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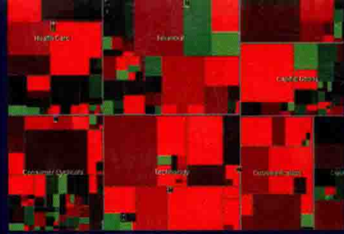
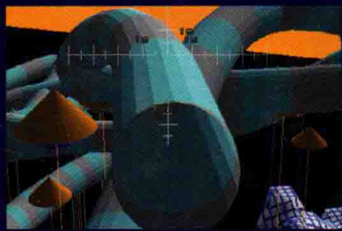
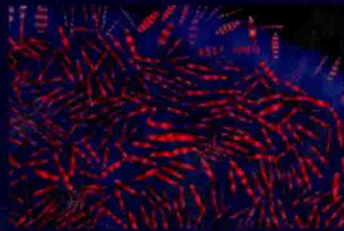


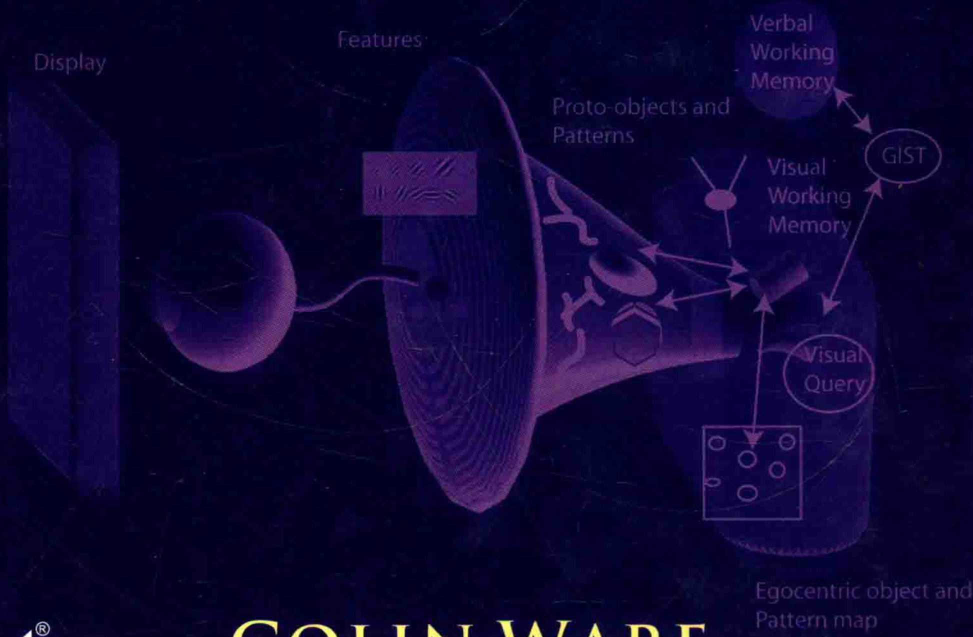




SECOND EDITION

INFORMATION VISUALIZATION

PERCEPTION FOR DESIGN



COLIN WARE

MORGAN

Second Edition

INFORMATION VISUALIZATION

Perception for Design

Colin Ware

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Perception for Design

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FOREWORD

I see what you mean. This common expression illustrates the deeply-held intuition that vision and artful images are an alternate and seemingly direct route to *insight*, which is itself another of the many words or phrases relating to vision and understanding. *A picture is worth 10,000 words*, to quote another example. Over history, visual abstractions have been developed to aid thinking: pictures from antiquity, maps from ancient Egypt, the geometry diagrams of Euclid, and the statistical diagrams of Playfair. In fact, disciplines of practice have grown up around how to do these: cartography; mechanical drawing; electrical schematics; information design for signs, labeling, and books; and statistical data graphics.

Information visualization, which is the use of interactive visual representations of abstract data to amplify cognition, is the latest of these disciplines. Because of the computer, information diagrams or visualizations can be prepared automatically at time of use, can be made dynamic and interactive, and can be integrated into a larger process of sensemaking and creation. The potential for information visualization is vast. Staggering advances in interactive computer graphics over the last two decades potentially enable building systems that give rapid insight into information-intensive problems in medicine, finance, business, and scholarship. But the design of information visualization systems is also very subtle, and there needs to be a supporting science for how to do it.

