Chapter 6

Vision, Graphic Design, and Visual Display

Principles of Effective Visual Communication for Graphical User Interface Design 425
Aaron Marcus
Color Graphics—Blessing or Ballyhoo (Excerpt) 442
Gerry M. Murch
Bringing Icons to Life 444
Ronald Baecker, Ian Small, and Richard Mander
Visual Information Seeking: Tight Coupling of Dynamic Query Filters with Starfield Displays 450
Christopher Ahlberg and Ben Shneiderman
A Comparison of Graphical User Interfaces (Excerpt) 457
Aaron Marcus

There is much talk today about information highways, the information economy, and the information revolution. Yet what modern technology has achieved thus far is better described as a data explosion. Data does not become information until it informs, that is, until it can be used as the basis for problem solving and decision making. One primary goal of interactive computer systems must therefore be to help us extract data that is required for a task from the mass of data available, and to suppress that which is superfluous or irrelevant.

But simply providing a selective "filter" is not enough. In evety transaction with a computer, the user is making decisions. We need to provide the relevant information for the task at hand, and to provide it in the most articulate, succinct, and appropriate manner possible. In doing so we exploit the human capacity for perceiving structure and organization—in short, for understanding.

The main vehicle today for delivery of information from a computer to a human being is the visual channel. This chapter deals with the visual representation, presentation, perception, and comprehension of information. It also deals with the discipline of graphic design, which has as its mission the design of effective visual presentations. Finally, it deals with methods and technologies for producing effective visual presentations and delivering them to users.

FROM SENSATION TO PERCEPTION

Effective human-computer interaction requires the presentation of information so that the eye and brain can see what the presenter intended to be seen. This is not always a trivial probiem because the viewer does not perceive an image that conforms exactly to the physical image displayed on a computer screen. The visual sensations reaching the eye are translated into perceptual experience by the brain through processes such as pattern recognition. We therefore need to acquaint ourselves with how we experience and perceive such phenomena as brightness, contrast, flicker, motion, and color.

We can only hint at the relevant material in this volume and provide pointers to generally accessible literature. Different sources provide complementary insights—the literatures of psychophysics and the psychology of perception, human factors, and graphic design and visual presentation. In this section we review principles of psychophysics and visual perception.

Although the chapter deals with vision, certain characteristics of the human sensorimotor system apply regardless of the modality. One of these is the difference between the magnitude of a physical stimulus and the magnitude of the psychological sensation of that stimulus. We must distinguish between visual intensity and brightness, between wavelength and hue, between aural intensity and' loudness, and between frequency and pitch. Research in *psychophysics* has concluded that psychological magnitude is related to physical stimulus by a power law that applies across a wide variety of sensory phenomena, with exponents ranging from 0.33 for visual brightness to 3.5 for the subjective strength of electric current applied to the finger (Stevens, 1961). Thus we cannot rely blindly upon the physical properties of a visual or auditory display, but must instead consider carefully how particular colors or sounds will be received by a human observer.

The science of psychophysics also contributes a number of other useful concepts (Van Cott and Kinkade, 1972), including

- sensitivity range along a stimulus scale from minimum perceivabie to maximum tolerable for a human observer
- relative discrimination sensitivity, measuring an observer's ability to distinguish between two stimuli or to detect a change in one stiiuius, also known as the "just noticeable difference" (JND)
- ability to make absolute judgments of stimuii or of their magnitude along some scale, expressed as a number of distinguishable values (Miller, 1956)

Absolute judgments are typically much more difficult than relative judgements. Thus, although we can distinguish several hundred different intensities of light or sound on a relative basis, we can only reliably identify on the order of a half dozen or a dozen different absolute stimuli arrayed along a single psychophysical dimension, such as brightness, hue, saturation, or value. Figure 6.1 reproduces a summary of visual coding methods, and provides some guidelines regarding our ability to discriminate displays that are coded using various individual stimulus dimensions. Multiple stimulus dimensions can often be combined to give us more discriminable stimuli.

FIGURE 6.1

Visual coding methods. The approximate number of levels that can he discriminated on an absolute basis under optimum conditions (Sanders and McCormick, 1993, p. 126)

Alphanumeric, single numerals	10
Alphanumeric, single letters	26
Color (hue of surfaces)	9
Color (hue, saturation, and brightness combinations)	24
preferable limit	9
Color (hue of lights)	10
preferable limit	3
Geometric shapes	15
preferable limit	5
Size of forms (such as squares)	5
preferable limit	3
Brightness of lights	3
preferable limit	2

The process of organizing sensations into perception also shares common elements independent of sensory modality (Lindsay and Norman, 1977, Chapter 1). Perhaps the most important of these is the brain's attempt to organize sensory messages info meaningful *patterns* and *structures.* It does this by applying rules that summarize its model of the way the world is organized and the way it should appear in various contexts. This allows us to integrate often incomplete and sometimes inconsistent sensations into a plausible perception of the structure of the source of the sensations.

Perception is an *active process.* What is seen is not merely a passive response to visual input, but the result of hypothesis formation and testing conditioned by our expectations. Lindsay and Norman (1977) describe this as the combination of "data driven" and "conceptually driven" processing, what computer scientists might call "bottom up" and "top down" computation.

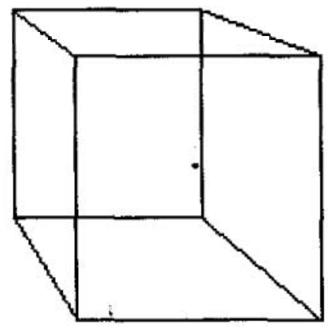
What kinds of hypotheses are generated? Haber and Wilkinson (1982, p. 25) suggest how we attempt to perceive *structure* in the images we see:

> ***The human visual system is designed to produce organized perception. Information consisting of a variety of such spatial features assize, shape, distance, relative position, and texture is structured by the mind to represent visual scenes. These spatial features areperceived as properties ofthings, objects in the scene, and not merely as abstract lines or surfaces: We do notperceive lines or unattached extents; we perceive objects. All parts of each object areperceived together in one construction—not as separate, independent, and free-floating elements. And all the objects are perceived as related to each other--near: far: behind, adjoining, and so forth. . . .***

Examples of perceived structure include the "perceptual constancies" that result in buildings appearing to stand still, people remaining the same size and shape, and snow remaining white, despite the fact that the retinal images may have radically different positions, shapes, and brightnesses depending upon the viewing conditions. Another central concept that emerges is that of *context,* how what is seen in one part of an image is affected by what appears in adjoining parts in space (within the current scene) and in time (in the immediate recent past). More generally, what is seen is very often not what is presented—optical *illusions* are perhaps the most dramatic example of this. Illusions are often the result of multiple possible structures and competing interpretations, as in the familiar figure-ground phenomena or the Neckar cube illusion (Figure 6.2). Thus, in structuring our screens, we must not automatically assume that our intentions can be easily translated into effective presentation and communication—we must work to achieve the desired results.

FIGURE 6.2

The Neckar cube—an optical illusion. Notice how one stimulus causing one optical sensation can result in two dramatically different perceptions of thefigure.



Given this framework, the interested student canaccess the literature to fill in other needed background—the basic anatomical and physiological properties of the eye and of the neural pathway to the brain, the dimensions of vision and the perception of brightness, contrast, fiicker, motion, and color. Particularly useful is a superb publication that presents an encyclopedic survey of perception and human performance (Boff, Kaufman, and Thomas, 1986). Other useful sources in the psychology literature are Thompson (1985), Chapters 2 and 3 of Lindsay and Norman (1977), and the book by Gregory (1966).

The human factors literature is complementary, focusing on the optimum characteristics of specialized kinds of displays. Typical treatments are Chapter 3 of Van Cott and Kinkade (1972), Chapter 7 of Kantowitz and Sorkin (1983), and Chapters 4 and 5 of Sanders and McCormick (1993). These consider, among other topics, the appropriate design of alphanumeric displays, visual codes and symbols, quantitative and qualitative displays of data, status indicators, signal and warning lights, and representational displays.

GRAPHIC DESIGN FOR EFFECTIVE VISUAL COMMUNICATION

The literature of psychology, psychophysics, and human factors typically describes and quantifies the possibilities and limits of human visual performance. The results tell us what cannot be done, what cannot possibly work. Graphic *design* is the art of the possible, the discipline of effective visual communication. Its application is essential to the design of effective displays and usable interfaces. We cannot here provide a course on graphic design, but can introduce key concepts and provide reliable pointers to the literature.

