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MODELS AND MODELING IN SCIENCE EDUCATION

Visualization in Mathematics, Reading and Science Education

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VISUALIZATION IN MATHEMATICS, READING AND SCIENCE EDUCATION

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Preface

Science education at school level worldwide faces three perennial problems that have become more pressing of late. These are to a considerable extent interwoven with concerns about the entire school curriculum and its reception by students.

The first problem is the increasing intellectual isolation of science from the other subjects in the school curriculum. Science is too often still taught didactically as a collection of pre-determined truths about which there can be no dispute. As a consequence, many students do not feel any "ownership" of these ideas. Most other school subjects do somewhat better in these regards. For example, in language classes, students suggest different interpretations of a text and then debate the relative merits of the cases being put forward. Moreover, ideas that are of use in science are presented to students elsewhere and then re-taught, often using different terminology, in science. For example, algebra is taught in terms of "*x*, *y*, *z*" in mathematics classes, but students are later unable to see the relevance of that to the meaning of the universal gas laws in physics, where "*p*, *v*, *t*" are used. The result is that students are confused and too often alienated, leading to their failure to achieve that "extraction of an education from a scheme of instruction" which Jerome Bruner thought so highly desirable.

The second of these is how to accommodate a "science education for citizenship", one that is relevant to the needs of all students, in a curriculum which has traditionally been focused on the purpose (albeit usually distorted) of "science education as a preparation to be a scientist/engineer". While there are commonalities between the two, there will be differences between what is taught, how it is taught, and why it is taught. Teachers need a justifiable basis on which to distinguish between the two treatments of science.

The third of these is a consequence of the exponentially increasing gap between the phenomena in which science is currently interested and what science education seems able to address. The inability of planners to agree to a rolling evolution of the content taught has led to a curriculum which is, to a substantial degree, permanently overloaded and out of date. While science faces the modern world, science education seems too concerned with the challenges of yesteryear.

If science education is to seem important and relevant to young people, then it must be based, to a far greater degree than at present, on concepts that transcend sets of allied phenomena and to a lesser degree on concepts that are tied to specific facts. The current emphasis on "nature of science" is an honest attempt to do so. One major problem with this approach is the lack of a concise definition of "nature of science"—there is no such thing as "*the* nature of science"—which arises from the fact that science is a collection of tools that are applicable to a huge diversity of phenomena, from the study of viruses to the study of galaxies. A second major problem is that the resources available to, as well as the social conditions of, scientific enquiry are very different from those of school science education. As attempts continue to be made to evolve authentic approaches to the conduct of scientific enquiry in schools, a worthwhile step forward is to focus on the intellectual skills that would be an integral part of all such approaches. Of these, learning how to produce and use models, the theme of this book series, has a very strong claim for attention in that it includes skills that are vital not only in science but also in other core subjects, such as reading/language and mathematics.

Modelling is the mental production and subsequent display to others of a simplified representation of an object, idea, system, event, process, initially produced for a particular purpose. That purpose is to provide an explanation, whether of physical constitution, behaviour, or causality, or better still all three, of a phenomenon. While models, the outcomes of modelling, ultimately reside in the mind, they can be shared with other people in some or all of gestural, material/concrete, visual, verbal, and mathematical forms. The key element in modelling is *visualization* which is often taken to mean either the formation of a mental image or the presentation of that image in the world-as-experienced; however, many other associated interpretations are to be found in the literature.

In "*Visualization in Mathematics, Reading and Science Education*", Linda M. Phillips, Stephen P. Norris, and John S. Macnab have brought together and critically reviewed the research literature on the psychology of visualization as well as its relevance to and manifestation in the teaching and learning of the three school subject areas. It is perhaps a consequence of the range of definitions for "visualization" in use that firm conclusions are difficult to arrive at. The situation might be summarized as follows: the science education community is convinced on the value of visualizations in teaching and learning, the language education community believing it to be useful for particular purposes, while the mathematics education community is not at all sure about its place and value. However, the current strong interest in research about visualization could, it is to be hoped, lead to firmer conclusions.

Such a resolution could provide the basis of an address to the three challenges faced by science education and outlined above. In respect to intellectual isolation, mathematical modelling techniques (usually in the form of equations and graphs) are an invaluable approach to scientific modelling. If such techniques, with their inbuilt use of visualization, were systematically taught in mathematics education, then their transfer into and use by science education should be eased. As regards didactic teaching, the widespread use of visualization in the teaching of the interpretation of written texts could be translated into science education, with beneficial outcomes. "Science education for citizenship" should include an introduction to the use and interpretation of that set of visualizations—here meaning diagrams and the like—in common cultural use yet which have their origins in science. That set of representations will form a major part in the public presentations of topical scientific ideas, the former thus enabling easier access to the latter.

