Images of science are evident throughout the media, with new technologies playing an important role in allowing the creation of science representation by communication practitioners, scientists, and the public. The role of visual literacy as a key ingredient in the effective communication of science among expert and lay audiences is explored, and a framework for addressing visual literacy is suggested. Visual literacy is defined in this context as a holistic construct that includes visual thinking, visual learning, and visual communication.

Visual Literacy and Science Communication

JEAN TRUMBO
University of Wisconsin–Madison

Imagination or visualization, and in particular the use of diagrams, has a crucial part to play in scientific investigation.

Rene Descartes

The abundant images of science in the media are manifestations of many factors—scientific inquiry, new technologies, exploration by scientists and visual communicators, and the public's interest in visual representation. Movie theaters are filled with special effects images of volcanoes, asteroids, and comets. Advertisers use images of X rays and CAT scans to sell products. The nightly news features animated images of cells (or mineral deposits or tumors) blasted by lasers. These visual images of science range in form from the purely symbolic to the highly representational. Visible science also varies

Author's Note: A number of online visual science sites and resources are available through a Visualizing Science and Technology link page on the author's Web site: http://www.wisc.edu/agjourn/trumbo/scilinks1.html. The author's Visual Communication Resource Site (URL: http://www.wisc.edu/agjourn/trumbo/vcindex.html) also includes course materials and reference information on science, technology, and visualization. Address correspondence to Jean Trumbo, Assistant Professor, Department of Agricultural Journalism, University of Wisconsin–Madison, 440 Henry Mall, Madison, WI 53706; phone: 608-262-0732; fax: 608-265-3042; e-mail: jmtrumbo@facstaff.wisc.edu; URL: http://www.wisc.edu/agjourn/trumbo/vcindex.html.

Science Communication, Vol. 20 No. 4, June 1999 409-425

in purpose from data sharing to entertainment. In many cases, the scientific theories or data that are expressed have no obvious physical form; therefore, technology, symbolic representation, and creative expression are used to produce a visible interpretation (Gershon, Eick, and Card 1998). The images of science and the underlying scientific principles that are represented may not clearly enhance public understanding. In fact, this article suggests that effective scientific visualization can only be shared among expert and lay audiences if there is a sufficient level of visual literacy.

This article describes an approach for integrating visual literacy within the disciplines of science communication. Science communication is broadly defined in this context to include communication among scientists and mediated communication from scientists to the public. Visual literacy will be addressed as a holistic construct that includes visual thinking, visual learning, and visual communication (Randhawa 1978; Seels 1994). Moriarty (1997) notes that this approach places primacy on the learning requirements of visual literacy rather than on the communication process. It is my contention that the visualization of science information places increased literacy demands on all participants in the communication process. Establishing a framework from which expert and public groups can examine the visual representation of science is an important first step. While it is possible to distinguish the literacy needs of scientists, science communicators, and the public in specific ways, this article will define a basic framework from which visual literacy can be addressed generally.

Scholars note the importance of clearly representing scientific data in the practice of science communication and journalism (Friedman, Dunwoody, and Rogers 1986; Nelkin 1995). At this juncture, very little attention has been paid to how the visual representation of science is understood as part of the process of communication among the many participants. Graphic designers such as Tufte (1983, 1990, 1997) and Wurman (1989) provide examples of effective information design and a foundation in graphic problem-solving and design principles. Statisticians such as Wainer (1997) and mathematicians such as Devlin (1998) introduce the reader to the visual aspects of quantitative data. A number of practitioners have identified the communication potential of charts, graphs, and diagrams (Meyer 1997). Communication educators have addressed the perceptual, cognitive, and design requirements of visual communication in the media (Lester 1995; Messaris 1994; Moriarty and Kenney 1995) but have not addressed science visualization specifically. Science historians (Ford 1992; Robin 1992) offer glimpses of the rich heritage of scientific illustration and instrumentation. In addition, biologists, geographers, astronomers, chemists, engineers, and physicists explore the role of scientific visualization and new technology within the diverse disciplines of life, physical, and social sciences (Pickover and Tewksbury 1994; Sprott and Pickover 1997).

