A Historical Review of Visualization in Human Cognition

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This paper presents a historical overview of visualization as a cognitive strategy in human creativity, discovery, and problem-solving. Visualization strategies, such as mental imagery, pervade historical accounts of scientific discovery and invention. A selected number of historical examples are presented and discussed on topics such as physics, aviation, and the science of chaos. Everyday examples are also discussed to show the value of visualization in cognition for all people. Several counter examples are also discussed showing that visualization can also lead to erroneous conclusions. Many educational implications are discussed, such as reconsidering the dominant role and value schools place on verbal, abstract thinking. These issues are also considered in light of emerging computer-based technologies, such as virtual reality.

☐ The increased availability of multimedia tools in education permits the design of instructional systems that incorporate unlimited variations and forms of verbal and visual information for both presentation and feedback. Our sense of vision arguably represents our most diverse source of information of the world around us (Sekuler & Blake, 1994). Society, including education, transmits tremendous amounts of information in visual form. Visualization is most frequently used in instruction in the presentation of information. However, visualization techniques are also powerful problem-solving tools, though they are rarely promoted as such in learning and instruction. This is unfortunate, as history is full of fascinating examples where visualization has been an important cognitive resource in human discovery and invention (Koestler, 1964).

The term *visualization* is used broadly here and can be considered synonymous to *imagery*. Visualization is defined as representations of information consisting of spatial, nonarbitrary (i.e. "picture-like" qualities resembling actual objects or events), and continuous (i.e. an "all-in-oneness" quality) characteristics (see Paivio, 1990). In contrast, verbal (or semantic) representations are arbitrary (e.g. there is no natural reason why the word *boat* should be used to represent the real object) and sequential (e.g. reading a description of a kitchen's design instead of randomly scanning a picture of it). Visualization includes both internal (e.g. mental imagery) and external representations (e.g. real objects, printed pictures and graphs, video, film, animation). Although visualization can extend to all cognitive and affective outcomes, this paper will limit its discussion to its

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role as a cognitive strategy. The purpose of this paper is to provide a historical context for current efforts by instructional technologists to exploit the full potential of visualization techniques, especially those that tap the computational and graphical power of the computer. This paper will present a variety of cases where people have used visualization techniques throughout history to solve a wide range of problems. In addition, some counter examples will be discussed to show how visualization can sometimes lead us astray. The paper will conclude by discussing the implications of visualization in education and instructional design. These issues will surely increase in importance and complexity as highly-visual computer-based systems continue to evolve, such as in the case of virtual reality. This paper suggests that history might be able to help us as we struggle for the most appropriate applications of visualization in education both now and in the future. It begins with a few general examples that illustrate the role of visualization in human problem-solving at the everyday level.

VISUALIZATION AS A COGNITIVE STRATEGY FOR SOLVING EVERYDAY PROBLEMS

Although historical examples of famous people using visualization to solve complex problems are often the most dramatic, everyday people using the same visual skills to solve everyday problems are the most poignant. Visualization is a powerful cognitive strategy for all people, not just a select few. Some attention first to some ordinary examples helps to establish this point.

Some problems, of course, are inherently spatial. Consider giving or getting directions to an unfamiliar part of town. It is interesting how often the direction giver starts with a purely verbal description, but then reverts to visualization tricks extemporaneously (such as pointing in the air to illustrate the many turns and distances). It is almost as if the person is going on a brief, imaginary trip to the final destination in the hope of showing by example how to get there. The direction receiver is at the same time trying to mentally form a visual imprint of the trip while memorizing key verbal labels (such as landmarks and street names).

Researchers who study the problem-solving process have long recognized visualization as an essential strategy (Finke, 1990; Finke, Ward, Smith, 1002), as the following problem demonstrates (Bransford & Stein, 1993, p. 30):

> A man had four chains, each three links long. He wanted to join the four chains into a single, closed chain. Having a link opened cost 2 cents and having a link closed cost 3 cents. The man had his chains joined into a closed chain for 15 cents. How did he do it?"

Take a few moments to try to solve the problem before reading ahead for the solution. As you do so, reflect on the strategies that you are using to solve the problem.

