only in the context of our own culture and using the tools of our own language. Languages are conventional means of communication in which the meanings of symbols are established through custom. Their point is that no one representation is “better” than another. All representations have value. All are meaningful to those who understand them and agree to their meanings. Because it seems entirely reasonable to consider visualizations as communications, their arguments strike at the root of the idea that there can be an applied science of visualization with the goal of establishing specific guidelines for better representations. We reject this view and instead argue that it is possible to have a new semiotics based not on philosophical claims for symbols being arbitrary, but instead on scientific evidence.

Are Pictures Arbitrary?

The question of whether pictures and diagrams are purely conventional or are perceptual symbols with special properties has been the subject of considerable scientific investigation. A good place to begin reviewing the evidence is the perception of pictures. There has been a debate over the past century between those who claim that pictures are every bit as arbitrary as words and those who believe that there may be a measure of similarity between pictures and the things that they represent. This debate is crucial to the theory presented here; if even “realistic” pictures do not embody a sensory language, it will be impossible to make claims that certain diagrams and other visualizations are better designed perceptually.

The nominalist philosopher, Goodman (1968), has delivered some of the more forceful attacks on the notion of similarity in pictures:

Realistic representation, in brief, depends not upon imitation or illusion or information but upon inculcation. Almost any picture may represent almost anything; that is, given picture and object there is usually a system of representation—a plan of correlation—under which the picture represents the object.

For Goodman, realistic representation is a matter of convention; it “depends on how stereotyped the model of representation is, how commonplace the labels and their uses have become.” Bieusheuvel (1947) expressed the same opinion: “The picture, particularly one printed on paper, is a highly conventional symbol, which the child reared in Western culture has learned to interpret.” These statements, taken at face value, invalidate any meaningful basis for saying that a certain visualization is fundamentally better or more natural than another, for if even a realistic picture must be

learned this would mean that all graphical representations of data are equally valid in that their conventions must be learned. If we accept this position, the best approach to designing visual languages would be to establish graphical conventions early and stick to them. It would not matter what the conventions were, only that we adhered to them in order to reduce the labor of learning new conventions.

In support of the nominalist argument, a number of anthropologists have reported expressions of puzzlement from people who encounter pictures for the first time. “A Bush Negro woman turned a photograph this way and that, in attempting to make sense out of the shadings of gray on the piece of paper she held” (Herskovits, 1948). The evidence related to whether or not we must learn to see pictures has been carefully reviewed and analyzed by Kennedy (1974). He rejected the strong position that pictures and other visual representations are entirely arbitrary. In the case of the reported puzzlement of people who are seeing pictures for the first time, Kennedy argued that these people are amazed by the technology rather than unable to interpret the picture. After all, a photograph is a remarkable artifact. What curious person would not turn it over to see if, perhaps, the reverse side contains some additional interesting information?

Here are two of the many studies that contradict the nominalist position and suggest that people can interpret pictures without training. Deregowski (1968) reported studies of adults and children in a remote area of Zambia who had very little graphic art. Despite this, these people could easily match photographs of toy animals with the actual toys. In an extraordinary but very different kind of experiment, Hochberg and Brooks (1962) raised their daughter nearly to the age of two in a house with no pictures. She was never read to from a picture book, and there were no pictures on the walls in the house. Although her parents could not completely block the child’s exposure to pictures on trips outside the house, they were careful never to indicate a picture and tell the child that it was a representation of something. Thus, she had no social input telling her that pictures had any kind of meaning. When the child was finally tested she had a reasonably large vocabulary, and she was asked to identify objects in line drawings and in black-and-white photographs. Despite her lack of instruction in the interpretation of pictures, she was almost always correct in her answers, indicating that a basic understanding of pictures is not a learned skill.

Nevertheless, the issue of how pictures, especially line drawings, are able to unambiguously represent things is still not fully understood. Clearly, a portrait is a pattern of marks on a page; in a physical sense, it is utterly unlike the flesh-and-blood person it depicts. The most probable explanation is that, at some stage in visual processing, the pictorial outline of an object and the object itself excite similar neural processes (Pearson, Hanna, & Martinez, 1990). This view is made plausible by the ample evidence that one of the most important products of early visual processing is the extraction of linear features in the visual array. These may be either the visual boundaries of objects or the lines in a line drawing. The nature of these mechanisms is discussed further in [Chapter 6](#).