This overview merely suggests the range of interest in the visual representation of science and the rich diversity of viewpoints that make up this multidisciplinary enterprise. However, it also presents a challenge for those concerned about the effective communication of science. There is currently no common theory to organize the effort, and there is no agreement on how to clearly represent scientific ideas, processes, or discoveries. There is an evolving collection of new technologies that facilitate the creation of captivating images. However, the resulting images may not express the appropriate scientific principle or may be incomprehensible to an audience. In essence, no cohesive foundation in visual literacy exists among those relying on the communication potential of science images.

Chemist Roald Hoffman laments that in spite of the need for visual literacy, the techniques of visual representation may not be part of the scientist's training. Hoffman (1995) regards the process of representation in chemistry as visual shorthand and notes that the ability to use visual, three-dimensional models and graphic language is essential for the scientist. He explains that the choice of how molecules are represented influences how scientists think about them. A two-dimensional diagram presents a different orientation from a three-dimensional illustration that attempts to show the overall shape of the molecule. To the chemist, the potential for synthesizing a derivative may be more or less clear depending on the illustration. Hoffman says:

> It is fascinating to see the chemical structures on the pages of every journal and to realize that from such minimal information people can actually see molecules in their mind's eye. . . . The molecule is certainly seen, but it may not be seen as the chemist thinks (in a dogmatic moment) that it is seen. It is represented as he chooses to see it, nicely superimposing a human illogic on top of an equally human logic. (pp. 76, 78)

The scientific process is a lengthy, formal method of investigation, with careful strictures designed to minimize the publication of "wrong" results. Goodfield (1981) notes that there is a reluctance among scientists to popularize scientific data through the media. Yet, the visualization of science is everywhere—on the World Wide Web, in science-oriented television shows, in magazines in the popular press, and in newspaper information graphics. Priest (1998) notes that maintaining the integrity of science representation involves training the public and the professional community in information literacy. This article supports that view, with a specific focus on visual literacy. The visual representation of scientific information also relies on the credibility of the source, on the degree to which the image is comprehensible, and on whether the image is an accurate reflection of the scientific principle or data. Visual literacy is a critical part of information literacy.

The conceptual structure for visual literacy used in this framework includes three operational constructs: visual thinking, visual learning, and visual communication. Visual thinking involves the incorporation of visual images as part of conscious and preconscious thought. Visual thinking also involves how we organize mental images using shapes, lines, colors, and compositions to make them meaningful (Wileman 1980). Visual learning is a process of developing visual images for instructional purposes, and it is also the process by which we use visual information to learn (Dwyer 1972, 1978; Randhawa, Bach, and Myers 1977). Visual communication involves the use of visual symbols to express ideas and convey meaning to others (Wileman 1980). Each of these operational constructs will be described in more detail, and a structural approach for applying the principles and concepts of visual thinking, learning, and communication will be introduced. Finally, I will offer some commentary on how these concepts might inform research and promote the examination of the visual aspects of science communication.

Visual Thinking

Leonardo da Vinci considered direct observation and experience to be the gateway to discovery. He called his visualization process *saper vedere*, "knowing how to see" (Boorstin 1992). Science that is in a conceptual stage of development often requires active visual thinking on the part of the scientist. This formative visualization is a creative, intuitive process that involves idea generation and question formation. The scientist works in a speculative way to examine the possibilities from among the foundation of known scientific principles while synthesizing these possibilities through creative thought. Images may be manipulated in the mind or scratched out on paper, but they are working tools rather than conclusive representations.

The visualization process of da Vinci had two components. The first step was to learn the thing by heart and to create a detailed internalized impression so complete that it need not be reproduced either in the mind or on paper. This process of focused observation secures the subject in the mind. The second step was to allow the deepest essence of the thing to be revealed as a universal form that could be combined with other universal forms to create new ideas.

Visual thinking can occur at a number of levels of consciousness. It may be highly conscious with great, focused mental effort, or it may be barely conscious, as in daydreaming. In any case, one of the major uses of graphic language is to communicate the result of visual thinking to other people. Visual thinking is a kind of synthesis or elaboration that can result in imagery that is speculative. While the scientist may employ representation that has a high or low level of correspondence to the real world, that is not the point. Rather, visual representation as a product of visual thinking is meant to prompt innovation and exploration. It may result in loose, undeveloped marks in the margins of a lab book, or it may be as aesthetically beautiful and intricately developed as the explorations of da Vinci.