Most people find the problem very difficult to solve mentally. The obvious solution of four links opened and closed would cost of twenty cents. A good strategy is to draw the four chains on paper—to construct a visual representation of the problem's entry conditions. After working through opening and closing links with a visual model, one discovers that the solution rests in opening all three links of one of the chains. These three links can then be used to join the other three chains. When the problem is converted into visual form, the solution is easy to derive. People often forget to use such inherent capabilities, perhaps because schools emphasize verbal skills over visual skills and abstract reasoning over concrete reasoning. Unfortunately, the idea of using simple visualization as a cognitive strategy to help ourselves solve a problem is frequently either overlooked or discouraged.

Norman (1988) presents another example that demonstrates the power of visualization in problem-solving. This example also aptly reveals the power of the human perceptual system to deal with problems efficiently and effectively when presented in visual form. The problem is a simple math strategy game for two players. The players begin the game by writing the numbers one to nine on index cards—one number per card. The nine cards are laid out on a table with the numbers facing up. The players then take turns choosing a number. Each number can be chosen only once in a game. The first player who gets *any* combination of three numbers that add up to 15 is the winner. The game is quite a challenge even for adults. One must anticipate appropriate combinations of three numbers summing to 15, while also anticipating possible winning combinations by the opponent. Numbers are chosen either to advance one's own hand or to block an approaching win by the opponent.

Playing this game in the pure mathematical form just described is quite difficult. Most adults do not remember ever playing this game, though many find it strangely familiar. The reason for this is that the game has another, more common form—tic-tac-toe. The similarity of the games can be recognized by carefully arranging the nine numbers so that all vertical, horizontal, and diagonal combinations of three squares add up to 15, as illustrated in Figure 1 (this special combination is known as a "magic square"). Strategies from one version of the game quickly transfer to the other. For example, capturing the middle square or the number 5 gives the player a distinctive advantage. Most adults consider tic-tac-toe to be a simple child's game not worth playing anymore because the game will inevitably end up in a draw once both players understand the secret to successfully blocking the opponent at every move. It is interesting that the pure math version of the game remains a challenge even when one knows that it is a disguised version of tic-tac-toe. The point is that the game becomes childish only when the perceptual ability of pattern recognition is used. The game itself has not changed, only the cognitive strategy used by the individual to play it.

Lave (1988) has described the ways everyday people, or "just plain folks," solve problems by exploiting all of the resources present in the problem situation. In one example, people were presented with an everyday problem of fixing food for three people with a recipe designed for four people. When the recipe called for two-thirds cup of cottage cheese, one

Figure 1 □ A Magic Square: all numbers across, down, and diagonally sum to 15.

8	1	6
3	5	7
4	9	2

person quickly solved this problem of "three-fourths of two-thirds" by measuring out two-thirds of a cup onto a table, patting it into a circle, and marking a cross on it. The person was then able to remove the one excess quarter and was left with the correct portion! Lave's work is often cited by proponents of situated cognition (e.g. Brown, Collins, & Duguid, 1989), though these examples also show how everyday people use spatial and concrete reasoning abilities to grapple with problems often expressed in abstract form in traditional mathematics. The concrete solutions are just as sophisticated and complex as those expressed abstractly, yet such a visualization strategy would probably not be allowed by most math teachers.

VISUALIZATION BY SCIENTISTS AND INVENTORS

Some of the most fascinating accounts of human problem solving show remarkably simple examples of how visualization coupled with imagination led to brilliant discoveries and flashes of insight (Burke, 1985; Shepard, 1988). It is interesting that we often refer to these people as visionaries, somehow able to see what others cannot. The use of this description may not be as metaphorical as one might first think. It is stunning to realize how many scientists and inventors placed a great deal of importance on the nonverbal in the act of creative imagination. Many describe the phenomenon of sudden *illumination* where solutions just "showed themselves" or came to them in sudden bursts of insight. Indeed, many described grasping a solution instantaneously and as a whole, only then having to face the arduous task of putting the idea, already completely conceived, into an appropriate verbal form to share with others (such as a scientific paper). Although this section does not pretend to present an exhaustive and comprehensive account of visualization by scientists and inventors, the few examples that follow make a convincing point about the value of visualization in cognition.

Among the most well known are Albert Einstein's unique methods of wrestling with the most puzzling problems of physics, such as light taking on characteristics of both particles and waves simultaneously. Einstein was known for using *thought experiments* to work out problems in a uniquely nonverbal manner. Perhaps his most famous thought experiment was imagining what it would be like to ride on a beam of light. This allowed him to make the conceptual leap of "seeing" light as though it were in static form. This helped him to resolve the paradoxes underlying what was to become his special theory of relativity. In another example, to help understand the absolute nature of the speed of light he imagined how two people would describe the behavior of a light flashing inside a moving truck if one person was riding in the truck and the other was standing on the street.