Bowman (1968) provides a brilliant and systematic introduction to the visual language of effective graphic communication. He describes a vocabulary of form elements—point, line, shape, value, and texture; a grammar of *spatial* organization—plane, multiplane, and continuous; an idiom of *volumetric perspective*—parallel, angular, and oblique; and a syntax for phrasing the *image*—relationship, differentiation, and emphasis. Then he discusses the visualization process in terms of the three basic steps of concept, design, and production. He concludes with an extensive design library of examples illustrating how to show

- *what*—natural appearance, physical structure, and organization of parts in relation to the whole
- *how*—physical movement, system of flow in relation to component parts, and process as a succession of related events
- *how much*—physical size, numerical quantity, trend of inaease or decrease, and division of its parts in terms of the whole
- where—natural area, environmental location, and position with respect to other individual elements ,

Dondis (1973) stresses that the process of composition is the most crucial step in visual problem solving She illustrates with examples combining what she defines as the basic elements of visual *communication—the* dot, the line, shape, direction, tone, color, texture, scale, dimension, and movement. The compositional technique she views as most important is that of contrast, and she devotes some effort to its explication. She also presents a variety of purposely polarized techniques for visual communication, for example, balance and instability, symmetry and asymmetry, regularity and irregularity, simplicity and complexity, and unity and fragmentation.

A third source of design ideas is Hofmann (1965), a catalog of challenging visual design examples organized around the themes of the dot, the l i e , confrontation, and letters and signs.

These volumes may seem far removed from human-computer interaction, but their insights can and must be applied to the design of effective displays and usable interfaces. No designer has within the past fifteen years argued this more forcefully and more articulately than Aaron Marcus (1983, included as a reading in Baecker and Buxton, 1987). Good introductions to the discipline of graphic design and its application to interface design are Marcus (1990), included here as a reading, and a recent book, Marcus (1992). He presents examples that demonstrate the importance of careful selection and arrangement in using typography, signs and symbols, charts and diagrams, color, and spatial and temporal arrangement. Echoing insights from psychology, he suggests the use of consistent layout and formatting conventions applied with reference to an appropriate grid. The resulting visual structure serves to guide the eye as the brain attempts to parse and interpret an image, and helps the user to navigate through the succession of displays and images presented by a system in the course of its use.

Marcus develops his recommendations for effective visual communication in terms of three basic principles—organize, economize, and communicate. He stresses that the application of design principles to the medium of computer displays and interactive systems is not a trivial process. The medium typically has numerous special features and restrictions such as limited spatial extent and resolution. Thus there is a compelling need to enlist the participation of skilled graphic designers in the design of screens and human-computer interfaces.

A comprehensive review of research results that inform effective screen design is Tullis (1988). Videos that deal with graphic design for effective visual communication include Easel Corp. (1992 video) and Henry Dreyfuss Associates (1992 video).

Typography at the Interface

The most basic element of graphic design, as it affects each and every user interface, is *typography*. The craft of typography begins with the design of attractive and legible *letterforms* in a variety of ***typefaces*** or *fonts*, that may be either *serif* or sans *serif*, and that are arranged in families encompassing variations in ***weight***, such as regular and *bold*, and variations in slant, such as roman and italic Typography includes the careful arrangement of sequences of letterforms on the page with the goal of enhancing readability. This is done by controlling parameters of individual characters, such as *point size* and *letterspacing*, of words, such as *word spacing*, and of lines, such as line *length*, *leading*, and *justification*. Finally, typography encompasses the augmentation of raw text with simple graphic elements such as *rules*, *leader* lines, and *logotypes*. These typographic parameters and possibilities are illustrated in Figure 6.3.

FIGURE 6.3

Some typographic *variations. These* are only a far, of *the many* possibilities.

A line of 10 point type, Times Roman serif font

A line of 10 point type, Helvetica sans serif font.

A line of 10 point type, Helvetica bold.

A line of 10 point type, Helvetica italic.

`A line of fixed-width type.`

Type with normal letter spacing.

Type with condensed letter spacing.

A n d   w i t h   e x p a n d e d   l e t t e r   s p a c i n g .

Two lines with a
shorter line length.

Two lines of type

with increased leading.

A line of type flush left.

A line of type flush right.

A line of type centered.

The discipline of typography was always relevant to screen design, even in the days of single font fixed-width 24 x 80 character displays (Marcus, 1982a). Bit-mapped displays on personal computers and workstations allow for richer possibilities, yet restraint is required. The computer scientist's undisciplined delight in typography sometimes leads to "fontitis," the inclusion of so many fonts and point sizes in a single display that the result is visual chaos. As the eminent graphic designer Chuck Bigelow cautioned at CHI+GI '87, "What good is all this power if you lay waste to the literate landscape?"

Rosen (1963) presents a catalog of classic typefaces whose grace and expressiveness put to shame the typical appearance of our screens and printouts. Ruder (1967) presents a rich body of evocative examples showing some of the uses and appearances of typography within design.

Bigelow and Day (1983, included as a reading in Baecker and Buxton, 1987), introduces some of the issues of digital typography including letterform design, representation of digital letterforms, letterform quality, legibility and readability of digital text at different resolutions, and the problem of *aliasing*, in which high spatial frequencies in an original image are reproduced as local spatial frequencies, leading to the characteristic *jaggies* that are still often seen in low-resolution digital images. Morris (1989) reviews the history and key research issues of digital typography. More comprehensive treatments may be found in Seybold (1984), which presents digital typesetting in the context of the entire typesetting and printing process, and Rubinstein (1988), which pays particular attention to the technology of composition and layout.

Within the literature of computer science, Witten (1985) presents the fundamentals of computer typography and some solutions to the difficult problems of line breaks, hyphenation, justification, and page makeup. Brown (1989) reviews and critiques two international standards for the representation and exchange of structured documents, the Office Document Architecture (ODA) and the Standard Generalized Markup Language (SGML). Naiman (1991) is a comprehensive treatment of technical and perceptual issues in the use of grayscale for improved character presentation. Bibliographies and research results on digital typography may be foundin-van Vliet (1986, 1988), Andre and Hersch (1989), and Naiman (1991).

There is also much to be learned from the literature on the legibility and readability of typography. Tinker (1963, 1965) and Huey (1968) present some classic research on the legibility of type and on the psychology of reading. Hartley (1978, 1980); Kolers, Wrolstad, and Bouma (1979, 1980); Felker (1980); and Felker et al. (1981) are more modern collections of articles on the readability of documents and structured text.

Generally, text on screens has been found to be less legible than text on paper Gould et al. (1987) surveys much of the relevant literature and presents the results of some experiments that fail to explain why this is so, but demonstrate some of the contributing factors. Gould et al. (1986) and Gould et al. (1987) show that reading speeds equivalent to that on paper may he obtained through the use of high-quality antialiased fonts displayed with dark characters on a light background on a high-resolution screen.

Videos dealing with typography include Xerox (1985a video, 1985b video), Russell (1987 video), Giannitrapani (1987 video), and Small, Ishizaki, and Cooper (1994 video).

Color in Interfaces

Color is another key component of graphic design for effective human-computer interaction. The appropriate use of color is difficult. Our reactions to color result from a complex set of physiological, perceptual, and cognitive phenomena, which are translated into principles and guidelines for the effective use of color in the third part of the reading by Marcus (1990), and also in the reading consisting of a short excerpt from a paper by Murch (1985), which in turn summarizes a longer treatment (Murch, 1984). Murch (1985) is reprinted in its entirety in Baecker and Buxton (1987). Two other readable introductions to the use of color in computer displays and interfaces are Marcus (1982b) and Salomon (1990).

Both Murch and Marcus stress the need for restraint in the use of color, avoiding the "fruit salad" appearance resulting from the undisciplined use of color. The serious student of color will need to review considerable material from the art and design literature, for example, Itten (1961), Albers (1963), Chevreul (1967), Yule (1967), Birren (1969a, 1969b), Hunt (1975), and Wong (1987). Wyszecki and Stiles (1982) is a comprehensive treatment of color science, including colorimetry, photomey, and color vision.