Figure 1.4 Two graphical methods for showing the same set of relationships between entities.

When we turn to diagrams and nonpictorial visualizations, it is clear that convention must play a greater role. Fig. 1.3(b) is not remotely “like” any scene in the real world under any system of measurement. Nevertheless, we can argue that many elements in it are constructed in ways that for perceptual reasons make the diagram easy to interpret. The lines that connect the various components, for example, are a notation that is easy to read, because the visual cortex of the brain contains mechanisms specifically designed to seek out continuous contours. Other possible graphical notations for showing connectivity would be far less effective. Fig. 1.4 shows two different conventions for demonstrating relationships between entities. The connecting lines on the left are much more effective than the symbols on the right.

Sensory versus Arbitrary Symbols

In this book, the word *sensory* is used to refer to symbols and aspects of visualizations that derive their expressive power from their ability to use the perceptual processing power of the brain without learning. The word *arbitrary* is used to define aspects of representation that must be learned, because the representations have no perceptual basis. For example, the written word *dog* bears no perceptual relationship to any actual animal. Probably very few graphical languages consist of entirely arbitrary conventions, and probably none is entirely sensory; however, the sensory-versus-arbitrary distinction is important. If well designed, sensory representations are effective because they are well matched to the first stages of neural processing. They tend to be stable across individuals, cultures, and time. A circle represents a bounded region for everyone. Conversely, arbitrary conventions derive their power from culture and are therefore dependent on the particular cultural milieu of an individual.

The theory that a visual representation can be good or poor depending on how well it fits with visual processing is ultimately based on the idea that the human visual system has evolved as a specialized instrument to perceive the physical world. It rejects the idea that the visual system can adapt to any universe. It was once widely held that the brain at birth was an undifferentiated neural net, capable of configuring itself to perceive in any world, no matter how strange. According to this theory, if a newborn human infant were to be born into a world with entirely different rules for the propagation of light, that infant would nevertheless learn to see. Partly, this view came from the fact that all cortical brain tissue looks more or less the same, a uniform pinkish

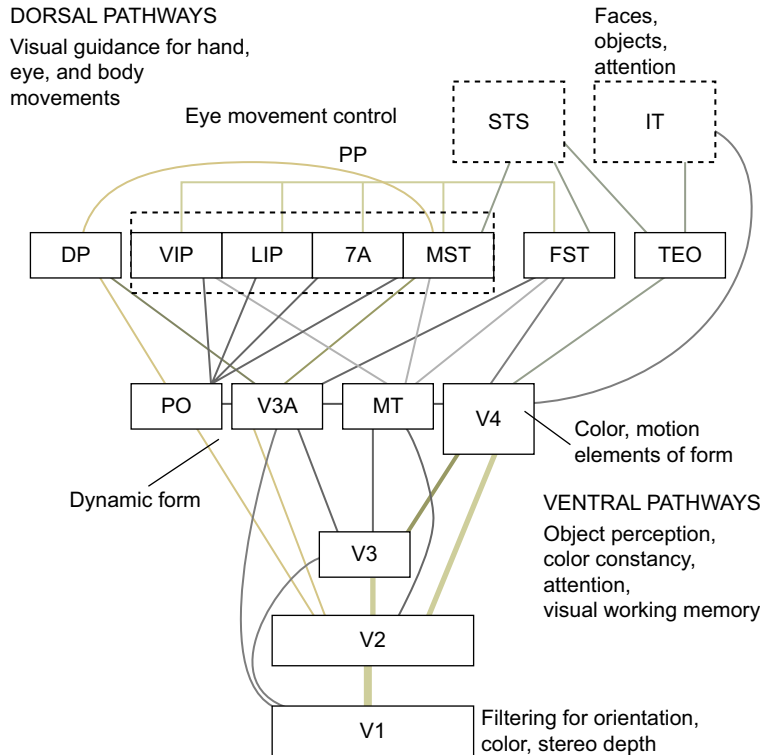


Figure 1.5 The major visual pathways of the Macaque monkey. This diagram is included to illustrate the structural complexity of the visual system and because a number of these areas are referenced in different sections of this book. V1 to V4, visual areas 1 to 4; PO, parietooccipital area; MT, middle temporal area; IT, inferotemporal cortex. (Redrawn from Distler *et al.* (1993))