The German chemist August Kekulé is another scientist famous for his reports of imagery. He often described how atoms appeared to "dance before his eyes." He is said to have discovered the ring-like molecular structure of benzene by gazing into a fire and seeing in the flames a ring of atoms looking like a snake eating its own tail. His accounts of problem solving through dreamlike visual imagery are echoed in the case stories of many other scientists, including Isaac Newton.

Roger Shepard (1988) offers one of the most interesting and detailed discussions of how famous scientists and inventors have been predisposed to visualization in their acts of creative imagination and discover. Beyond those of Einstein and Kekulé, Shepard describes the creative inventiveness of dozens of famous scientists, such as: Michael Faraday's visualization of the lines of magnetism; Nikola Tesla's invention of the self-starting induction motor; Omar Snyder's solution to the containment problem of uranium in the Manhattan project; James Watson's conception of the double-helix shape of DNA; and Richard Feynman's invention of Feynman's diagrams for use in quantum electrodynamics. A curious similarity of many of these famous thinkers is that they were often able to grasp their solutions instantly as a whole.

Based on his investigations, Shepard

described a composite caricature of individuals who have reported extraordinary instances of visual-spatial creative imagery. Three commonalties can be found in these people's early formative years. Many were kept home from school in their first years and had limited contact with peers of their own age. Many were below average in verbal ability, such as language development. Finally, most were fond of engaging in play with concrete physical objects, such as blocks, cubes, and mechanical models. Most of these skills, abilities, and strategies were developed apart from the educational systems of their day.

Shepard goes on to suggest some provocative implications of this composite profile of a highly creative, nonverbal thinker. Working in private without much contact with formal educational institutions (such as schools), these people are likely to engage in unorthodox and nontraditional thinking which, unfortunately, may be met with disapproval or punishment in a traditional classroom. These individuals are more likely to engage in concrete visual imagery, instead of the more abstract, verbal strategies commonly promoted in the schools. Consequently, these people are likely to bring the uniquely human competency of spatial intuition and manipulation to bear on a problem. Finally, the dominance of visual imagery in problem solving is more likely to trigger the motivational and affective forces thought to be more aligned with visual elements of the human psyche.

Shepard also discusses some of the educational implications of his research on the creative imagery of famous scientists. Not surprisingly, he criticizes traditional education for failing to promote visually-based creative tendencies in children. As children, the scientists he studied equated learning with becoming "engrossed in a direct, interactive exploration of such objects and event . . ." and were "unconstrained by conventional, verbalized, and rigidly compartmentalized interpretations . . ." (p. 181). He suggests education must find a way to nurture creative imagination without sacrificing formal education, though the two often appear to be in direct conflict with one another.

Other Examples

A few remaining examples of the historic role of visualization as a cognitive strategy will be presented in this section. These are presented in chronological order beginning with the cholera epidemic in the mid-1800s and ending with the new science of chaos, an emerging field of study in which people and computers work together in partnership through scientific visualization.

The Cholera Epidemic of London in the mid-1800s. One of the classic examples of how visualization aided human problem solving was Dr. John Snow's plotting of cholera deaths in the mid-1800s on a map of London. The obvious clustering of deaths around the Broad-street water pump, as shown in Figure 2, sufficiently convinced authorities to remove the pump's handle even though a direct link had not been made between the disease and a contaminated water supply. Within days, the epidemic in the London neighborhood ended (Tufte, 1983).

Wilbur Wright's Wing-Warping System. The story of the invention of the airplane contains many interesting insights to design and technology. One simple example aptly illustrates the role of everyday visualization and imagination. Controlling an airplane in its three-dimensional environment (i.e. pitch, roll, and yaw) was one of the most difficult problems the Wright Brothers and others faced. The Wrights had already successfully used a rudder to control yaw and an elevator to control pitch, but were having much difficulty controlling the plane's roll (i.e. the motion along the axis going through the fuselage from the plane's nose to tail). Wilbur Wright solved this problem of human-controlled powered flight while holding and twisting an inner tube box in his bicycle shop in Dayton, Ohio, and visualizing the remarkable wing-warping system used by the Wright Brothers' Flyer I at Kitty Hawk. Moolan (1980, p. 112) writes:

> Then one day in the latter part of July 1899, while Wilbur was alone in the bicycle shop, a customer came in to buy a new inner tube. Wilbur chatted with the customer awhile, idly toying with the empty inner tube box before throwing it away; as he

talked he realized that he had absently twisted the ends of the narrow cardboard box in opposite directions. When the customer left, Wilbur tore off the ends of the box and saw in his mind's eye a pair of biplane wings, vertically rigid yet twisted in opposing angles at their tips.