The computer science literature has tended to focus on issues of choosing the appropriate color space and of automating the mapping from one space to another (Joblove and Greenberg, 1978; Meyer and Greenberg, 1980; Smith, 1978). Robertson and O'Callaghan (1986) deals with the use of color to display quantitative information. In 1986, the journal *Color Research and Application* contained the proceedings of a meeting covering a broad range of issues in both softcopy and hardcopy computer-generated color. Stone, Cowan, and Beatty (1988; see also Stone, 1987 video; Beretta and Stone, 1990 video) discusses the problem of mapping gamuts of display monitor colors to gamuts of printer colors in order to enable the faithful reproduction of screen images on paper.

Two recent books are particularly valuable. Travis (1991) reviews color display hardware, color vision, methods of color specification, and the appropriate use of color. Durrett (1987) discusses many of the same issues, and then examines the use of color in applications ranging from process control to cartography to education.

Pictures, Symbols, Signs, and Icons

Human-computer interfaces increasingly incorporate images as well as text. Arnheim (1969) states that images can function as *pictures*, symbols, and *signs*.

> *An image sows mere@as a* **sign** *to the extent to which it stands for a particular content without reflecting its characteristics visually. . . . Images are* pictures *to the extent to which they portray things located ai a lower level of abstractness than they are themselves. They do heir work by grasping and rendering some relevant qualities—shape, color, movement—of the objects or activities they depict. . . . An image acts as a* symbol *to the extent to which it portrays things which are at a higher level of abstractness than is the symbol itself. . . .*

One trend in user interfaces, arising from advances in computer graphics, is the incorporation of increasingly realistic three-dimensional portrayals (Greenberg, 1982). Mills (1982, 1985) suggests that this by itself is not sufficient to make optimal use of the medium of computer graphics and argues that we need also pay attention to the insights into pictorial representation and communication that arise out of art, art history, design, and the psychology of visual perception (Arnheim, 1954; Gombrich, 1961). Mills shows how man's background, history, and knowledge are embodied in his "cognitive schemata" and his capacity for metaphorical thinking, and how the choice of pictorial representation can facilitate his understanding of images and his problem-solving ability. The imaginative and appropriate choice of visual representation is thus a key determinant of the success of a user interface.

Another trend is that of incorporating in the interface *icons*, images representing system commands, objects, states, or results. Many icons function as pictures. For example, a schematic pen may be used to indicate that the user may now paint, or a short thick line can indicate that lines about to be input will be drawn with a thick stroke. Some icons function as symbols, as for example, in the use of an hourglass, clock, spinning globe, or "smiling Buddha" to indicate that the system is working and the user should be patient. A discussion of the development and testing of icons for use in the Xerox Star appears in the introduction to Case B.

The design of icons is a demanding craft. Dreyfuss (1972) has catalogued the incredible variety of icons in his guide to some of the 20,000 known international graphic symbols. The American Institute of Graphic Arts (AIGA) has analyzed the strengths and weaknesses of passenger/pedestrian-oriented symbols in three distinct dimensions: *semantic, syntactic,* and *pragmatic* (1981, p. 20):

> *The* semantic *dimension refers to the relationship of a visual image to a meaning. How well does this symbol represent the message? Do people fail to understand the message that the symbol denotes? Do people from various cultures misunderstand this symbol? Do people of various ages fail to understand this symbol? Is it difficult to learn this symbol? Has this symbol already been widely accepted? Does this symbol contain elements that are unrelated to the message?*
>
> *The* syntactic *dimension refers to the relationship of one visual image to another. How does this symbol look? How well do the parts of this symbol relate to each other? How well does this symbol relate to other symbols? Is the construction of this symbol consistent in its use of figure/ground, solid/outline, overlapping, transparency, orientation, format, scale, color, and texture? Does this symbol use a hierarchy of recognition? Are the most important elements recognized first? Does this symbol seriously contradict existing standards or conventions? Is this symbol, and its elements, capable of systematic application for a variety of interrelated concepts?*
>
> *The* pragmatic *dimension refers to the relationship of a visual image to a user. Can a person see the sign? Is this symbol seriously affected by poor lighting conditions, oblique viewing angles, and other visual "noise"? Does this symbol remain visible throughout the range of typical viewing distances? Is this symbol especially vulnerable to vandalism? Is this symbol difficult to reproduce? Can this symbol be enlarged and reduced successfully?*

Every aspect of this discussion applies equally well to the design of icons for computer systems. The difficulty of the task is illustrated in a reading included in Baecker and Buxton (1987) that provides excerpts from AIGA (1981) showing possible designs for icons representing "information," "arriving flights," and "exit."

Horton (1994) is an excellent recent comprehensive guide to the roles, design, construction, and testing of icons for computer systems and documentation. He stresses that the perceived meaning of an icon depends upon the context in which it appears and the background, knowledge, and interests of the viewer. Thus, icons are not automatically universal and do not necessarily work in all cultures, but must be carefully designed and tailored for international use. Horton presents a process for developing icons that reflects the principles of task-centered, iterative design we have presented throughout this book.

Is the use of icons in interfaces a fundamental breakthrough enabling new levels of ease of learning or ease of use, or a fad, eventually to disappear and be replaced with traditional textual representations? Arguments on both sides of this debate are presented in the reading by Baecker, Small, and Mander (1991). Both sides would likely agree that the meaning of an icon should be obvious to experienced users of a system, and be evocative and self-evident to new users. Some icons fail to meet the former criterion; many fail to meet the latter criterion. The reading suggests that the use of animation could be a solution to the problem of icon comprehensibility and provides some evidence for this hypothesis through a quasi-experiment comparing static to dynamic, animated icons. We shall return below to a further discussion of the possible roles of animation at the interface.

PRINCIPLES FOR EFFECTIVE VISUALIZATION

A special class of images used increasingly in computer-generated displays are those portraying quantitative data, geographic data, and complex symbolic relationships. This is done by encoding and interpreting the data and relationships in a chart, graph, map, or diagram. The formulation and generation of intelligent varieties of these images can contribute significantly to the communicative and expressive power of computer displays.

No individual has presented this case more eloquently than Edward R. Tufte (1983). His goal is *graphical excellence*, which he defines (p. 13) as "the efficient communication of complex quantitative ideas":

> *Excellence in statistical graphics consists of complex ideas communicated with clarity, precision, and efficiency. Graphical displays should:*
>
> - *show the data*
> - *induce the viewer to think about the substance rather than about methodology, graphic design, the technology of graphic production, or something else*
> - *avoid distorting what the data have lo say*
> - *present many numbers in a small space*
> - *make large data sets coherent*
> - *encourage the eye to compare different pieces of data*
> - *reveal the data at several levels of detail, from a broad overview to the fine structure*
> - *serve a reasonably clear purpose: description, exploration, tabulation, or decoration*
> - *be closely integrated with the statistical and verbal description of a data set.*

"Graphics *reveal* data," says Tufte. He then presents in his beautiful book "a language for describing graphics and a practical theory of data graphics." He concludes with humility and a healthy skepticism (p. 191):

> ***Design is choice. The theory of the visual display of quantitative information consists of principles that generate design options and that guide choices among options. The principles should not be applied rigidly or in a peevish spirit; they are not logically or mathematically certain; and it is better to violate any principle than to place graceless or inelegant marks on paper. Most principles of design should be greeted with some skepticism, for word authority can dominate our vision, and we may come to see only through the lenses of word authority rather than with our own eyes.***
>
> ***What is to be sought in designs for the display of information is the clear portrayal of complexity. Not the complication of the simple; rather the task of the designer is to give visual access to the subtle and the difficult—that is, the*** revelation of the complex.

Those wishing to learn about the art of "the revelation of the complex" will need to supplement the Tufte book with additional readings. His more recent work, Tufte (1990), is another beautiful and insightful compendium of heuristics and examples of effective information visualization.

Another useful source to consult is Cleveland (1985), which presents principles of graphical construction, a catalog of appropriate graphical methods, and a paradigm for graphical perception. The use of a theory of visual perception and experimental results on visual perception to guide the design of displays is a welcome addition to the literature.

Three valuable books with a nice "how-to" flavor are Spear (1969), Schmid and Schmid (1979), and Schmid (1983). These three books, as well as the classic by Huff (1954) and the more recent Monmonier (1991), include illustrations of what not to do, that is, how to lie with graphic presentation. Far more insidious, however, is the well-intentioned but ill-conceived *chartjunk* (Tufte's term) intended to enliven and entertain, but actually conceals or even distorts the data. Herdeg (1981), a classic catalog of lively diagrams now in its fourth edition, presents numerous examples of imaginative and appropriate work interspersed with chartjunk. Holmes (1984) is even more replete with chartjunk. The student should look at these various books and think about what makes a visual presentation honest, communicative, and effective.