Design methodologist John Zeisel (1984) describes a process of "imaging" as an ability to go beyond the given information, from a vague mental picture to a refined representation that becomes more specific as the problem is resolved. Zeisel suggests that visual representations (images) are deductive constructs or conjectures that parallel the working hypotheses of researchers. As such, these images represent subjective knowledge.

It was da Vinci's belief that true knowledge comes from synthesizing a variety of points of view into a whole. He referred to his drawings as *dimostrazione* (demonstrations) and believed that they could only be rendered when the subject was deeply understood. His notebooks are filled with detailed scientific exposition drawn from multiple perspectives—below, above, sides—that reveal da Vinci's experience of the visible world. In addition, da Vinci had a strong sense for selecting the appropriate form of visualization. Some explanation was best conveyed through drawings, and some explanation was most appropriately recorded using text. His notebooks are filled with explorations that synthesize language and graphic diagrams (Boorstin 1992; Mattimore 1994b).

McKim (1980) suggests that visual thinking is not necessarily language thinking. For example, Einstein felt that language had the potential to be a "dangerous source of error and deception." To get beyond the inherent assumptions of language and to keep the concepts that are encoded by words closer to the world of impressions, Einstein used imagery as a way to conduct his "thought experiments" (Mattimore 1994a).

Anecdotal evidence of inspiration prompted through visual thinking is abundant in the sciences. For example, one legend recounts the story of chemist Friedrich Kekule who, in 1865, saw a mental image of a snake biting its own tail while he struggled to understand how the six carbon and six hydrogen atoms in the chemical benzene were aligned. This insight led him to envision the ring structure of the molecule (Friedhoff and Benzon 1991). In trying to find an explanation for the atomic structure of elements, Niels Bohr used the image of tiny spheres circling in orbits, which became a miniature planetary system as he envisioned the processes within the atom. James D. Watson describes the complex visual thinking process that prompted him and his colleagues to develop a large three-dimensional model of the DNA molecule that allowed them to see its structure—the double helix—for the first time (McKim 1980).

Loehle (1994) argues that scientific discoveries are made through a process of pattern recognition and elaboration. He observes that science is not based on a fixed recipe or method but, rather, is a complex process of problem solving and pattern synthesizing. These patterns consist of networks of relationships among facts, assumptions, observations, mathematical relations, measurements, and observations. Science, says Loehle, is largely about the struggle to convert an intuitively perceived pattern into something definite. This idea is not necessarily at odds with the scientific method. Rather, it acknowledges the importance of visual information in the conceptual and interpretive process.

Each individual builds knowledge structures or schemata that are personal, internal representations about the nature of the world. As we combine and add schemata, we create new knowledge (Halpern 1996). Thinking is a building process, and knowledge is the building. Visual thinking is conceptualized as both a cognitive process and as a set of skills that can be addressed through a number of perspectives.

Cognitive scientists and education researchers approach the process of thought in more objective ways. Scholars have suggested that differences exist in preferred modes of thinking. For example, education theorist Howard Gardner (1982, 1993) describes a concept of multiple intelligences, and others support the notion that some people prefer spatial over verbal modes of thought (Halpern 1996). Perceptual psychologist Richard Gregory (1974) describes the inner logic of perception in visual problem solving as an ability to see patterns that allow a meaningful whole to be created. Gregory and Gombrich's (1973) work in understanding visual illusion has many implications for the creation of effective science visualization. The principles of Gestalt perceptual psychology have been applied to visual representation and explain the tendency of individuals to visually group elements into cohesive wholes (Koffka [1935] 1963; Kohler 1938). Friedhoff suggests that two consistent findings persist in research on visual thinking: the way people think varies among individuals, and the degree to which individuals rely on visual thinking is measurably distributed in the general population. As Friedhoff notes, "some individuals think more visually than others" (Friedhoff and Benzon 1991, 16).