New disciplines or areas tend to go through phases. First there is the phase of exploratory design—point designs that explore the space of what can be done with the new capabilities. This has already been completed for information visualization. Then there is the characterization phase, taxonomizing or otherwise organizing the methods that have been developed and developing theories of what works. This is the current frontier of information visualization and the one most directly attacked in this book. It is necessary to progress to the future stages of validating that the theories can be used to form new designs and, finally, the codification into handbooks of engineering principles.

What information visualization is really about is external cognition, that is, how resources outside the mind can be used to boost the cognitive capabilities of the mind. Hence the study of information visualization involves analysis of both the machine side and the human side. Almost any interesting task is too difficult to be done purely mentally. Information visualization enables mental operations with rapid access to large amounts of data outside the mind, enables substituting of perceptual relation detection for some cognitive inferencing, reduces demands on user working memory, and enables the machine to become a co-participant in a joint task, changing the visualizations dynamically as the work proceeds.

Successful design of information visualization systems depends on adequately characterizing the task, the human visual system, visual displays, and the dynamic interaction among all of these. The apparent simplicity of seeing belies the complex mechanisms to achieve it. Colin Ware has written a book that brings together what is know about information visualization and its connection to vision, perception, and visual cognition. He is the perfect person to do it, with a long history of prominent contributions to the visual interaction with machines and to information visualization directly. This book starts with the visual system and moves out to its interaction with displays, visual forms, and tasks. It fills in and makes accessible much of the supporting science needed for the progress of this field beyond intuitions of what makes a useful picture. tithes book goes a long way toward joining science to the practical design of information visualization systems.

Stuart Card

PREFACE

The problem of visual thinking provided the motivation for another edition of this book. From the moment I finished the first edition, I felt the need to explore further the broader issues of how we use visualizations as cognitive tools in problem solving. The initial inspiration for the account that has emerged came from an essay by Kevin O'Regan (1992), wherein he argued that we do not have a detailed image of the world in our heads. As he put it, the world is "its own memory." He maintained that the reason we see a coherent world is that we can sample it any time we need to with a rapid eye movement or a redirection of attention within a single fixation. O'Regan was not the first to make this point, and I had already argued something similar with respect to space perception in the first edition. However, after reading O'Regan's eloquent essay I started to think more seriously about the implications of the detailed representations of the visual world.

This fact—that most of what we see is actually "out there," not in our heads—has profound implications. It explains why one's ability to think is extremely limited without external props and tools. Most cognition can be regarded as a distributed process that includes cognitive components, such as the visual system, verbal processing systems, and memory structures traditionally studied by psychologists, plus cognitive tools such as paper and pencil, diagrams, books, and the manipulation of external symbols on paper. Very rapid problem solving can be done with the right interactive display, as we pull out patterns through rapid visual searches. Increasingly, cognitive tools are computer-based, and an interactive visualization is a critical interface between the human and machine. The much-debated issue of whether or not computers can be intelligent is beside the point—people are not very intelligent without external cognitive tools. Intellectual products, such as books, pictures, theories, designs, and plans are, with few exceptions, the products of cognitive systems made up of human brains acting in concert with cognitive tools. Thus, productive intelligence can be said to reside in the system as a whole.

The process of visual thinking is the subject of an entirely new final chapter. This provides an account of visual thinking that has visual queries as a central component. Visual queries are acts of attention, pulling out patterns from the display, to meet the requirements of the task at hand. The other key components of this account of visual thinking are the data representation and the cost of acquiring knowledge—a function of both the cognitive overhead of using the computer interface and various navigation costs. Eye movements, zooming, and hyperlinks can all be treated as navigation devices whose various tradeoffs must be considered carefully in cognitive systems design.