The advanced student can eventually progress to the monumental works of Tukey and Bertin. Tukey (1977) focuses on the exploratory analysis of data, and the use of novel forms of graphic presentation to assist in the task. Bertin (1983) begins from a cartographic perspective, but enlarges this to a comprehensive exploration of methods of applying graphic presentation to the construction of complex yet communicative diagrams, networks, and maps.

INFORMATION VISUALIZATION SOFTWARE

Charts, graphs, maps, and diagrams are examples of vehicles for what is now known more generally as *information visualization* (McCormick, DeFanti, and Brown, 1987; Gershon et al., 1994; Visualization Software, 1991 video; see also the proceedings of the new ACM and IEEE conferences on scientific visualization). As computers are used to manage larger and larger sets of more and more complex data, better means of manipulating, analyzing, and visualizing data are needed (Goldstein and Roth, 1994). Traditional methods of portraying data such as charts and graphs are being augmented by new computer-based techniques for information visualization.

The reading by Ahlberg and Shneiderman (1994; 1994 video), for example, describes the use of dynamic query filters and starfield displays to facilitate the process of visual information seeking. Dynamic query filters allow the rapid updating of search results as query parameters are adjusted with sliders and buttons. Starfield displays are two-dimensional scatterplots of sets of results (for an early example of such a display, see the last scene of Baecker, 1981 video). Zooming and panning over the displays, and recomputing them rapidly as queries are reformulated, powerfully support human capabilities for intelligent browsing and pattern recognition.

Part VI of Shneiderman (1993) reviews other work on information visualization carried out in Shneiderman's lab, including earlier papers on dynamic queries (Ahlberg, Williamson, and Shneiderman, 1992; Shneiderman, Williamson, and Ahlberg, 1992 video; Plaisant and Jain, 1994 video) and their application to searching a real-estate data base (Williamson and Shneiderman, 1992). Another technique is that of tree maps (Johnson and Shneiderman, 1991; Turo, 1994 video), which displays large tree structures by partitioning a rectangular display space into a collection of hierarchically nested rectangular bounding boxes.

Viewers of large information visualizations need to perceive both local detail and global context (see Spence, 1983 video, for an early demonstration of this). Traditional computer graphic systems allow users to pan and zoom over information spaces. Unfortunately, when one is zoomed in to see detail, the context is not visible, and when one is zoomed out for purposes of orientation, the detail cannot be seen. A solution to this problem is to provide overview and detail displays in multiple windows with independent pan and zoom capabilities, yet this can lead to divided visual focus, as well as screen clutter or window overlap.

Furnas (1986) proposed ***generalized fisheye views*** as another solution to the problem of providing both context and detail in a single information display. The key idea is to show "local" detail in full while displaying successively less detail for "global" information at the periphery. This can be done in three ways, by graphically distorting the view, thereby shrinking the peripheral information; by filtering the view, so that less detail appears at the periphery; or by replacing details at the periphery with smaller representations, abstractions, and clusters. Examples of such approaches are Sarkar and Brown (1992; Brown, 1993 video), which proposes fisheye displays of graphs; Rao and Card (1994), which investigates fisheye displays of tables; and Noik (1993) and Schaffer et al. (1995), which study the fisheye display of hierarchically clustered networks and graphs. The latter paper also includes a recent review of this literature and an experiment comparing the efficacy of fisheye and full-zoom methods in a process control application.

Another area of recent research is work on intelligent automatic information visualization. A pioneeering work in this area is Mackinlay's Ph.D. thesis (1986a, 1986b) exploring the automated design of graphical presentations of relational information. This is accomplished using AI techniques, graphic design expressiveness and effectiveness criteria, and a composition algebra that composes a small set of primitive graphical languages. More recent work in this area includes Roth et al. (1994), which uses automated design knowledge to assist both in the process of creating new designs and in the process of finding and customizing relevant existing designs, and Myers, Goldstein, and Goldberg (1994), which shows how to create charts by demonstration.

Videos documenting work in information visualization include Hill and Hollan (1392 video) and Tweedie et al. (1994 video).

Finally, one kind of information visualization that deserves special mention is software *visualization*, the use of interactive computer graphics and the disciplines of graphic design, typography, animation, and cinematography to portray the function, structure, and behavior of algorithms and computer programs. Pioneering work in this area is represented by Sorting Out Sorting, a 30-minute computer-animated portrayal of sorting algorithms (Baecker, 1981 video); Balsa, an elegant system for the interactive construction and display of such visualizations (Brown, 1988); and Baecker and Marcus (1988), which applies graphic design principles to improve the presentation of computer program source code. Recently, Eick and his colleagues have developed lovely applications of high-resolution color data visualization to aid in the comprehension of large computer programs, networks, relational data bases, and other complex systems (Eick, Steffen, and Sumner, 1992; Eick, Nelson, and Schmidt, 1994; AT&T Bell Laboratories, 1994; AT&T Bell laboratories, 1993 video).

A comprehensive recent ovemiew of work in this field is Price, Baecker, and Small (1993). Other videos presenting work in software visualization as well as programming environments with superior visualization capabilities include CCA (1983 video), Abelson (1985 video), Lieberman (1985 video), Xerox (1985c video), Tektronix (1985 video), Eisenstadt and Brayshaw (1988 video), ParcPlace Systems (1989 video), Carnegie Mellon University (1991 video), and Brown (1992 video).

DISPLAY METHODS AND TECHNOLOGIES

Our final topic in this chapter examines a number of methods for defining and creating user interfaces and visual presentations—three-dimensional displays, animation, structured editors, and graphical user interfaces (GUIs)—as well as the technology whereby such displays are produced and presented to users.

Three-Dimensional Display

Most interactive applications to date have used the computer to display two-dimensional worlds. The dominant conceptual model is that of the "desktop metaphor," originally pioneered with the Star personal workstation which we analyzed in Case B. Yet the field of three-dimensional computer graphics (Foley et al., 1990) has vividly demonstrated the power of three-dimensional modeling, rendering, display, and interaction through compelling applications to fields such as computer animation and computer-aided mechanical, industrial, and architectural design.

Why limit ourselves to two-dimensional metaphors in human-computer interaction? An early attempt to use three-dimensional representations for information visualization of complex semantic networks was the MCC SemNet project (Fairchild, Poltrock, and Furnas, 1988; Fairchild and Poltrock, 1987 video).

More recently, Card, Robertson, and Mackinlay (1991), Robertson, Mackiay, and Card (1991 video), and Robertson, Card, and Mackinlay (1993) apply human information-processing principles (see Chapter 9) to suggest that information workspaces be mediated and accessed through three-dimensional representations. A prototype information visualizer suggesting how to facilitate information retrieval is presented in these papers, and in more detail in two companion papers, Mackinlay, Robertson, and Card (1991), which proposes 3D, fisheye-like views of linear information; and Robertson, Mackinlay, and Card (1991), which explores cone trees, animated 3D visualizations of hierarchical information.

Gomez et al. (1994) is a recent review of issues in facilitating 3D interaction. Brookshire Connor et al. (1992) explore the design of three-dimensional widgets. One interesting example is the "interactive shadow" widget, which provides valuable perceptual cues about the spatial relationship between objects and also a direct manipulation interface to constrained transformation techniques (Herndon et al., 1992) More recently, Zeleznik et al. (1993) discuss the design of a toolkit for constructing 3D widgets. Further discussion of 3D interaction appears in Chapter 7.

The most comprehensive vision of the potential of three-dimensional display and interaction is that of immersing users in an environment that is rendered and portrayed so vividly that it appears to be real. We shall return to this concept of virtual reality in Chapter 14.

Animation

Interactive computer systems should portray phenomena using dynamic displays as well as static images, so we require, in addition to the skills of the graphic designer, the skills of the cinematographer and animator. We can look to the language of cinema for models of how our interfaces should behave. They should enable us to include, as global changes to the entire screen, the cut, the *fade* in (fade out), the dissolve, the wipe, the overlay (superimposition), and the multiple exposure (image combination). Locally, within a region of the screen, interfaces should allow the pop on (pop *off*), the pull down (*pull* up), the *flip*, and the spin. Finally, they should allow, as either global or local phenomena, reverse video, color changes, scrolling, panning, zooming in (zooming out), the close up, and full motion, possibly through simulations of three-dimensional worlds and environments. With such effects, an interface can more easily be made memorable and vivid, captivating and enjoyable to use.