Marzano et al. (1988) established a framework that describes five dimensions of thinking: metacognition (thinking about thinking), creative and critical thinking, thinking processes (concept formation, comprehension, decision making, and problem solving), thinking skills, and the relationship of

TABLE 1
Visual Thinking Dimension

Metacognition
Awareness of the process of visual thinking
Thinking about visual images or representation
Thinking in visual images or representation
Visual thinking as a substitute for real-world action
Creative and critical thought
Pattern recognition and elaboration
Intuitive thinking
Flexibility and the fluency of ideas
Innovation and an ability to arrive at unique solutions
Analytical thinking and reasoning
Visual thinking process
Role of the eye and brain in the process of vision
The nature of consciousness and thought
Awareness of visual form and composition
Ability to interpret visual representation
A systematic approach to the evaluation of visual representation
Visual thinking skills
Perceptual skill
Mental imaging skill
Aesthetic sense
Content knowledge and visual thinking
Knowledge of the scientific principles being represented
Knowledge of the symbols and notation used within the discipline
Knowledge of the conventions of visual representation used within the discipline

content knowledge to thinking. The visual thinking dimension (see Table 1) is adapted from this framework.

Visual Learning

There are two components to visual learning: the process of gaining awareness of the meaning of visuals and the process an individual uses to interpret meaning from a visual representation (Couch, Caropreso, and Miller 1994). The dual responsibility of visual representation as a teaching and learning tool and as an integral component in the cognitive process employed by the learner suggests the tremendous importance of visual literacy in the sciences. We use images to learn about science, and while we are learning about science, we visualize these concepts in images.

Visual learning involves gaining familiarity with the icons and systems of symbols that constitute specialized vocabularies within science disciplines and then interpreting the meaning associated with a particular representation. In his studies of laboratory settings, Lynch (1985) observes that scientists are obsessed with using papers, representations, diagrams, archives, and abstracts as part of the process of science. He notes that communication with colleagues is only attempted when an effective visual representation is developed. He observes that with every scientific dispute, great pains are taken to invent a new instrument or process of visualization that will enhance the process of discovery. In this respect, the tools of visualization increase the scientist's ability to learn and to share or communicate this knowledge to others.

There are a variety of potential uses for visual representation as a learning tool: illustrate concepts, verify research or solve problems, clarify ideas, assist in concept development, provide a source for comparison and contrast, correct misconceptions, and summarize a topic (Dwyer 1978). The scientist, the science communicator, and the public all use visual images in many of these capacities, as news and information about science is made available.

The power of the image as a tool in visual learning in the sciences can be seen in its ability to dominate the written word when images and text appear together. Written language must be cognitively processed, while the image is processed along the same perceptual pathways as direct experience. We react emotionally to the image before it is cognitively understood (Barry 1997). This factor is important in scientific visualization, in which the sensory potential of a representation is engaging on a variety of perceptual levels. For example, computer graphics animation makes it possible to create models of substances or processes that have three-dimensional qualities, movement, color, and high levels of realism. Learning to interpret these images is essential for both the scientist and science communicator. As perceptual psychologist Gregory (1989) notes:

> Like language, pictures can project into the past or imagined future and create new or even impossible worlds. But they work only for observers with knowledge and intelligence to create meaning from the pictures, as one creates meaning from the words of a language. So the key to understanding the power of pictures, or any symbols, lies in the human brain or the mind. (p. 8)

In its purest sense, visual learning occurs as the scientist attends to the artifacts of exploration: the experimental data or the process itself, the plant or animal specimen, the microscopic image, or the chemical reaction. Visual learning is a process of synthesizing what the scientist knows (expert knowledge) with what the scientist perceives (conceptualization or perception). The internal image in the mind's eye is seamlessly combined with external images—scientific notation, diagrams, photographs, sketches, or computer models. The expert uses visual representation to advance science and to enrich the process of discovery.

Visual learning for the nonexpert involves competencies that are somewhat distinct from those of the expert. The nonexpert may have only limited access to the specialized notation and vocabulary within a scientific discipline and may not be privy to the constraints of various forms of visual representation. For example, sense of scale or distance may not be comprehensible to an average individual looking through a telescope at the Orion nebula. The subjective nature of an artist's expressive, conceptual illustration of DNA sequencing may not be easily understood by those who are not intimately involved in the science. An animated, three-dimensional computer model of a new virus may use color and movement to enhance the structural features of the organism rather than to serve as an exact representation. Visual learning in the public arena involves educating observers on the conventions of visual representation, the nature of the medium through which it is presented, and the science itself. The science communicator is a mediator who must make careful choices about the form of visual representation in an effort to share the science in accurate, articulate ways.