gray, so it was thought to be functionally undifferentiated. This tabula rasa view has been overturned as neurologists have come to understand that the brain has a great many specialized regions. Fig. 1.5 shows the major neural pathways between different parts of the brain involved in visual processing (Distler, Boussaoud, Desmone, & Ungerleider, 1993). Although much of the functionality remains unclear, this diagram represents an amazing achievement and summarizes the work of dozens of researchers. These structures are present in both higher primates and humans. The brain is clearly not an undifferentiated mass; it is more like a collection of highly specialized parallel processing machines with high-bandwidth interconnections. The entire system evolved to extract information from the world in which we live, not from some other environment with entirely different physical properties.

Certain basic elements are necessary for the visual system to develop normally; for example, cats reared in a world consisting only of vertical stripes develop distorted visual cortices, with an unusual preponderance of vertical-edge detectors. Nevertheless, the basic elements for the development of normal vision are present in

all but the most abnormal circumstances. The interaction of the growing nervous system with everyday reality leads to a more or less standard visual system. This should not surprise us; the everyday world has ubiquitous properties that are common to all environments. All earthly environments consist of objects with well-defined surfaces, surface textures, surface colors, and a variety of shapes. Objects exhibit temporal persistence—they do not randomly appear and vanish, except when there are specific causes. At a more fundamental level, light travels in straight lines and reflects off surfaces in certain ways. The law of gravity continues to operate. Given these ubiquitous properties of the everyday world, the evidence suggests that we all develop essentially the same visual systems, irrespective of cultural milieu.

Monkeys and even cats have visual structures very similar to those of humans; for example, although [Fig. 1.5](#) is based on the visual pathways of the Macaque monkey, a number of lines of evidence show that the same structures exist in humans. First, the same areas can be identified anatomically in humans and animals. Second, specific patterns of blindness occur that point to the same areas having the same functions in humans and animals; for example, if the brain is injured in area V4, patients suffer from achromatopsia (Milner & Goodale, 1995; Zeki, 1992). These patients perceive only shades of gray, and they cannot recall colors from times before the lesion was formed. Color processing occurs in the same region of the monkey cortex. Third, new research imaging technologies, such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI), show that in response to colored or moving patterns the same areas are active in people as in the Macaque monkey (Beardsley, 1997; Zeki, 1992). The key implication of this is that, because we all have the same visual system, it is likely that we all see in the same way, at least as a first approximation. Hence, the same visual designs will be effective for all of us.

Sensory aspects of visualizations derive their expressive power from being well designed to stimulate the visual sensory system. In contrast, arbitrary, conventional aspects of visualizations derive their power from how well they are learned. Sensory and arbitrary representations differ radically in the ways they should be studied. In the former case, we can apply the full rigor of the experimental techniques developed by sensory neuroscience, while in the latter case visualizations and visual symbols can best be studied with the very different interpretive methodology, derived from the structuralist social sciences. With sensory representations, we can also make claims that transcend cultural and racial boundaries. Claims based on a generalized perceptual processing system will apply to all humans, with obvious exceptions such as color blindness.

This distinction between the sensory and social aspects of the symbols used in visualization also has practical consequences for research methodology. It is not worth expending a huge effort carrying out intricate and highly focused experiments to study something that is only this year's fashion; however, if we can develop generalizations that apply to large classes of visual representations, and for a long time, the effort is worthwhile. If we accept the distinction between sensory and arbitrary codes,

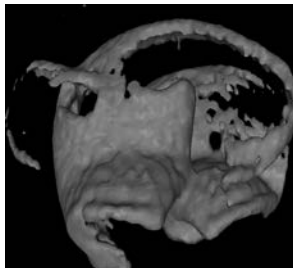


Figure 1.6 The expanding wavefront of a chemical reaction is visualized (Cross et al., 1997). Even though this process is alien to most of us, the shape of the structure is readily perceived.

we nevertheless must recognize that most visualizations are hybrids. In the obvious case, they contain both pictures and words, but in many cases the sensory and arbitrary aspects of a representation are much more difficult to tease apart. There is an intricate interweaving of learned conventions and hardwired processing. The distinction is not as clean as we would like, but there are ways of distinguishing the different kinds of codes.