We have already presented one reading that illustrates this very well. Baecker, Small, and Mander (1991) employ animation to make icons livelier and more comprehensible. The addition of movement enabled viewers who were confused by several static icons to identify their roles quickly and accurately.

Baecker and Small (1991) is a systematic analysis of possible roles of animation at the interface. Card, Robertson, and Mackinlay (1991), Robertson, Mackinlay, and Card (1991 video), and Robertson, Card, and Mackinlay (1993) employ animation to facilitate exploration and perception of large information spaces. Sukivirya and Foley (1990) demonstrate the automatic generation of context-sensitive animated help.

The Structure and Editing of Graphic Representations

The pioneering work of Ivan Sutherland (1963, 1963 video) demonstrated that the underlying structure of displays is wen more important than what appears on the screen. A number of videos present recent advances in exploring this concept. Pier (1989 video) deals with the processing of digital images. Bier (1989 video) considers "graphical search and replace" in synthetic pictures. Furnas (1990 video) demonstrates a prototype system capable of reasoning about graphical interfaces. Pier and Bier (1991 video) presents a prototype system in which documents act as user interfaces in the sense that any document element can behave as a "button." Gleicber (1992 video) demonstrates the use of constraints in a direct manipulation graphical editor, and Karsenty (1993 video) explores ways in which the computer can assist the user in dealing with constraints. Finally, so that users need not think about two representations, what is on the screen and what underlies it, Kim (1988 video) treats the pixel on the screen as the sole representation, *the* state of the system.

The Technology of Visual Displays

As interface designers, we need to understand the kinds of images that facilitate human-computer interaction, and also be aware of the technology capable of generating and displaying these images. The process occurs in four steps: (1) understanding the fundamental characteristics of images as represented on computer displays; (2) understanding the kinds of changes to images that must be supported by the technology to enable interactive applications to be effective; (3) understanding the basic technology and architecture of display systems; and (4) understanding how to apply this technology to the generation of appropriate imagery and the dynamic changes to the imagery that are required.

The technology is advancing at breakneck speed (compare, for example, Sproull, 1986, to Baecker, 1979). Sproull (1986), which is included as a reading in Baecker and Buxton (1987), is an overview of the technology and architecture of current visual displays. It focuses on how technological parameters and architectural design of display update processors, frame buffer memories, and video generators can either facilitate or hinder the production of the displays, picture changes, and interactive techniques that interface designers require. These techniques include the incorporation of color and antialiasing, smooth scrolling and dragging, rapid pop-up menus and color table animation. Chapter 4, "Graphics Hardware", and Chapter 18, "Advanced Raster Graphics Architecture" of Foley et al. (1990) are more recent treatments of computer graphics hardware, with an emphasis in the latter chapter on the use of pipelined and parallel architectures for computing in hardware relatively realistic renderings of three-dimensional scenes.

Of equal or often greater importance to the interface designer are the physical and pragmatic characteristics of the resulting workstation and terminal. The last two decades have seen increasing interest in the use of flat *panel displays* to overcome the fundamental problems of too much size, weight, and power consumption that characterize cathode ray tube (CRT) terminals. Work has concentrated on three technologies:

- *Liquid crystal displays* (LCDs), in which a voltage reorients molecules within a layer of liquid crystals sandwiched between glass plates so that light is reflected or absorbed
- *Electroluminescent displays*, in which a thin film deposited in layers on a glass plate glows when a voltage is applied
- *Plasma displays*, in which neon gas sandwiched between glass plates is ionized and thereby emits light

A number of books and survey papers (Refioglu, 1983; Aldersey-Williams and Graff, 1985; Perry et al., 1985; Tannas, 1986; Castellano, 1992; Werner, 1993) report that flat panel technologies are capturing an increasing percentage of the market for computer displays. Yet the only technology with significant success has been LCDs, both passive and active matrix, because of their use in laptop computers. Meanwhile, the CRT has continued its many decades of improvement in brightness, luminous efficiency, color, resolution, and cost. The interested reader may want to begin with Tannas (1985) and Castellano (1992), which present comprehensive overviews of the technologies of visual displays, and with the monthly *Information Display Magazine* (published by the Society for Information Display). Snyder (1988) reviews both vision science and display hardware determinants of image quality.

One important realization of the past two decades has been of the significance of *scale,* that is, physical size of devices, in enabling new kinds of computer use. First came *personal computers;* which are now daily tools of hundreds of millions of individuals around the world. Next came *laptop computers*, which allow machines to be used free of the desk and the office. This was followed by *palmtop computers*, sometimes known as *personal digital assistants* (PDAs), which reduce the size and weight and increase the mobiiity of computational devices even further. Even more recently, researchers have begun to work on what has become known as *ubiquitous computing* (see Chapter 14 and especially the reading by Weiser), in which highly portable tiny badges and tabs as well as large wall-size displays, all of which contain compute engines, are interconnected and communicating in order to enable new kinds of applications.

Putting It All Together: GUIs

Ultimately, typography and layout, symbolism and color, dimensionality and animation, must be brought together in an interface style for a particular program, system, or environment. The term *graphical user interface,* or GUI, is variously used to refer to the "look and feel" of an interface style, the common functionality available to a user, and the underiying software that impiements and supports user interactions. Employing the terminology introduced in Chapter 5, we can state that the look and feel of a GUI is typically implemented by a user interface toolkit sitting on top of a windowing system.

Recall our discussion of consistency in Chapter 2. Users would find it very difficult if every application and every computer system presented a different look and feel. The software industry is trying to respond to this problem, Apple Computer (1992), for example, is a published set of human interface guidelines intended to encourage those developing software for the Macintosh to provide consistent interfaces. Corresponding documents from other dominant look-and-feels are IBM (1991), Microsoft (1992), Open Software Foundation (1992), and Sun Microsystems (1990).

Marcus (1992) defines a "common user interface" as "a set of rules used across a group of products that formally specifies the visual presentation of data and functions, the user's interaction, and the logical organization and behavior of information," and suggests defining and documenting the common user interface in a "user interface standards manual." Smith (1988) compares the use of standards versus guidelines in designing user interface software.

Despite the generally shared goal of interface consistency, there are many different GUIs in use today. The reading by Marcus (1992) describes six that in 1992 had established a strong market presence or had been important to the development of the field. After introducing these six—the Macintosh, NextStep, Open Look, Windows, presentation Manager, and Motif—he presents an overview of key windowing system concepts, and then describes how windows and menus are realized in the six annoyingly diierent, yet tantalizingly similar systems. More recently, Marcus, Smilonich, and Thompson (1995) is a detailed comparison of the technology, appearance, interaction, and common actions of six GUIs (those listed above with Open Look replaced by Windows NT), thereby providing a framework for developers to design and implement cross-platform applications that nonetheless have a consistent look-and-feel.

Users would likely benefit if all look-and-feels were identical, as they would be able ro learn new systems with greater ease. Yet this goal is unlikely to be realized Premature standardization could damage the industry more than inconsistent interfaces. Furthermore, GUI and other software developers produce unique interfaces and look-and-feels because they believe they can do it better than others have before them, and they desire to establish a distinctive appearance for their products. They then seek to protect their developments and prevent others fmm copying and using their work. This has led to look-andfeel copyright infringement lawsuits, an area of intense legal activity whose outcome is as of the writing of this book still in question (Shneiderman, 1991; Samuelson, 1132, 1133).

CONCLUDING REMARKS

We have reviewed some of the disciplines involved in enhancing interactive computing through the use of the human visual channel. In isolation, individual factors such as typography and color are already complicated. The issues become even more subtle, however, in the combined and interacting effects of typography, symbolism, graphics, layout, and color. Because the contributing factors are numerous and difficult to control, and the effects of task and context profound, it is difficult to see how to generalize the few concrete results we have from the human factors literature. See, for example, such studies as Tullis (1981, 1983), Dickson, DeSanctis, and McBride (1986), and Bensabat, Dexter, and Todd (1986).

Good progress may therefore best be achieved through the multidisciplinary collaboration of the technologist telling us what is possible, the psychologist telling us what not to do, and the designer suggesting what to do.

REFERENCES

Note: A ● before a reference indicates a reading.

● Ahlberg, C., and Shneiderman, B. (1994). Visual Information Seeking: Tight Coupling of Dynamic Query Filters with Starfield Displays. *Proceedings of CHI '94*, ACM, 313–317, 479–480.