Visual literacy is sometimes equated with language literacy, and the subsequent assumption is that learning about or through visual images is a similar process to learning a language. McKim (1980) notes it is common to move from one graphic language to another while visual thinkers apply the built-in mental operations of each language. In this respect, visual thinkers use graphic languages to expand the range of their thinking. Dondis (1973), on the other hand, concludes that visual literacy could never be a clear-cut, logical system similar to language. Languages are made-up systems, constructed by people to encode, store, and decode information. According to Dondis, language structure has a logic that visual literacy is unable to parallel. Messaris (1994, 1998) also argues against thinking of visual images as language. He suggests that learning to understand images does not require the lengthy initiation or education required to learn a language. Pictures, says Messaris, make sense to inexperienced viewers despite the discrepancies between image and reality. Visual literacy in Messaris's view regards images as sources of aesthetic delight, instruments of potential manipulation, and conveyors of some kinds of information. Visual literacy is a valuable complement to verbal language.

Barry (1997) distinguishes between the linear, logical structure of verbal language and the holistic, amalgamated, synthetic, dynamic, and open structure of visual language. For example, written equations and visual diagrams are created in accordance with the formal vocabulary and grammar of the discipline. Furthermore, the function of visual representation in each of these disciplines is directed toward recording information, communicating information, and processing information. The communication potential of both forms of expression—visual and verbal—may involve the same subject, but the languages are distinct. Language, visual or verbal, is the key to making science communication possible. Learning the visible languages of science and of visual representation is integral to the process of effective communication.

The process of learning about visual representation can be described in a variety of ways. This description is based on the taxonomy developed by education theorist Benjamin S. Bloom and his colleagues (1956), who outline an approach to classifying learning objectives. His model encompasses three domains—cognitive, affective, and psychomotor. The cognitive domain includes concept formation and the creation of understanding. Bloom et al. describe six categories in the cognitive domain: knowledge, comprehension, application, analysis, synthesis, and evaluation. These categories described in the visual learning dimension (see Table 2) have been adapted to define visual learning strategies in science communication.

Visual Communication

> We speak (and hear)—and for 5,000 years have preserved our words. But, we cannot share vision. To this oversight of evolution, we owe the retardation of visual communication compared to language. Visualization by shared communication would be much easier if each of us had a CRT in the forehead. (DeFanti, Brown, and McCormick 1989, 12)

Visual representation to express scientific principles, experimental data, or discoveries helps augment the text to convey meaning or to clarify ideas. Effective visual representation is a tremendous tool in the communication of science to both expert and public audiences. In large part, the visual representation of science information is one-way communication, in that most examples are not designed to encourage feedback. We see the illustration or diagram, and we attend to the animated model within a Web site. However, we typically are not able to have dialogue about that representation. Without some understanding of how visual representation functions, we are left out of

TABLE 2
Visual Learning Dimension

Knowledge	
	Using visual representation to recall concepts
	Using visual representation as visible language
	Organizing concepts or processes through visual representation
Comprehension	
	An ability to interpret visual representation
	An ability to conceptualize using visual representation
Application	
	Using scientific notation
	Using charts, graphs, diagrams, and other informational graphic formats
	Selection of the appropriate mode of visual representation
	Technical skills acquisition
	Using the principles of design and perception
	Applying the appropriate method of visual representation
Synthesis	
	Using visual representation to reveal scientific processes
	Incorporating text or narrative and visual representation
	Using visual representation as part of a collaborative or multidisciplinary exploration
	Using visual representation as an interactive tool
	Exploring the aesthetic, technical, or cognitive potential of visual representation
Evaluation	
	Making judgments based on visual representation
	Evaluating the potential use of visual representation
	Assessing the effectiveness of visual representation

an important, powerful level of discourse. We receive messages but have no parity in response; as such, we are visually illiterate (Saunders 1994).

The communication of scientific thought largely has been confined to the printed and spoken word, with visual media generally performing descriptive or illustrative functions. That is, they are used to amplify, extend, or fill in details or processes that are articulated in the text. Ruby (1975) suggests two possible reasons that visual media have acquired such limited function. First, there may be inherent limitations in visual media that curtail their communicative value. Another possibility is that the perceived limitations of visual media exist in our culturally derived attitudes. Ruby argues that while humans have examined the nature of spoken and written communication for thousands of years, the technologies to produce images are recent, and the scientific examination of their communication potential is still in its infancy.