Plate Tectonics. It was long believed that the earth's continents had remained in their general positions immediately after the surface of the earth cooled, even though the vertical shape of the land masses had been subjected to dramatic changes, evidenced by such findings as dried-up sea beds in the mountains. However, some peculiar facts puzzled scientists. For example, identical fossil evidence was found on the east coast of South America and the west coast of Africa. These were explained in various ways, such as the wanderings of migratory animals who used now submerged land bridges. Other evidence, such as striking geological similarities between the two coasts, was much more difficult to explain away.

Figure 2 ☐ The famous dot map of Dr. John Snow plotting the cholera deaths in London in relation to neighborhood water pumps. This map provided strong evidence that the water in the Broad Street pump was contaminated.

In 1915, Alfred Wegener, a German meteorologist, proposed a different solution (Burke, 1985). He noticed how many of the outlines of the continents seem to fit together like a giant jigsaw puzzle, the most dramatic example being how the east coast of South America seemed to fit the west coast of Africa. Perhaps, he suggested, at one time there was a large land mass which eventually broke apart. At the time, Wegener's proposal was ridiculed by geologists. The idea of continents drifting through solid rock seem ludicrous. It was not until about 50 years later that Wegener's visual solution was accepted based on the discovery of mid-ocean ridges and evidence of sea-floor spreading. Rock samples increased in age proportionally to the distance from which they were taken from the mid-ocean ridges. Also, evidence indicated that the earth's magnetic field apparently changes direction every few hundred million years or so. Since rocks retain their magnetic "finger print" it was possible to correlate the ages of rock with their inherent magnetic direction. When sections of the sea floor were mapped using this magnetic evidence, magnetic "stripes" appeared on each side of mid-ocean ridge showing that sections of the sea floor were systematically alternating in their magnetic direction. As molten rock emerged from the mid-ocean ridges and cooled, it captured the earth's magnetic direction at that geological period of time. Current theories now accept that the earth's crust is made up of distinct plates that "float" on the earth's mantle. Wegener's elegant solution was based on the most visual of available evidence.

Armor Plating of World War II Aircraft. A very practical example of visualization's role in problem solving comes from World War II. A novel strategy was used to better armor combat planes. The bullet holes on returning aircraft were plotted on crude pictures of the planes. Using this information it was determined to add armor to planes in places other than those indicated by the bullet holes. The idea was that since it was assumed that the planes were all hit more or less at random, the planes that did not return must have been hit in vital places not marked on the picture (Wainer, 1992).