Ahlberg, C., Williamson, C., and Shneiderman, B. (1992). Dynamic Queries for Information Exploration: An Implementation and Evaluation. *Proc. CHI '92*, ACM, 619–626.

Albers, J. (1963, 1975). *Interaction of Color*. Yale University Press.

Aldersey-Williams, H., and Graff, G. (1985). The Flat Panel Challenge. *High Technology*, 39–45.

American Institute of Graphic Arts (1981). *Symbols Signs: The System of Passenger/Pedestrian Oriented Symbols Developed for the U.S. Department of Transportation*. Hasting House.

Andre, J., and Hersch, R. (Eds.) (1989). *Raster Imaging and Digital Typography*. Cambridge University Press.

Apple Computer (1992). *Macintosh Human Interface Guidelines*. Addison-Wesley.

Arnheim, R. (1954). *Art and Visual Perception: A Psychology of the Creative Eye*. University of California Press.

Arnheim, R. (1969). *Visual Thinking*. University of California Press.

AT&T Bell Laboratories (1994). Data Visualhation at AT&T Bell Laboratories. Unpublished report. For further information contact Brian Johnson at bsj@research.att.com.

Baecker, R. (1979). Digital Video Display Systems and Dynamic Graphics. *Computer Graphics* 13(2), 48-56.

Baecker, R., and Buxton, W. (1987). *Readings in Human-Computer Interaction. A Multidisciplinary Approach*. Morgan Kaufmann.

Baecker, R., and Marcus, A. (1988). *Human Factors and Typography for More Readable Programs*. ACM Press.

Baecker, R., and Small, I. (1991). Animation at the Interface. In laurel, B. (Ed.), *The Art of Human-Computer Interface Design*. Addison-Wesley, 261–267.

● Baecker, R., Small, I., and Mander, R (1991). Bringing Icons to Life. *Proceedings of CHI '91*, ACM, 1–6.

Bensabat, I., Dexter, A., and Todd, P. (1986). An Experimental Program Investigating Color-Enhanced and Graphical Information Presentation: An Integration of the Findings. *Communications of the ACM* 29(11), 1094–1105.

Bertin, J. (1983). *Semiology of Graphics: Diagrams, Networks, Maps*. University of Wisconsin Press.

Bigelow, C., and Day, D. (1983). Digital Typography. *Scientific American* 249(2), 106–119.

Biiren, F. (Ed.) (1969a). *Principles of Color*. Van Nostrand Reinhold Company.

Birren, F. (Ed.) (1969b). *A Grammar of Color: A Basic Treatise on the Color System of Albert H. Munsell*. Van Nostrand Reinhold.

Boff, K., Kaufman, L., and Thomas, J. (1986). *Handbook of Perception and Human Performance*. 2 volumes. John Wiley & Sons. See esp. Chapters 4–10, 28-29, and 33–38.

Bowman, W. (1968). *Graphic Communication* John Wiley & Sons.

Brookshire Connor, D., Snibbe, S., Herndon, K., Robbins, D., Zeleznik, R., and van Dam, A. (1992). Three-Dimensional Widgets. *Computer Graphics* 25(2), 183–188.

Brown, H. (1989). Standards for Structured Documents. *The Computer Journal* 32(6), 505–514.

Brown, M (1988). *Algorithm Animation*. ACM Distinguished Disswtation. MIT Press.

Card, S., Robertson, G., and Mackinlay, J. (1991). The Information Visualizer, An Information Workspace. *Proceedings of CHI '91*, ACM, 181–188.

Castellano, J. (1992). *Handbook of Display Technology.* Academic Press.

Chevreul, M (1967). *The Principles of Harmony and Contrast of Colors and Their Application to the Arts.* Van Nostrand Reinhold.

Cleveland, W. (1985). *The Elements of Graphing Data.* Wadsworth Advanced Books. Color Research and Application (1986). Supplement to Volume 11. John Wiley & Sons.

Dickson, G., DeSanctis, G., and McBride, D. (1986). Understanding the Effeaiveness of Compter Graphics for Decision Support: A Cumulative Experimental Approach. *Communications of the ACM* 29(1), 40–47.

Dondis, D. (1973). *A Primer of Visual Literacy.* MIT Press.

Dreyfuss, H. (1972). *Symbol Sourcebook: An Authoritative Guide to International Graphic Symbols.* Van Nostrand Reinhold.

Dunett, J. (Ed.) (1987). *Color and the Computer* Academic Press.

Eick, S., Nelson, M., and Schmidt, J. (1994). Graphical Analysis of Computer Log Files. *Communications of the ACM* 37(12), 50–56.

Eick, S., Steffen, J., and Sumner, E. (1992). Seesoft (TM)—A Tool for Visualizing Line Oriented Software Statistics. *IEEE Transactions on Software Engineering* 18(11), 957–968.

Fairchild, K., Poltrock, S., and Furnas, G. (1988). SemNet: Three-Dimensional Graphic Representations of Large Knowledge Bases. In R. Guirdon (Ed.), *Cognitive Science and Its Applications to Human-Computer Interaction.* Lawrence Edbaum Associates.

Felker, D. (Ed.) (1980). *Document Design: A Review of the Relevant Research.* American Institutes for Research.

Felker, D., Pickering, F., Charrow, V., Holland, V., and Redish, J. (1981). *Guidelines for Document Designers.* American Institutes for Research.

Foley, J., van Dam, A., Feiner, S., and Hughes, J. (1990). *Computer Graphics: Principles and Practice.* Second Edition. Addison-Wesley.

Furnas, G. (1986). Generalized Fisheye Views. *Proceedings of CHI '86*, ACM, 16–23.

Gershon, N., Bushell, C., Mackinlay, J., Ruh, W., Spoerri, A., and Tesler, J. (1994). Information Visualization: The Next Frontier. *Proc. SIGGRAPH '94*, ACM, 485–486.

Goldstein, J., and Roth, S. (1994). Using Aggregation and Dynamic Queries for Exploring Large Data Sets. *Proc. CHI '94*, ACM, 23–29.

Gombrich, E. (1961). *Art and Illusion: A Study in the Psychology of Pictorial Representation*, Second Edition. Pantheon Books.

Gomez, J., Carey, R., Fields, T., van Dam, A., and Venolia, D. (1994). Why Is 3-D Interaction So Hard and What Can We Really Do about It? *Proc. SIGGRAPH '94*, ACM, 492–493.

Gould, J., Alfaro, L., Barnes, V., Finn, R., Grischkowsky, N, and Minuto, A. (1987). Why Reading Is Slower from CRT Displays than from Paper: Attempts to Isolate a Single Variable Explanation. *Human Facrors* 29(3), 269–299.

Gould, J., Alfaro, L., Pinn, R., Haupt, B., and Minuto, A. (1986). Reading from CRT Displays Can Be as Fast as Reading from Paper. *IBM Research Report* RC-12083.

Gould, J., Alfaro, L., Finn, R., Haupt, B., Minuto, A., and Salaun, J. (1987). Why Reading Was Slower from CRT Displays than from Paper. *Proc. CHI+GI '87*, ACM, 7–11.

Greenberg, D. (1982). An Overview of Computer Graphics. In Greenberg, D., Marcus, A., Schmidt, A., and Goiter, V. (Eds.), *The Computer Image: Applications of Computer Graphics*, Addison-Wesley, 7–75.

Gregory, R (1966). *Eye and Brain: The Psychology of Seeing.* World University Library.

Haber, R., and Wilkinson, L. (1982). Perceptual Components of Computer Displays. *IEEE Computer Graphics and Applications* 2(3), 23–35.

Hartley, J. (1978). *Designing Instructional Text.* Kogan Page Limited.

Hartley, J. (Ed.) (1980). *The Psychology of Written Communication.* Kogan Page Limited.

Helander, M. (Ed.) (1988) *Handbook of Human-Computer Interaction.* North-Holland.

Herdeg, W (1981). *Diagrams: The Graphic Visualization of Abstract Data*, Fourth Expanded Edition. Graphics Press Corp.

Herndon, K., Zeleznik, R., Robbins, D., Brookshire Connor, D., Snibbe, S., and van Dam, A. (1992). Interactive Shadows. *Proc. UIST '92*, ACM, 1–6.

Hofmann, A. (1965). *Graphic Design Manual.* Van Nostrand Reinhold.