Another possibility should be considered. Visual literacy has not been a priority within the traditional education system. Seels (1994) suggests that the teaching of visual literacy only gained attention as concern grew about the influence of television on behavior and learning in children. In fact, visual literacy and scientific and mathematical literacy often are neglected. An article in the *Chronicle of Higher Education* argued that universities need to do a better job of training scientists to explain their work verbally and graphically while training science communicators or journalists to become proficient in basic sciences (Chappell and Hartz 1998).

According to the chapter on public understanding in the most recent *Science and Engineering Indicators* report (National Science Board 1998), only one in ten Americans can explain what a molecule is. Only one in five Americans can provide a minimally acceptable definition of DNA, despite the public discussion of genetics, cloning, and forensic blood evidence in widely publicized court trials and on dramatic television shows. And despite substantial media attention to deep-space probes and pictures from the Hubble telescope, only half of all Americans know that the Earth rotates around the Sun once a year. Researchers conclude that only 23 percent of Americans understand the nature of scientific inquiry well enough to make informed judgments about the scientific basis of results reported in the media. While the researchers point out that the level of understanding of basic scientific terms and concepts is closely associated with formal education, they also emphasize that Americans receive most of their information about public policy issues from television news programs and newspapers. During the 12 months of 1997, Americans watched an average of 432 hours of news on television and read an average of about 200 newspapers. At the same time, Americans watched about 70 hours of televised science programming (National Science Board 1998). It seems logical to conclude that visual literacy and scientific literacy are both important prerequisites of effective science communication.

Communication is a process of sharing information with others; it is also a means of sending and receiving messages through a variety of channels. The definition of what constitutes communication varies according to the theoretical perspective that is used. Watson and Hill (1993) suggest that there are five fundamental factors (elements) in the process of communication regardless of the theoretical framework. These elements include the initiator, a recipient, a mode or vehicle, a message, and an effect. The communication process begins when a message is conceived by a sender, encoded into a sequence of signals, and transmitted via a particular medium or channel to a receiver who decodes it (Littlejohn 1996).

Visual communication is a process of sending and receiving messages using visual images and representation to structure the message. Lester

(1995) defines *visual communication* as an optically stimulating message that is understood by the receiver. The goal in visual communication, says Lester, is to produce powerful images that enable the viewer to understand and remember their content. Berger (1998) notes that much of the information we encounter is of a visual nature, and it is important that everyone know something about how images function and how people learn to read or interpret images.

The visual representation of science information includes a diverse stylistic and technical range within a number of categories of images. Photographs, diagrams, symbolic notation, and computer visualization are among the choices from which the scientist and science communicator may select in an effort to "show" rather than "tell" the science. Each form of representation carries its own conventions and potential for interpretation or misinterpretation. Relating visual representation to the larger context of communication processes can help establish a framework to guide the development of visual communication strategies in science communication. The visual communication dimension (see Table 3) presented in this context represents an outline of this basic process.

Conclusion

Contemporary science communication relies on visual representation to clarify data, illustrate concepts, and engage a public informed through an ever-increasing arsenal of computer graphics and new media tools. Examples of visual representation in science communication are abundant, but relatively little attention has been directed toward the challenge of building visual literacy among scientists, communicators, and the public. This article offers a framework from which we might examine the complexity of achieving visual literacy in science communication by attending to three dimensions: visual learning, visual thinking, and visual communication.

The challenges of achieving visual literacy among scientists, communicators, and the public have been noted across disciplines as diverse as the arts, computer science, cognitive psychology, communication, engineering, and the life and physical sciences. It is important to recognize that while the tools of data visualization and visual representation are all evolving quickly, the potential for visual representation of science information to carry meaning or to be understood in an accurate way by an audience is an important issue for researchers to examine. Computer graphics animations of data offer tremendous advantages for all of the participants in a science communication effort.

TABLE 3
Visual Communication Dimension

Source of the message—the communicator or person delivering the message
The scientist
The science organization
Message—the information
The concept to be communicated
The design and visualization process
Defining the problem
Analyzing the data
Conceptualizing the visual possibilities
Selecting the appropriate form and format
Visualizing the concept and developing the form
Refining the form
Evaluating the effectiveness of the visual representation
The nature of the medium—the channel through which the information is being conveyed as well as the technical and social qualities of that channel
Content
Documentary—journalism, visual anthropology, information archiving, information design
Persuasion—advertising, public relations, public information
Artistic expression
Entertainment—fiction, games
Dialog
Role
Historical perspective
Access and availability
Uses and effects
Technical qualities
Sensory potential
Aesthetic qualities
Technology or technical constraints
Interactive potential and adaptability
Audience—person or people who receive the message
Reception of the message
Visual perception
Interpretation of the message
Comprehension of the message
Response to the message

Communication researchers can contribute to the effectiveness of such efforts by turning a critical eye toward the functions, purposes, and effects of visual representation in the sciences.