Properties of Sensory Representation

The following paragraphs summarize some of the important properties of sensory representations:

Understanding without training. A sensory code is one for which the meaning is perceived without additional training. Usually, all that is necessary is for the audience to understand that some communication is intended. For example, it is immediately clear that the image in Fig. 1.6 has an unusual spiral structure. Even though this visual represents a physical process that cannot actually be seen, the detailed shape can be understood because it has been expressed using an artificial shading technique to make it look like a 3D solid object. Our visual systems are built to perceive the shapes of 3D surfaces.

Resistance to alternative denotation. Many sensory phenomena, such as the illusions shown in Fig. 1.7, persist despite the knowledge that they are illusory. We can tell someone that the lines are the same length, but they will still seem to that person as different. When such illusions occur in diagrams, they are likely to be misleading. What is important to the present argument, though, is that some aspects of perception will be taken as facts that we contradict at our peril; for example, using connecting lines to denote that two objects are *not* (conceptually) connected would be a very bad idea, as it would contradict a deep perceptual metaphor.

Sensory immediacy. The processing of certain kinds of sensory information is hardwired and fast. We can represent information in certain ways that are

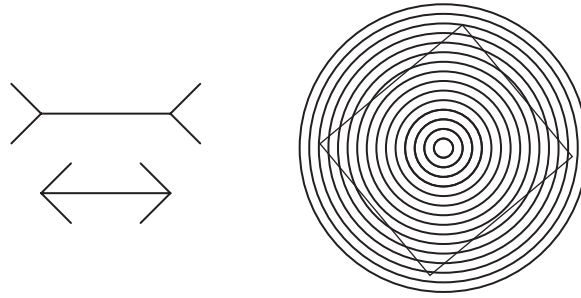


Figure 1.7 In the Muller-Lyer illusion on the left, the horizontal line in the upper figure appears longer than the one below. On the right, the rectangle appears distorted into a pincushion shape.

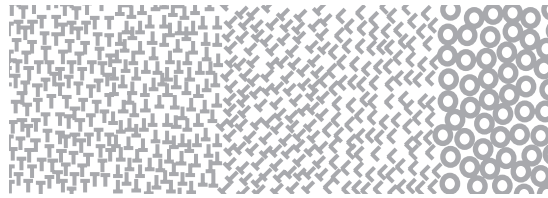


Figure 1.8 Five regions of texture. Some areas are easier to distinguish from others. (Adapted from Beck (1966).)

neurally processed in parallel. This point is illustrated in [Fig. 1.8](#), which shows five different textured regions. The two regions on the left are very difficult to separate; the upright Ts and inverted Ts appear to be a single patch. The region of oblique Ts is easy to differentiate from the neighboring region of inverted Ts. The circles are the easiest to distinguish (Beck, 1966). The way in which the visual system divides the visual world into regions is called *segmentation*. The evidence suggests that this is a function of early rapid-processing systems. ([Chapter 5](#) presents a theory of texture discrimination.)

Cross-cultural validity. A sensory code will, in general, be understood across cultural boundaries. These may be national boundaries or the boundaries between different user groups. Instances in which a sensory code is misunderstood occur when some group has dictated that a sensory code be used arbitrarily in contradiction to the natural interpretation. In this case, the natural response to a particular pattern will, in fact, be wrong.

The foregoing analysis leads us to our first guideline.

[G1.1] Design graphic representations of data by taking into account human sensory capabilities in such a way that important data elements and data patterns can be quickly perceived.

Exactly how this can be done is the subject of this book, but we will begin with two fundamental principles.

[G1.2] Important data should be represented by graphical elements that are more visually distinct than those representing less important information.

Important information should be easy to find. The neural basis for visual search is now quite well understood, and as we shall see this, it allows us to determine with some precision which items are more findable than others.