Holmes, N. (1984). *A Designer's Guide to Creating Charts and Diagrams.* Watson-Guptill Publishing Company.

Horton, W. (1994). *The Icon Book: Visual Symbols for Computer Systems and Documentation.* John Wiley & Sons.

Huey, E. (1968). *The Psychology and Pedagogy of Reading.* MIT Press.

Huff, D. (1954). *How to Lie with Statistics.* W.W. Norton.

Hunt, R. (1975). *The Reproduction of Color*, Third Edition. John Wiley & Sons.

IBM (1991). *IBM Systems Application Architecture: Common User Access: Advanced Interface Design.*

Itten, J. (1961). *The Art of Color.* Van Nostrand Reinhold.

Joblove, G., and Greenberg, D. (1978). Color Spaces for Computer Graphics. *Computer Graphics* 12(3), 20–25.

Johnson, B., and Shneiderman, B. (1991). Treemaps: A Space-Filling Approach to the Visualization of Hierarchical Information Structures. *Proc. 2nd International IEEE Visualization Conference*, 284–291.

Kantowitz, B., and Sorkin, R (1983). *Human Factors: Understanding People-System Relationships.* John Wiley & Sons.

Kolers, P., Wrolstad, M., and Bouma, H. (1979). *Processing of Visible Language*, Vol. 1. Plenum Press.

Kolers, P., Wrolstad, M., and Bouma, H. (1980). *Processing of Visible Language*, Vol. 2. Plenum Press.

Lindsay, P., and Norman, D. (1977). *Human Information Processing: An Introduction to Psychology*, Second Edition. Academic Press.

Mackinlay, J. (1986a). Automated Design of Graphical Presentations. Stanford University Department of Computer Sciences Report No. STAN-CS-86-1138.

Mackinlay, J. (1986b). Automating the Design of Graphical presentations of Relational Information. *ACM Transactions on Graphics* 5(2), April 1986, 110–141.

Mackinlay, J., Robertson, G., and Card, S. (1991). The Perspective Wall: Detail and Context Smoothly Integrated. *Proc. CHI '91*, 173–179.

Marcus, A. (1982a). Designing the Face of an Interface. *IEEE Computer Graphics and Applications* 2(1), 23–29.

Marcus, A. (1982b). Color: A Tool for Computer Graphics Communication. In Greenberg, D., Marcus, A., Schmidt, A., and Gorter, V., (Eds.) *The Computer Image: Applications of Computer Graphics*, Addison-Wesley, 76-90.

Marcus, A. (1983). Graphic Design for Computer Graphics. *IEEE Computer Graphics and Applications* 3(4), 63–70.

Marcus, A. (1990). Principles of Effective Visual Communication for Graphical User Interface Design. *UnixWorld*, August 1990, 107–111; September 1990, 121–124; and October 1990, 135-138 (revised and reformatted).

Marcus, A. (1992). A Comparison of Graphical User Interfaces. In Marcus, A. *Graphic Design for Electronic Documents and User Interfaces*, ACM Press (Excerpt included 137–159, 187–188).

Marcus, A., Smilonich, N., and Thompson, L. (1995). *The Cross-GUI Handbookfor Multiplatform User Interface Design*. Addison-Wesley.

McCormick, B., DeFanti, T., and Brown, M. (1987). Special Issue on Visualization in Scientific Computing. *Computer Graphics* 21(6).

Meyer, G., and Greenberg, D. (1980). Perceptual Color Spaces for Computer Graphics. *Computer Graphics* 14(3), 254–261.

Microsoft (1992). *The Windows Interface: An Application Design Guide*. Microsoft Press.

Miller, G. (1956). The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information. *Psychological Review* 63, 81–97.

Mils, M (1982). Cognitive Schema and the Design of Graphics Displays. *Proc. Graphics Interface '82*, 3–12.

Mils, M (1985). Image Synthesis: Optical Identity or Pictorial Communication? *Proc. Graphics Interface '85*, 303308.

Monmonier, M (1991). *How to Lie wid? Maps*. The University of Chicago Press.

Morris, R. (1989). Rendering Digital Type: A Historical and Economic View of Technology. *The Computer Journal* 32(6), 524–532.

Murch, G. (1984). The Effective Use of Color, Part 1: Physiological Principles. *Tekniques* 7(4), 13–16; Part 2: Perceptual Principles. *Tekniques* 8(1), 4–9; Part 3: Cognitive Principles. *Tekniques* 8(2), 25–31. Tektronix Corporation.

Murch, G. (1985). Color Graphics—Blessing or Ballyhoo? *Computer Graphics Forum* 4, North-Holland, 127–135. (Excerpt included 133135.)

Myers, B., Goldstein, J., and Goldberg, M. (1994). Creating Charts by Demonstration. *Proc. CHI 94*, ACM, 106–111, 475.

Naiman, A. (1991). The Use of Grayscale for Improved Character Presentation. Ph.D. Thesis, Department of Computer Science, University of Toronto, March.

Noik, E. (1993). Exploring large Hyperdocuments: Fisheye Views of Nested Networks. *Proc. ACM Conference on Hypertext and Hypermedia*, 192–195.

Open Software Foundation (1992). *OSF/Motif Style Guide*. Prentice Hall.

Perry, T., Wallich, P., Apt, C., and Baldauf, D. (1985). Computer Display: New Choices, New Tradeoffs. *IEEE Spectrum*, July, 52–73.

Price, B., Baecker, R., and Small, I. (1993). A Principled Taxonomy of Software Visualization. *journal of Visual Languages and Computing* 4(3), 211–266.

Rao, R., and Card, S. (1994). The Table Lens: Merging Graphical and Symbolic Representations in an Interactive Focus+Context Visualhation for Tabular Information. *Proc. CHI '94*, ACM, 318–322, 481–482.

Refioglu, H. (Ed.) (1983). *Electronic Displays*. IEEE Press.

Robertson, G., Card, S., and Mackinlay, J. (1993). Information Visualization Using 3D Interactive Animation. *Communications of the ACM* 36(4), 57–71.

Robertson, G., Mackinlay, J., and Card, S. (1991). Cone Trees: Animated 3D Visualizations of Hierarchical Information. *Proc. CHI PI*, ACM, 189–194.

Robertson, P., and O'Callaghan, J. (1986). The Generation of Color Sequences for Univariate and Bivariate Mapping. *IEEE Computer Graphics and Applications* 6(2), 24–32.

Rosen, B. (1963). *Type and Typography: The Designer's Type Book*. Van Nostrand Reinhold.

Roth, S., Kolojejchick, J., Mattis, J., and Goldstein, J. (1994). Interactive Graphic Design Using Automatic Presentation Knowledge. *Proc. CHI '94*, ACM, 112–117, 476.

Rubinstein, R. (1988). *Digital Typography: An Introduction to Type and Compositionfor Computer System Design*. Addison-Wesley.

Ruder, E. (1967). *Typography: A Manual of Design*. Hastings House Press.

Salomon, G. (1990). New Uses for Color. In laurel, B. (Ed.) (1990), *The Art of Human-Computer Interface Design*, Addison-Wesley, 269–278.

Samuleson, P. (1992). Updating the Copyright Look and Feel lawsuits. *Communications of the ACM* 35(9), 25–31.

Samuleson, P. (1993). The Ups and Downs of Look and Feel. *Communications of the ACM* 36(4), 29–35.

Sanders, M., and McCormick, E. (1993). *Human Factors in Engineering and Design*, Seventh Edition. McGraw-Hill.

Sarkar, M., and Brown, M (1992). Graphical Fisheye Views of Graphs. *Proc. CHI '92*, ACM, 83–91.

Schaffer, D., Zuo, Z., Greenberg, S., Bartram, L., Dill, J., Dubs, S., and Roseman, M. (forthcoming). Navigating Hierarchically Clustered Networks through Fisheye and Full-Zoom Methods. *ACM Transactions on Information Systems*.

Schmid, C. (1983). *Statistical Graphics: Design Principles and Practice*. John Wiey & Sons.

Schmid, C., and Schmid, S. (1979). *Handbook of Graphic Presentation*, Second Edition. John Wiley & Sons.

Seybold, J. (1984). *The World of Digital Typesetting*. Seybold Publications, Inc.

Shneiderman, B. (1991). Protecting Rights in User Interface Designs. *ACM SIGCHI Bulletin* 22(2), 18–19.