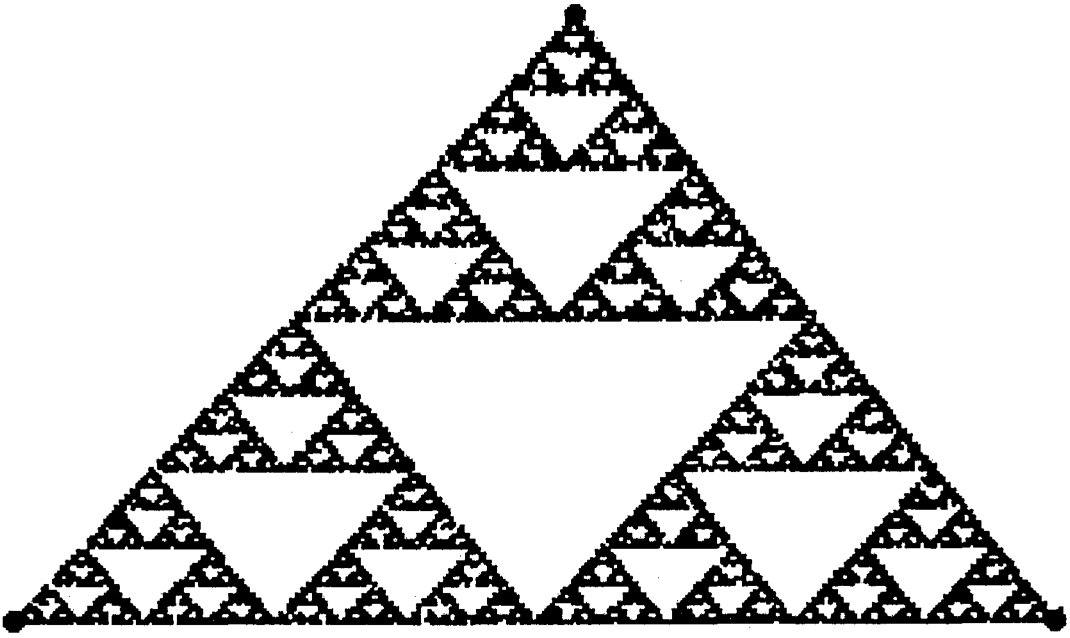
The Science of Chaos. Some consider the computer as the tool by which the world will be turned into a mechanized and inhuman place to live; but a contrasting view considers the computer as our liberator because it performs the tedious, routine tasks poorly suited to humans and frees us to more fully realize our potential. This collaboration between people and computers is perhaps best illustrated in the founding of the new science of chaos, which is the study of nonlinear systems (Gleick, 1987). Such systems, though seemingly random and haphazard on the surface actually have a hidden order lurking below. The universe is inundated with such systems, though some of the best examples are from the everyday world, including the weather, flags waving in the breeze, ribbons of smoke, and dripping water faucets. Even human problem solving is believed to be a nonlinear system. The study of nonlinear systems has only been made more accessible with the advent of computers. The patterns of complex, nonlinear systems often only show themselves when the raw data is converted into visual form. The innate human ability of pattern recognition in combination with the computer's forte of working through millions of iterations with complex data structures has allowed many of the mysteries of chaotic systems to be explored and better understood.

One of the most interesting examples is fractal geometry, where a pattern repeats itself to infinity, such as the Sierpinski gasket shown in Figure 3. This figure is created through an astonishingly simple set of rules (Michael Barnsley, as cited in Gleick, 1987, referred to this as "The Chaos Game"). Begin the game by drawing three *game dots* on a piece of paper (such as those at the three corners of an equilateral triangle). Now draw another dot, the *starting dot,* anywhere on the piece of paper. Then, randomly choose one of the three game dots (such as by throwing a die). Next, carefully draw another dot at the midpoint between the randomly chosen game dot and the starting dot. This midpoint now becomes the next starting point. Repeat this procedure for thousands of trials and the result will be the Sierpinski gasket. Although the rules of the chaos game might lead one to expect a random collection of dots on the paper, a hidden order emerges when the numeric information is converted into a visual form.

Of course, few people are willing to invest the time or energy necessary to play the chaos game (and its many variations). That is where the computer comes in. Computers are wonderfully equipped to handle the tremendous number of accurate calculations necessary in the chaos game whereas people are wonderfully equipped to interpret the visual patterns that emerge. The science of chaos represents a powerful partnership between people and machines—it lets each do what they do best.

Lessons to Be Learned. All of these examples demonstrate the natural tendency for people to use visualization as cognitive strategies. Cognitive strategies are ways in which people manage their own learning, especially during problem solving (Weinstein & Mayer, 1986). People also seem very capable in adapting whatever materials and resources are at hand to support their visualization strategies, from cardboard boxes to computers. Seemingly random objects act as timely props to help work through an idea as it emerges, similar to the everyday experience of doodling while considering a perplexing problem. We can turn almost any object within our reach into a tool for visualization. Just as a hammer extends our ability to perform physical tasks, things that extend our ability to perform cognitive tasks and processes have been referred to as *cognitive tools* (Salomon, Perkins, & Globerson, 1991). Visualization appears to be the source of some of our most versatile and robust cognitive tools. Not surprisingly, the idea of using a computer as a cognitive tool to extend and enhance human intelligence is receiving increased attention by instructional technologists (Jonassen & Reeves, in press; Lajoie & Derry, 1993; Pea, 1985). While the computer certainly offers much potential as a rich source of cognitive tools, these historical examples remind us to focus more attention on how the machine supports human cognition and less attention on the machine itself. Finally, it is interesting to note the tendency by some to reject a visual solution as too simplistic or too

Figure 3 ☐ The Sierpinski Gasket: This fractal geometric figure repeats itself to infinity. Though it contains an infinite number of points, its total area is 0.



obvious to be correct or valuable (e.g., compare the case of Wegener's proposal for plate tectonics to Jean Lave's work with everyday cognition). Educators are well advised to resist the temptation to prematurely dismiss any creative solution that appears too simple or out of step with some preferred method. We are easily fooled in believing that powerful ideas must be sophisticated, complex, or abstract.