References

Barry, A.M.S. 1997. *Visual intelligence: Perception, image, and manipulation in visual communication*. Albany, NY: SUNY Press.

Berger, A. A. 1998. *Seeing is believing: An introduction to visual communication*. Mountain View, CA: Mayfield.

Bloom, B. S., M. D. Engelhart, E. J. Furst, W. H. Hill, and D. R. Krathwohl, eds. 1956. *Taxonomy of educational objectives: The classification of educational goals. Handbook I: Cognitive domain*. New York: David McKay.

Boorstin, D. J. 1992. *The creators: A history of heroes of the imagination*. New York: Random House.

Chappell, C. R., and J. Hartz. 1998. The challenge of communicating science to the public. *Chronicle of Higher Education*, March 20, p. B7.

Couch, R. A., E. J. Caropreso, and H. B. Miller. 1994. Making meaning from visuals: Creative thinking and interpretation of visual information. In *Visual literacy: A spectrum of visual learning*, edited by D. M. Moore and F. M. Dwyer, 277-92. Englewood Cliffs, NJ: Educational Technology.

DeFanti, T. A., M. D. Brown, and B. H. McCormick. 1987. Visualization in scientific computing. *Computer Graphics* 21 (6): 12-25.

Devlin, K. 1998. *Life by the numbers*. New York: John Wiley.

Dondis, D. A. 1973. *A primer of visual literacy*. Cambridge, MA: MIT Press.

Dwyer, F. M. 1972. *A guide for improving visualized instruction*. State College, PA: Learning Services.

———. 1978. *Strategies for improving visual learning*. State College, PA: Learning Services.

Ford, B. J. 1992. *Images of science: A history of scientific illustration*. London: British Library.

Friedhoff, R. M., and W. Benzon. 1991. Visualization: The second computer revolution. New York: Freeman.

Friedman, S. M, S. Dunwoody, and C. L. Rogers. 1986. *Scientists and journalists: Reporting science as news*. New York: Free Press.

Gardner, H. 1982. *Art, mind, and brain: A cognitive approach to creativity*. New York: Basic Books.

———. 1993. *Creating minds*. New York: HarperCollins.

Gershon, N., S. G. Eick, and S. Card. 1998. Information visualization. *Interactions* 5 (2): 9-15.

Goodfield, J. 1981. *Reflections on science and the media*. Washington, DC: American Association for the Advancement of Science.

Gregory, R. L. 1974. *Concepts and mechanisms of perception*. London: Duckworth.

———. 1989. Foreword. In *Visualization: The second computer revolution*, edited by R. M. Friedhoff and W. Benzon. New York: Freeman.

Gregory, R. L., and E. H. Gombrich. 1973. *Illusion in nature and art*. London: Gerald Duckworth.

Halpern, D. F. 1996. *Thought and knowledge: An introduction to critical thinking*. Mahwah, NJ: Lawrence Erlbaum.

Hoffmann, R. 1995. *The same and not the same*. New York: Columbia University Press.

Koffka, K. [1935] 1963. *Principles of Gestalt psychology*. New York: Harcourt, Brace & World.

Kohler, W. 1938. Some Gestalt problems. In *A source book of gestalt psychology*, edited by W. D. Ellis. London: Routledge Kegan Paul.

Lester, P. M. 1995. *Visual communication: Images with messages*. Belmont, CA: Wadsworth.

Littlejohn, S. W. 1996. *Theories of human communication*. Belmont, CA: Wadsworth.