[G1.3] Greater numerical quantities should be represented by more distinct graphical elements.

This can be accomplished, for example, by making those elements, larger, more vividly colored, or more strongly textured. The basis for this claim is that even nonvisual thought as embodied in spoken and written language is grounded in sensory metaphors (Pinker, 2007).

Notice that guidelines G1.2 and G1.3 propose using the same kind of coding (visual distinctness) for different purposes, and this can lead to design conflicts. Also, sometimes a large quantity of something may not be especially important. Indeed, if we are running out of a critical asset (such as petroleum in the gas tank), we will want whatever represents this small quantity to be visually distinct. Ultimately, deciding how to use visual coding principles is a design issue. In any complex design problem, the optimal perceptually based coding solution may not be possible for each individual piece of information because some graphic resource (e.g., a bright color) may have already been used. It is only possible to provide perceptually based design guidelines for relatively simple situations. Where requirements are complex, it is the designer's task to make the right choices and use graphic resources wisely. The solution in the gas tank problem, for example, can be something additional and very visually salient—a blinking light—to indicate the shortage of gas.

Testing Claims About Sensory Representations

Entirely different methodologies are appropriate to the study of representations of the sensory and arbitrary types. In general, the study of sensory representations can employ the scientific methods of vision researchers and biologists. The study of arbitrary conventional representations is best done using the techniques of the social sciences, such as sociology and anthropology; philosophers and cultural critics have much to contribute. [Appendix C](#) provides a brief summary of the research methodologies that apply to the study of sensory representations. All are based on the concept of the controlled experiment. For more detailed information on techniques used in vision research and human-factors engineering, see Palmer (1999) and Wickens (1992).

Representations That Are Arbitrary

One way of looking at the sensory-versus-arbitrary distinction is in terms of the time the two modes have taken to develop. Sensory codes are the products of the millions of years it has taken for our visual systems to evolve. The development of arbitrary conventional representations (such as number systems) occurred over the past thousands of years, but many more have had only a few decades of development. High-performance interactive computer graphics have greatly enhanced our capability to create new codes. We can now control motion and color with flexibility and precision. For this reason, we are currently witnessing an explosive growth in the invention of new graphic codes.

Arbitrary codes are by definition socially constructed. The word *dog* is meaningful because we all agree on its meaning and we teach our children the meaning. The word *carrot* would do just as well, except we have already agreed on a different meaning for that word. In this sense, words are arbitrary; they could be swapped and it would make no difference, as long as they are used consistently from the first time we encounter them. Arbitrary visual codes are often adopted when groups of scientists and engineers construct diagramming conventions for new problems that arise. Examples include circuit diagrams used in electronics, diagrams used to represent molecules in chemistry, and the unified modeling language used in software engineering. Of course, many designers will intuitively use perceptually valid forms in the codes, but many aspects of these diagrams are entirely conventional. Arbitrary codes have the following characteristics:

Hard to learn. It takes a child hundreds of hours to learn to read and write, even if the child has already acquired spoken language. The graphic codes of the alphabet and their rules of combination must be laboriously learned. The Chinese character set is reputed to be even harder to work with than the Roman.

Easy to forget. Arbitrary conventional information that is not overlearned can easily be forgotten. It is also the case that arbitrary codes can interfere with each other. In contrast, sensory codes cannot be forgotten.

Embedded in culture and applications. Different cultures have created their own distinctive symbol sets. An Asian student in my laboratory was working on an application to visualize changes in computer software. She chose to represent deleted entities with the color green and new entities with red. I suggested to her that red is normally used for a warning, while green symbolizes renewal, so perhaps the reverse coding would be more appropriate. She protested, explaining that green symbolizes death in China, while red symbolizes luck and good fortune.

Many graphical symbols are transient and tied to a local culture or application. Think of the graffiti of street culture or the hundreds of new graphical icons that are being created on the Internet. These tend to convey meaning with little or no syntax to bind the symbols into a formal structure. On the other hand, in some cases, arbitrary



Figure 1.9 Two methods for representing the first five digits. The code given below is easier to learn but is not easily extended.

representations can be almost universal and have elaborate grammars associated with their use. The Arabic numerals shown in Fig. 1.9 are used widely throughout the world. Even if a more perceptually valid code could be constructed, the effort would be wasted. The designer of a new symbology for Air Force or Navy charts must live within the confines of existing symbols because of the huge amount of effort invested in the standards. We have many standardized visualization techniques that work well and are solidly embedded in work practices, and attempts to change them would be foolish. In many applications, good design is standardized design.