Visualization Gone Awry: Some Counter Examples

It seems only fair to consider some examples of where the powers of visualization actually worked against some people. Visualization, like perception, is not like a camera objectively capturing images on film. Interpretation and understanding are continually filtered through one's entire knowledge, values, and beliefs. People often see and imagine what they *want* to see and imagine. Visualization, like any cognitive process, is greatly influenced by prior knowledge. Two examples are presented here where visualization led to erroneous conclusions. The result of one example led, however briefly, to wide pandemonium, excitement, and fantastic stretches of the imagination—Percival Lowell's report of seeing artificially constructed canals on Mars. The repercussions of the other example, in contrast, dramatically changed the world forever—Columbus's voyage to find a westward route to China and India.

Percival Lowell was a prominent astronomer at the turn of the century (he founded the Lowell Observatory in Arizona). Lowell became interested in the planet Mars based on early observations in 1877 by Giovanni Schiaparelli that showed some interesting fine lines on the Martian surface (Ronan, 1983). Lowell subsequently studied the planet in the early 1900s using the most sophisticated telescopic equipment available at that time. Lowell, like Schiaparelli, also observed the peculiar long crossing lines on the Martian landscape. Lowell became convinced that these were the remnants of canals constructed by some ancient civilization. The purpose of the canals, Lowell inferred, was a desperate attempt to bring water down from the polar caps to the desert-like continental areas. Unfortunately, the "canals" turned out to be an optical illusion. This is a classic case of jumping to conclusions based on initial and ambiguous evidence, known by cognitive psychologists as *top-down processing*—initial information triggers an early interpretation against which all subsequent information is judged. This important psychological mechanism helps us find order and organization in an otherwise chaotic environment. Of course, sometimes it works against us. This same phenomenon causes people's tendency to see dead presidents in fluffy white clouds.

The story of Columbus is not as amusing or innocent as that of Lowell, if only because his adventures changed forever the global view of the world. The intent here is not to discuss the details of his trip or its ramifications, but simply why Columbus chose to make it in the first place. Apparently the most compelling reason Columbus dared to risk such an expedition is simply that he greatly underestimated the size of the earth; he also dramatically misconceived what proportion of the earth consisted of water and land (of course, we should not forget how important the potential wealth and fame figured in his decision-making as well) (Dor-Ner, 1991). Had he accepted an accurate account of these two facts, it is almost certain he and his sponsors would have thought the trip impractical and foolhardy at best and impossible at worst.

Historians believe that Columbus's views were heavily influenced by the writings of Marco Polo, Pierre d'Ailly, Pope Pius II, Pliny, and Ptolemy. Both Polo and d'Ailly overestimated the size of Asia considerably. The question of the earth's circumference had been a source of scientific debate for centuries, going back at least to the Greeks. The true figure is 60 nautical miles per degree of longitude at the equator. Though Eratosthenes came close to estimating the true circumference of the earth (about 59.5 nautical miles per degree), Columbus chose figures closer to those estimated by Ptolemy (50 nautical miles per degree). Columbus also and inexplicably downsized the figure even further, to about 45 nautical miles per degree of longitude. Therefore, Columbus envisioned a globe that was only two-thirds its true size and most of that, he thought, was covered by land. Columbus estimated a journey from the Canary Islands to Japan to be only about 2,400 miles instead of the 11,000 miles it actually is. Using this information, Columbus successfully argued his case for such a journey. The result was, of course, the accidental discovery of a new continent. Columbus, however, died believing instead that he had reached islands near the coast of Asia. Of course, one could argue that Columbus may have used these misconceptions on purpose to persuade King Ferdinand and Queen Isabella of Spain to fund the trip and to find a crew willing to join him. Even if this were to be true, Columbus's use of visualization for deception deserves equal attention. Interestingly, Columbus *did* admit later to falsifying information kept in the log to alleviate the crew's fears during the voyage (Fuson, 1987).