Loehle, C. 1994. Discovery as a process. *Journal of Creative Behavior* 28 (4): 239-50.
Lynch, M. 1985. *Art and artifact in laboratory science*. London: Routledge Kegan Paul.
Marzano, R. J., R. S. Brandt, C. S. Hughes, B. F. Jones, B. Z. Presseisen, S. C. Rankin, and C. Suhor. 1988. *Dimensions of thinking: A framework for curriculum and instruction*. Alexandria, VA: Association for Supervision and Curriculum Development.
Mattimore, B., ed. 1994a. Albert Einstein. Metaphors at play. In *99% Inspiration*, chap. 14, pp. 72-76. New York: AMACON.
———, ed. Leonardo Da Vinci: Sapere Vedere—Learning to see. In *99% Inspiration*, chap. 13, pp. 66-71. New York: AMACON.
McKim, R. H. 1980. *Thinking visually: A strategy manual for problem solving*. Belmont, CA: Wadsworth.
Messaris, P. 1994. *Visual literacy: Image, mind, and reality*. Boulder, CO: Westview.
———. 1998. Visual aspects of media literacy. *Journal of Communication* 48 (1): 70-80.
Meyer, E. 1997. *Designing infographics: Theory, creative techniques & practical solutions*. Indianapolis, IN: Hayden.
Moriarty, S. E. 1997. A conceptual map of visual communication. *Journal of Visual Literacy* 17 (2): 9-24.
Moriarty, S. E., and K. Kenney. 1995. Visual communication: A taxonomy and bibliography. *Journal of Visual Literacy* 15 (2): 7-156.
National Science Board. 1998. *Science and engineering indicators 1998*, chap. 7, Science and Technology: Public Attitudes and Public Understanding [On-line]. Washington, DC: Government Printing Office. Available: http://www.nsf.gov/sbe/srs/seind98/access/toc.htm.
Nelkin, D. 1995. *Selling science: How the press covers science and technology*. Rev. ed. New York: Freeman.
Pickover, C. A., and S. K. Tewksbury. 1994. *Frontiers of scientific visualization*. New York: John Wiley.
Priest, S. H. 1998. Public opinion, expert opinion, and the illusion of consensus: Gleaning points of view electronically. In *The electronic grapevine: Rumor, reputation, and reporting in the new on-line environment*, edited by D. L. Borden and K. Harvey, 23-29. Mahwah, NJ: Lawrence Erlbaum.
Randhawa, B. S. 1978. Visual trinity: An overview. In *Visual learning, thinking, and communication*, edited by B. S. Randhawa and W. E. Goffman, 191-211. New York: Academic Press.
Randhawa, B. S., K. T. Bach, and P. J. Myers. 1977. Visual learning. Paper presented at the annual meeting of the Association for Educational Communications and Technology, Miami Beach, FL, April (ERIC Document Reproduction Service No. ED 143319).
Robin, H. 1992. *The scientific image: From cave to computer*. New York: Harry Abrams.
Ruby, J. 1975. Is ethnographic film a film ethnography? *Visual Communication* [On-line], 2 (2). Available: http://www.temple.edu/anthro/ruby/is.html.
Saunders, A. C. 1994. Graphics and how they communicate. In *Visual literacy: A spectrum of visual learning*, edited by D. M. Moore and F. M. Dwyer, 183-92. Englewood Cliffs, NJ: Educational Technology.
Seels, B. 1994. Visual literacy: The definition problem. In *Visual literacy: A spectrum of visual learning*, edited by D. M. Moore and F. M. Dwyer, 97-112. Englewood Cliffs, NJ: Educational Technology.
Sprott, J. C., and C. A. Pickover. 1997. Scientific visualization in mathematics and physics. *Interactions* 4 (1): 78-79.
Tufte, E. 1983. *The visual display of quantitative information*. Cheshire, CT: Graphics.
———. 1990. *Envisioning information*. Cheshire, CT: Graphics.
———. 1997. *Visual explanations*. Cheshire, CT: Graphics.

Wainer, H. 1997. *Visual revelations*. New York: Copernicus.
Watson, J., and A. Hill. 1993. *A dictionary of communication and media studies*. London: Edward Arnold.
Wileman, R. E. 1980. *Exercises in visual thinking*. New York: Hastings House.
Wurman, R. S. 1989. *Information anxiety*. New York: Doubleday.
Zeisel, J. 1984. *Inquiry by design: Tools for environment-behavior research*. Cambridge, UK: Cambridge University Press.

JEAN TRUMBO is Assistant Professor in the Department of Agricultural Journalism, University of Wisconsin–Madison. She teaches visual communication, computer-mediated communication, and interactive media design and analysis. Her research explores user interaction in multimedia, visual literacy in new media, and the visualization of science information.