Conventional symbol systems persist because they have become embedded in ways in which we think about problems. For many geologists, the topographic contour map is the ideal way to understand relevant features of the Earth's surface. They often resist shaded computer graphics representations, even though these appear to be much more intuitively understandable to most people. Contour maps are embedded in cartographic culture and training.

Formally powerful. Arbitrary graphical notations can be constructed that embody formally defined, powerful languages. Mathematicians have created hundreds of graphical languages to express and communicate their concepts. The expressive power of mathematics to convey abstract concepts in a formal, rigorous way is unparalleled; however, the languages of mathematics are extremely difficult to learn (at least for most people). Clearly, the fact that something is expressed in a visual code does not mean that it is easy to understand.

The foregoing analysis leads to our fourth guideline.

[G1.4] Graphical symbol systems should be standardized within and across applications.

It is important, however, that they first be designed to be perceptually efficient.

The Study of Arbitrary Conventional Symbols

The appropriate methodology for studying arbitrary symbols is very different from that used to study sensory symbols. The tightly focused, narrow questions addressed by psychophysics are wholly inappropriate to investigating visualization in a cultural context. A more appropriate methodology for the researcher of arbitrary symbols may derive from the work of anthropologists such as Geertz (1973), who advocated "thick description." This approach is based on careful observation, immersion in culture,

and an effort to keep “the analysis of social forms closely tied ... to concrete social events and occasions.” Also borrowing from the social sciences, Carroll and coworkers developed an approach to understanding complex user interfaces that they call *artifact analysis* (Carroll, 1989). In this approach, user interfaces (and presumably visualization techniques) are best viewed as artifacts and studied much as an anthropologist studies cultural artifacts of a religious or practical nature. Formal experiments are out of the question in such circumstances, and if they were actually carried out, they would undoubtedly change the very symbols being studied. Unfortunately for researchers, sensory and arbitrary aspects of symbols are closely intertwined in many representations, and although they have been presented here as distinct categories the boundary between them is very fuzzy. There is no doubt that culture influences cognition; it is also true that the more we know, the more we perceive. Pure instances of sensory or arbitrary coding may not exist, but this does not mean that the analysis is invalid. It simply means that for any given example we must be careful to determine which aspects of the visual coding belong in each category.

In general, our scientific understanding of how visualizations work is still in its infancy. There is much about visualization and visual communication that is more craft than science. For the visualization designer, training in art and design is at least as useful as training in perceptual psychology. For those who wish to do good design, the study of design by example is generally most appropriate, but the science of perception can provide a scientific basis for design rules, and it can suggest entirely new design ideas and methods for displaying data that have not been tried before.

Gibson's Affordance Theory

The great perception theorist J. J. Gibson brought about radical changes in how we think about perception with his theories of ecological optics, affordances, and direct perception. Aspects of each of these theoretical concepts are discussed throughout this book. We begin with affordance theory (Gibson, 1979).

Gibson argued that we perceive in order to operate on the environment. Perception is designed for action. Gibson called the perceivable possibilities for action *affordances*, and a cornerstone of his theory is that affordances are perceived in a *direct* and immediate way. They are not *inferred* from sensory clues. This theory is clearly attractive from the perspective of visualization, because the goal of most visualization is decision-making. Thinking about perception in terms of action is likely to be much more useful than thinking about how two adjacent spots of light influence each other's appearance (which is the typical approach of classical psychophysicists). Much of Gibson's work was in direct opposition to the approach of theorists who reasoned that we must deal with perception from the bottom-up, as with geometry. The pre-Gibsonian theorists tended to have an atomistic view of the world. They thought we should first understand how single points of light were sensed, and then we could work on understanding how pairs of lights interacted. Gradually, building layers of theory from the bottom-up, we would eventually gain understanding of how people