CONCLUSIONS AND IMPLICATIONS

This paper has presented some simple examples of how visualization has served as an important cognitive strategy for people throughout history. A historical context not only provides the most dramatic examples of visualization in problem solving, but also helps to promote reflection on one of our most distinctly human capabilities. Though we may never adequately understand the psychology of visualization, it will and should continue to serve as one of our most versatile problem-solving tools. Instructional designers, teachers, and all educators are therefore encouraged to consider innovative visualization strategies to nurture the creative problem-solving process. Concrete, visual solutions should not be considered inferior to those that are abstract. Of course, the two counter examples given here also serve to caution against unwarranted and inappropriate applications.

Despite the relatively small number of examples presented here, one soon discovers the pervasive nature of visualization in scientific discovery and invention. These examples were meant only to suggest the case for the continued value of visualization strategies and should not be mistaken for an exhaustive survey. The list of examples not accounted for is, of course, large. Some domains, like geometry are inherently spatial in nature and have their own visualization histories to tell. Some other notable examples missing from this paper include the following: Kepler's formulation of the laws of planetary motion; the discovery of chemical "fingerprints" of elements as lines in a spectrum (another good example of pattern recognition); and the spatial arrangement of the periodic table of elements. In contrast, some concepts seem impossible to visualize, such as the idea of curved space or physical universe consisting of more than three dimensions, concepts suggested by Einstein and modern day physicists. Similarly, other historical problems, such as accurately describing the motion of a projectile through space (such as cannon balls), provide interesting insights to people's attempts to visualize phenomena that have few visual clues.

There are many important implications that one can draw from this review. The trends in multimedia learning environments, especially those that are computer based, are slowly moving from verbal to visual, from analog to digital, and from passive to interactive. The implications for the learning process are more far reaching than media dominance, however, especially when the computer's processing and graphical abilities are considered. As already noted, the computer has the potential to become one of our most important cognitive tools, similar to the way paper and pencil reduced demands on human memory. Highly visual computer-based learning environments, such as *Geometer's Sketchpad* and *Interactive Physics*, allow individuals to grapple with sophisticated ideas from math and science in visual ways that are at once both concrete and intuitive. Computers and people working closely as partners in cognition have potential for fundamental qualitative changes to how we view human cognition (Salomon et al., 1991).

The implications for instructional designers and teachers are likewise exciting and challenging. Instructional materials should be designed to enable, not hinder, visually-oriented problem-solving approaches. Some have indicated that the idea of teaching any one solution or interpretation to a problem is misguided. Instead, more emphasis should be placed on teaching people how to learn. For example, Papert (1993) argues that "the kind of knowledge children most need is the knowledge that will help them get more knowledge" (p. 139). Recent approaches to instructional design echo the need to place more emphasis on teaching people how to generate and use cognitive strategies rather than restricting instruction to predetermined outcomes (see Smith & Ragan, 1993, for examples). Papert (1993) quotes the African proverb that "if a man is hungry you can give him a fish, but it is better to give him a line and teach him to catch fish himself" (p. 139). Instructional materials, like good fishing lines and tackle, should support and encourage the use of cognitive strategies to help people "catch" knowledge. This review suggests that these instructional materials should give careful consideration to visualization strategies. Similarly, educators are cautioned not to fall prey to the common misconception that abstract verbal strategies are necessarily better than concrete visual strategies. Of course, verbal or numeric representations should likewise not be ignored, though the bridge to and from visual and verbal representations should be as seamless as possible.

Highly visual and interactive computer-based tools may allow the user to take on an unprecedented role in the design process. Rather than designing only ready-made visual presentations for learners, the evidence in this paper suggests giving people opportunities to use the design tools (computer-based or not) for their own creative visualization to solve problems. Instead of striving for learner-centered instruction that takes into account individual differences, instructional technology may be poised to let the user become a true co-designer of learning environments. Relinquishing more instructional control to the learner than is commonly practiced seems warranted given the evidence presented here that creative problem solving is not easily anticipated.