In addition to the new chapter on visual thinking, this edition is expanded and updated throughout. It contains new sections on topics including color sequences, flow visualization, and face perception. It has many new references and figures. A new appendix deals with how to evaluate visualization techniques.

I wish to acknowledge two individuals for their contributions to the visual thinking chapter. The work of my graduate student, Matt Plumlee, has been especially helpful in showing how useful, practical guidelines for interface design can come from a relatively simple cognitive systems model. Conversations with Ron Rensink, of the University of British Columbia, also substantially influenced my thinking.

I very much appreciate the continuing support of Diane Cerra and Mona Buehler at Morgan Kaufmann. Credit for improved grammar and many corrections in references is due to the patient and polite assistance of production editor Denise DeLancey and her team. Also, my wife Dianne Ramey read the whole manuscript once again and made countless suggestions for improvement, most of which I adopted. The remaining errors, both grammatical and factual, are all mine.

PREFACE TO THE FIRST EDITION

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 sixties and early seventies, I decided to become an artist and explore perception in a different way. But after three years with only 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 Ph.D. in the psychology of perception at the University of Toronto, I took a position at the National Research Council of Canada to work on color perception. Three years later I moved on to 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 why the words *understanding* and *seeing* are synonymous. We know that 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 *DATA,* shown in Figure 1, is much more visible in the bottom version 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, 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 rules for displaying information. Following perception-based rules, we can present 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.

Figure 1 The word *DATA* is easier to read when the overlapping bars are visible. *Adapted from Nakayama et al. (1989).*

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 couched in language that is accessible only to the specialist. 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 discusses the theoretical context for a vision science–based approach. The next four chapters discuss what can be considered 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 2D pattern perception and later 3D space perception. Visualization design, data space navigation, interaction techniques, and visual problem solving are all discussed.

Here is a road map to the book: 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 access the book randomly to learn about specific topics. When it is needed, missing background information can be obtained by consulting the index.

Chapter 1: Foundation for a 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 a science of perception–based approach. 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. The 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. The way 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, pseudocolor sequences for mapping, color reproduction, and color for multidimensional discrete data.

Chapter 5: Visual Attention and Information That Pops Out 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 that 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, node–link diagrams, and layered displays.

Chapter 7: 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 8: Space Perception and the Display of Data in Space 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 seven spatial tasks and the perceptual issues associated with each.

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

Chapter 9: Images, Words, and Gestures 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.

The applications discussed include integrating images and words, 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.

The applications discussed include interacting with data, selection, scrolling, zooming interfaces, and navigation.

Chapter 11: Thinking with Visualization The process whereby a visualization is used as part of a decision-making process is outlined. Central to this is a description of how visual queries are formed to guide attention and determine what is loaded into visual working memory. This model provides insights into how to balance the tradeoffs between navigation costs and screen layout in the design of visual information systems.

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

These are exciting times for visualization design. The computer technology used to produce visualizations has reached a stage at which sophisticated, interactive 3D views of data can be produced on ordinary desktop computers. 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 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 can help us to avoid such mistakes. If we can harness the knowledge that has been accumulated about how perception works, we can make visualizations into more transparent windows into the world of information.

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 Kelly Booth, Dave Wells, Tim Dudely, Scott Mackenzie, and Eric Neufeld. It has been my good fortune to work with many talented graduate students and research assistants on visualization-related projects: Daniel Jessome, Richard Guitard, Timothy Lethbridge, Siew Hong Yang, Sean Riley, Serge Limoges, David Fowler, Stephen Osborne, K. Wing Wong, Dale Chapman, Pat Cavanaugh, Ravin Balakrishnan, Mark Paton, Monica Sardesai, Cyril Gobrecht, Suryan Stalin, Justine Hickey, Yanchao Li, Rohan Parkhi, Kathy Lowther, Li Wang, Greg Parker, Daniel Fleet, Jun Yang, Graham Sweet, Roland Arsenault, Natalie Webber, Poorang Irani, Jordan Lutes, Nhu Le, Irina Padioukova, Glenn Franck, Lyn Bartram, and Matthew Plumlee. Many of the ideas presented here have been refined through their efforts.

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