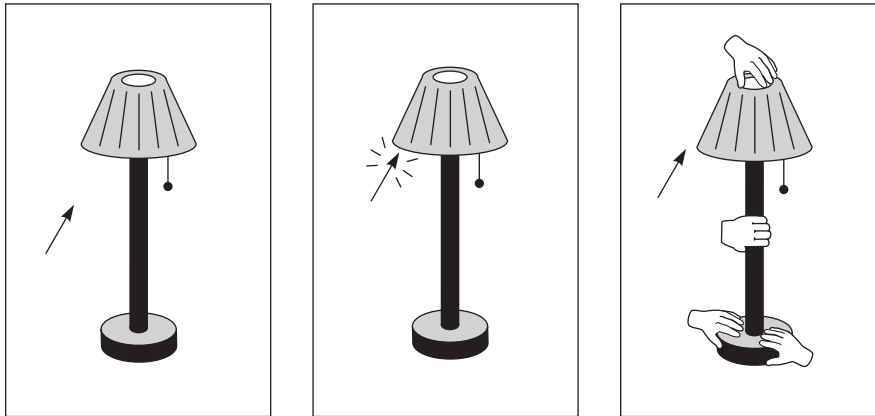


Figure 1.10 Cartoon cues are used to illustrate what interactions are possible. (From Houde (1992). Reproduced with permission.)

perceive the vibrant, dynamic visual world in which we live. Gibson took a radically different, top-down approach. He claimed that we do not perceive points of light; rather, we perceive possibilities for action. We perceive surfaces for walking, handles for pulling, space for navigating, tools for manipulating, and so on.

In general, our whole evolution has been geared toward perceiving useful possibilities for action. In an experiment that supports this view, Warren (1984) showed that subjects were capable of accurate judgments of the “climbability” of staircases. These judgments depended on their own leg lengths. Gibson’s affordance theory is tied to a theory of direct perception. He claimed that we perceive affordances of the environment directly and immediately, not indirectly by piecing together evidence from our senses.

Translating the affordance concept into the interface domain, we might construct the following principle: A good interface has affordances that make the user’s task easy; for example, if we have a task of moving an object in 3D space, it should have clear handles to use in rotating and lifting the object. Fig. 1.10 shows a design for a 3D object manipulation interface from Houde (1992). When an object is selected, “handles” appear that allow the object to be lifted or rotated. The function of these handles is made more explicit by illustrations of gripping hands that show the affordances.

Gibson’s theory, however, presents problems if it is taken literally. According to Gibson, affordances are physical properties of the environment that we directly perceive. Many theorists, unlike Gibson, think of perception as a very active process. They show that the brain continuously predicts properties of the environment based on the available sensory evidence, and continuously updates and tests these predictions. Gibson rejected this view in favor of the idea that our visual system is tuned to perceiving the visual world and that we perceive it accurately except under extraordinary circumstances. He preferred to concentrate on the visual system as a whole and not to break perceptual processing down into components and operations. He used the term

resonating to describe the way the visual system responds to properties of the environment. This view has been remarkably influential and has radically changed the way vision researchers think about perception; nevertheless, few would accept it today in its pure form.

There are three problems with Gibson's direct perception approach in developing theories of how visualizations work. The first problem is that even if perception of the environment is direct, it is clear that visualization of data through computer graphics is very indirect. Typically, there are many layers of processing between the data and its representation. In some cases, the source of the data may be microscopic or otherwise invisible. The source of the data may be quite abstract, such as company statistics in a stock-market database. Direct perception is not a meaningful concept in these cases.

Second, there are no clear physical affordances in any graphical user interface. To say that a screen button "affords" pressing in the same way as a flat surface affords walking is to stretch the theory beyond reasonable limits. In the first place, it is not even clear that a real-world button affords pressing. In another culture, these little bumps might be perceived as rather dull architectural decorations. Clearly, the use of buttons is arbitrary; we must learn that buttons, when pressed, do interesting things in the real world. Perception and action are linked in even more indirect ways when we use a computer; for instance, we must learn that a picture of a button can be "pressed" using a mouse, a cursor, or yet another button. This is far from being direct interaction with the physical world.