Finally, some of the emerging technologies, such as virtual reality, point to design considerations that have never been examined before (Heim, 1993). Some of these are also among the most exciting, though we should be quite cautious early on. The nature of how people construct their own reality may become muddled when immersed in visually overwhelming environments. The question of whether *telepresence,* the state of interacting in one location (even an imaginary one) while physically located in another (Pimental & Teixeira, 1993), will be an acceptable state of "existence" in the future should not be casually considered. Some feel that telephones already achieve a degree of telepresence since people focus on their conversation with the person on the other end and not on the distance that separates them. Yet, at the awareness level of an adult, there is no mistaking the physical reality of distance while using phone technology. This distinction may become blurred with the advent of virtual reality technology. This is a particularly important issue as our children begin to experience virtual reality. There is the risk that their cognitive development of reality may become confused, as when very young children become angry that grandma cannot come through the phone receiver to be with them at that very moment. Intellectual development of space and time are important issues to consider. The implications of these technologies demand attention and guidance by instructional technologists today in preparation for tomorrow. History offers many relevant lessons in this effort. ☐

REFERENCES

Bransford, J.D., & Stein, B.S. (1993). *The ideal problem solver* (2nd ed.). New York: W.H. Freeman and Company.

Brown, J., Collins, A., and Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher, 18*(1), 32–42.

Burke, J. (1985). *The day the universe changed.* Boston: Little, Brown, and Company.

Dor-Ner, Z. (1991). *Columbus and the age of discovery.*

New York: William Morrow & Company.

Finke, R.A. (1990). *Creative imagery: Discoveries and inventions in visualization.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Finke, R.A., Ward, T.B., & Smith, S.M. (1992). *Creative cognition: Theory, research, and applications.* Cambridge, MA: The MIT Press.

Fuson, R.H. (1987). *The log of Christopher Columbus.* Camden, Maine: International Marine Publishing Co.

Gleick, J. (1987). *Chaos: Making a new science.* New York, NY: Penguin Books.

Heim, M. (1993). *The metaphysics of virtual reality.* New York: Oxford University Press.

Jonassen, D.H., & Reeves, T.C. (in press). Learning *with* technology: Using computers as cognitive tools. In D.H. Jonassen (Ed.), *Handbook of research on educational communications and technology.* New York: Scholastic.

Koestler, A. (1964). *The act of creation.* New York: Macmillan.

Lajoie, S.P. (1993). Computer environments as cognitive tools for enhancing learning. In S.P. Lajoie & S.J. Derry (Eds.), *Computers as cognitive tools* (pp.261–288). Hillsdale, NJ: Lawrence Erlbaum Associates.

Lajoie, S.P., & Derry, S.J. (Eds.). (1993). *Computers as cognitive tools.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Lave, J. (1988). *Cognition in practice: Mind, mathematics, and culture in everyday life.* Cambridge: Cambridge University Press.

Moolan, V. (1980). *The road to Kitty Hawk.* Chicago: Time-Life Books.

Norman, D. (1988). *The psychology of everyday things.* New York: BasicBooks.

Paivio, A. (1990). *Mental representations: A dual coding approach*(2nd ed.). New York: Oxford University Press.

Papert, S. (1993). *The children's machine: Rethinking school in the age of the computer.* New York: BasicBooks.

Pea, R.D. (1985). Beyond amplification: Using the computer to reorganize mental function. *Educational Psychologist, 20,* 167–182.

Pimental, K., & Teixeira, K. (1993). *Virtual reality: Through the new looking glass.* New York: McGraw-Hill.

Ronan, C. (1983). *The atlas of scientific discovery.* London: Crescent Books.

Salomon, G., Perkins, D.N., & Globerson, T. (1991). Partners in cognition: Extending human intelligence with intelligent technologies. *Educational Researcher, 20*(3), 2–9.

Sekuler, R., & Blake, R. (1994). *Perception* (3rd ed.). New York: Alfred A. Knopf.

Shepard, R. (1988). The imagination of the scientist. In K. Egan & D. Nadaner (Eds.), *Imagination and education* (pp. 153–185). New York: Teachers College Press.

Smith, P.L., & Ragan, T.J. (1993). *Instructional design.* New York: Merrill.

Tufte, E.R. (1983). *The visual display of quantitative information.* Cheshire, Connecticut: Graphics Press.

Wainer, H. (1992). Understanding graphs and tables. *Educational Researcher, 21*(1), 14–23.

Weinstein, C.F., & Mayer, R.F. (1986). The teaching of learning strategies. In M. C. Wittrock (Ed.), *Handbook of research on teaching.* New York: Macmillan.

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