Shneiderman, B. (Ed.) (1993). *Sparks of Innovation in Human-Computer Interaction* Ablex.

Smith, A. (1978). Color Gamut Transform Pairs. *Computer Graphics* 12(3), 12–19.

Smith, S. (1988). Standards Versus Guidelines for Designing User Interface Software. In Helander (1988), 877–889.

Snyder, H. (1988). Image Quality. In Helander (1988), 437–474.

Spear, M. (1969). *Practical Charting Techniques*. McGraw-Hill.

Sproull, R. (1986). Frame-Buffer Display Architectures. In *Annual Review of Computer Science*, Annual Reviews, 19–46.

Stevens, S. (1961). The Psychophysics of Sensory Function. In Rosenblith, W. (Ed.), *Sensory Communication*, MIT, 1–34.

Stone, M., Cowan, W., and Beatty, J. (1988). Color Gamut Mapping and the Printing of Digital Color Images. *ACM Transactions on* [illegible] 7(4), 249–292.

Sukiviriya, P., and Foley, J. (1990). Coupling a UI Framework with Automatic Generation of Context-Sensitive Animated Help. *Proc. UIS '90*, ACM, 152–166.

Sun Microsystems (1990). Open *Look Graphical User Interface Application Style Guidelines*. Addison-Wesley.

Sutherland, I. (1963). Sketchpad: A Man-Machine Graphical Communication System. *AFIPS Conference Proceedings* 23, 329–346.

Tannas, L. (1985). *Flat-Panel Displays and CRTs.* Van Nostrand Reinhold.

Tannas, L. (1986). Electroluminescence Catches the Public Eye. *IEEE Spectrum* 23(10), 3742.

Thompson, P. (1985). Visual Perception: *An* Intelligent System with Limited Bandwidth. In A. Monk, (Ed.), *Fundamentals of Human-Computer Interaction*, Academic Press.

Tinker, M. (1963). *Legibility of Print.* Iowa State University Press.

Tinker, M. (1965). *Bases for Effective Reading*. University of Minnesota Press.

Travis, D. (1991). *Effective Color Displays: Theory and Practice.* Academic Press.

Tufte, E. (1983). *The Visual Display of Quantitative Information.* Graphics Press.

Tuhe, E. (1990). *Envisioning Information* Graphics Press.

Tukey, J. (1977). *Exploratoy Data Analysis*. Addison-Wesley.

Tullis, T. (1981). An Evaluation of Alphanumeric, Graphics, and Color Information Displays. *Human Factors* 23(5), 541–550.

Tullis, T. (1983). The Formatting of Alphanumeric Displays: A Review and Analysis. *Human Factors* 25(6), 657–682.

Tullis, T. (1988). Screen Design. In Helander (1988), 377–411.

Van Cott, H., and Kinkade, R. (Eds.) (1972). *Human Engineering Guide to Equipment Design*, Revised Edition. American Institutes for Research.

Van Vliet, J. (Ed.) (1986). *Text Processing and Document Manipulation*. Cambridge University Press.

Van Vliet, J. (Ed.) (1988). *Document Manipulation and Typography.* Cambridge University Press.

Werner, K. (1993). The Plat Panel's Future. *IEEE Spectrum* 30(11), 18-26.

Williamson, C., and Shneiderman, B. (1992). The Dynamic Home Finder: Evaluating Dynamic Queries in a Real-Estate Information Exploration System. *Proc. SIGIR '92*, ACM, 338–346.

Witten, I. (1985). Elements of Computer Typography. *International Journal of Man-Machine Studies* 23,623687.

Wong, W (1987). *Principles of Color Design* Van Nostrand Reinhold.

Wyszecki, G., and Stiles, W (1982). *Color Science: Concepts and Methods, Quantitative Data and Formulae,* Second Edition. John Wiley & Sons.

Yule, J. (1967). *Principles of Color Reproduction.* John Wiley & Sons.

Zeleznik, R., Herndon, K., Robbi, D., Huang, N., Meyer, T., Parker, N., and Hughes, J. (1993). *An* Interactive 3D Toolkit for Constructing 3D Widgets. *Computer Graphics* 27(3), 81–84.

VIDEOS

Abelson, H. (1985). Boxer: Applications of a Personal Computing Environment. *ACM SIGGRAPH Video Review (SGVR)* 18.

Ahlberg, C., and Shneiderman, B. (1994). Visual Information Seeking Using the FilmFinder. *ACM SGVR* 97.

AT&T Bell laboratories (1993). High Interaction Data Visualization—Using Seesoft to Visualize Program Change History. *ACMSGVR* 88.

Baecker, R. (1981). *Sorting Out Sorting*. 30-minute computer-animated teaching film. Distributed by Morgan Kaufmann Publishers. Excerpted in *ACM SGVR* 1.

Beretta, G., and Stone, M. (1990). Color Selection. *ACM SGVR* 55.

Bier, E. (1989). MatchTool: Interactive Graphical Search and Substitute. *ACMSGVR* 48.

Brown, M. (1992). *An* Introduction to ZEUS. *ACM SGVR* 77.

Brown, M. (1993). Browsing Graphs Using a Fisheye View. *ACM SGVR* 88.

Carnegie Mellon University (1991). GENIE: Developing and Assessing State-of-the-Art Integrated Programming Environments. *ACM SGVR* 65.

CCA (1983). Program Visualization. *ACM SGVR* 13.

Easel Corp. (1992). Graphic Design of an Executive Information System. *ACM SGVR* 78.

Eisenstadt, M., and Brayshaw, M. (1988). Visualizing the Execution of Prolog Programs. *ACM SGVR* 58.

Fairchild, K., and Poltrock, S. (1987). SemNet 2.1. *ACM SGVR* 27.

Furnas, G. (1990). Graphical Reasoning for Graphical Interfaces. *ACM SGVR* 56.

Giannitrapani, L. (1987). Three Dimensional Font Design *ACM SGVR* 34.

Gleicher, M (1992). Briar—A Constraint-based Drawing Program. *ACM SGVR* 77.

Henry Dreyfuss Associates (1992). Computer Interface Design 1992. *ACM SGVR* 78.

Hill, W., and Hollan, J. (1992). Pointing and Visualization. *ACM SGVR* 77.

Karsenty, S. (1993). Inferring Graphical Constraints with Rockit. *ACM SGVR* 89.

Kim, S. (1988). Viewpoint: Toward a Computer for Visual Thinkers. *ACM SGVR* 58.

Lieberman, H. (1985). ZStep: A Stepper for LISP-based Visual Inspection. *ACM SGVR* 19.

ParcPlace Systems (1989). A Navigator for UNIX. *ACM SGVR* 46.

Pier, K. (1989). Digital Darkroom. *ACM SGVR* 48.

Pier, K., and Bier, E. (1991). Documents as User Interfaces. *ACM SGVR* 63.

Plaisant, C., and Jain, V. (1994). Dynamaps: Dynamic Queries on a Health Statistics Atlas. *ACM SGVR* 97.

Robertson, G., Mackinlay, J., and Card, S. (1991). Information Visualization Using 3D Interactive Animation. *ACM SGVR 63*.

Russell, A. (1987). MIT Visible Language Workshop. *ACM SGVR* 33.

Shneiderman, B., Williamson, C., and Ahlberg, C. (1992). Dynamic Queries: Database Searching by Direct Manipulation. *ACM SGVR* 77.

Small, D., Ishizaki, S., and Cooper, M. (1994). Typographic Space. *ACM SGVR* 97.

Spence, R. (1983). Office of the Professional. *ACMSGVR* 13.

Stone, M. (1987). Color Selection Tool. *ACM SGVR* 33.

Sutherland, I. (1963). Sketchpad. *ACM SGVR* 13. Originally filmed in 1963, published in 1983.

Tektronix (1985). Magpie. *ACM SGVR* 19.

Turo, D. (1994). Hierarchical Visualization with Treemaps: Making Sense of Pro Basketball Data. *ACM SGVR* 97.

Tweedie, L., Spence, R., Williams, D., and Bhogal, R. (1994). The Attribute Explorer. *ACM SGVR* 97.

Visualization Software (1991). Special Issue on Visualization Software. *ACM SGVR* 70.

Xerox (1985a). Human Interface Aspects of Typefounder. *ACM SGVR* 18.

Xerox (1985b). Multilingual Typing. *ACMSGVR* 18.

Xerox (1985c). Cedar Programming Environment. *ACM SGVR* 19.