Third, Gibson's rejection of visual mechanisms is a problem. To take but one example, much that we know about color is based on years of experimentation, analysis, and modeling of the perceptual mechanisms. Color television and many other display technologies are based on an understanding of these mechanisms. To reject the importance of understanding visual mechanisms would be to reject most of vision research as irrelevant. This entire book is based on the premise that an understanding of perceptual mechanisms is basic to providing visualization designers with sound design principles. The modern theory of predictive perception is the basis for the final two chapters.

Despite these reservations, Gibson's theories influence much of this book. The concept of affordances, loosely construed, can be extremely useful from a design perspective. The idea suggests that we build interfaces that beg to be operated in appropriate and useful ways. We should make virtual handles for turning, virtual buttons for pressing. If components are designed to work together, this should be made perceptually evident, perhaps by creating shaped sockets that afford the attachment of one object to another. This is the kind of design approach advocated by Norman in his famous book, *The Psychology of Everyday Things* (1988). Nevertheless, on-screen widgets present affordances only in an indirect sense. They borrow their power from our ability to represent pictorially, or otherwise, the affordances of the everyday world. Therefore, we can be inspired by affordance theory to produce good designs, but we cannot expect much help from that theory in building an applied science of visualization.

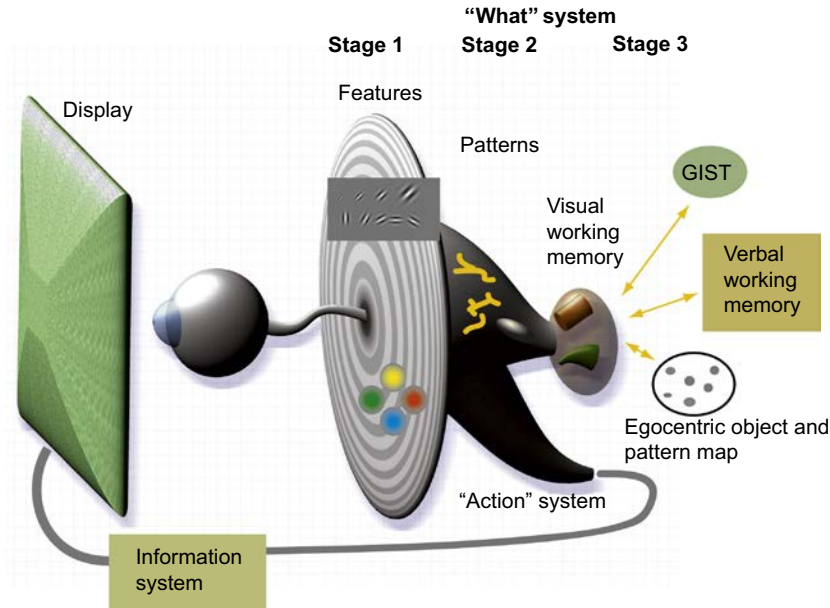


Figure 1.11 A three-stage model of visual information processing.

A Model of Perceptual Processing

In this section, we introduce a simplified information processing model of human visual perception. As Fig. 1.5 shows, there are many subsystems in vision, and we should always be wary of overgeneralization. Still, an overall conceptual framework is useful in providing a starting point for more detailed analysis. Fig. 1.11 gives a broad schematic overview of a three-stage model of perception. In Stage 1, information is processed in parallel to extract basic features of the environment. In Stage 2, active processes of pattern perception pull out structures and segment the visual scene into regions of different color, texture, and motion patterns. In Stage 3, the information is reduced to only a few objects held in visual working memory by active mechanisms of attention to form the basis of visual thinking.

Stage 1. Parallel Processing to Extract Low-Level Properties of the Visual Scene

Visual information is first processed by large arrays of neurons in the eye and in the primary visual cortex at the back of the brain. Individual neurons are selectively tuned to certain kinds of information, such as the orientation of edges or the color of a patch of light. In Stage 1 processing, billions of neurons work in parallel, extracting features from every part of the visual field simultaneously. Treisman (1985) described the result as a set of feature maps. This parallel processing proceeds whether we like it or not and is largely independent of what we choose to attend to (although not where we look). It is also rapid. If we want people to understand information quickly, we should