Switching the focus on visualization from science education in the foreground to the background, considerable benefits can be seen for both reading education and mathematics education. These form one clear argument: science provides a body of phenomena, facts, and ideas that can be visualized through both reading and mathematical representations. The bringing together of these three educational areas under the umbrella of visualization should enable students to become better educated and not merely instructed in separate subjects. Phillips, Norris, and Macnab are thus very appropriately placed within the "Models and Modelling in Science Education" series.

London, UK John K. Gilbert

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Overview

This time is both exciting and controversial for research on visualization. It is exciting because computers have made it possible for graphics, images, illustrations, animations, and virtual reality to reach new heights in colour, realism, interactivity, appeal, and complexity. Many producers of visualization media simply assume that visualization makes learning easier. In fact, some advocates imply that visualizations are the best way to learn. It is a controversial time because the evidence is sometimes equivocal and frequently unclear on whether these new heights achieved through powerful computers actually enhance learning. Nonetheless, the increased use of technology and the visualizations it can make available for teaching and learning cannot be ignored.

This book is about the history of visualizations dating back to the 1880s, the evolution of the concept since the first studies were conducted in the early 1960s, and a comprehensive analysis and synthesis of empirical studies across the disciplines of mathematics, reading, and science education. The questions of whether there is a defensible model of visualization and whether the use of visualizations has pedagogical merit are raised and discussed. Comments, recommendations, and suggestions for future research are proposed.

There is a dearth of research and scholarship on visualizations. The total number of empirical research articles we identified in mathematics, reading, and science education on the topic of visualization for the last 50 years is approximately 250, which is remarkably low when placed in the context of all the journal articles published across these three subject areas during the same period of time, which number in the thousands. One important conclusion of this book is that there are a number of important open questions with regard to the development and utilization of visualization objects and activities in education that warrant further empirical study.

A recent Google$^{\text{TM}}$ search on “visualization and education” yielded about 800,000 results. Given the comparatively small number of empirical articles in the area, this is a remarkable number. Whatever visualization in education is believed to be and whatever the evidence is for its efficacy, a lot of people are taking note of it. A number of distinct ideas seem to be rolled into the current discourse on visualization. One common usage involves the idea that visualization is something that people do—they visualize. This process is typically seen as a mental process in which certain thoughts have content that is related to—perhaps is identical to—the content of something that is seen with the eyes. A second sense of the term visualization refers simply to imagining: “Visualize yourself as financially successful”, perhaps. In another common usage, computer-generated animations are referred to as visualizations. Such animations might attempt to depict the motion of the molecules of a gas or the orbits of planets.

In all three senses of visualization mentioned in the previous paragraph, there is a common thread: visualization is considered to be educationally useful. Visualizations are touted, sometimes unreflectively, as aids to learning and understanding. This book contains a critical evaluation of the educational worth of visualizations. Five questions are answered:

1. How is visualization defined in the literature?
2. What constitutes a good visualization and what is necessary for individuals to interpret and evaluate them?
3. Do visualizations aid the development of reading ability, and, if so, how?
4. Do visualizations aid in the development of mathematical and scientific concepts, and, if so, how? and
5. How is computer technology affecting the development and use of visualizations?

The book is structured into three parts. Part I provides an introduction to the idea of visualizations: first, a commonsense view of visualization; second, a more precise examination of the meanings of visualization and the characteristics of good visualizations as found in the research literature; and, third, a look at three cognitive theories of the mechanisms of visualization and recommendations for the design of effective visualizations based on the theories. Part II examines the research on the use of visualizations in the three areas of the curriculum that we have selected for attention: mathematics, reading, and science. Part III contains two chapters. The first deals with computer-generated visualizations as a special case of visualization found in mathematics, reading, and science and provides some cautions against overenthusiasm about their beneficial effects on learning and recommendations on the use. The second chapter offers some conclusions and recommendations derived from our entire summary and some suggestions about research that might be done.

Part I
An Introduction To Visualization

Part I of this book consists of four chapters. Chapter 1 provides a commonsense review of visualization. We briefly examine mathematics, reading, and science teaching for clear and obvious uses of visualization. The commonsense view is that visualizations provide realistic depictions of the world. Closer examination reveals, however, that for many visualizations realistic depiction is neither their function nor intention. Indeed, they work precisely because of their abstraction and idealization. Chapter 2 provides a history of how visualization entered psychology, beginning with Sir Francis Galton's explorations in the 1890s and tracing a line of research into the twenty-first century and of how it has developed in science, with a reconstruction of views on the use of visualization in scientific writing from Galileo to the twentieth century. The chapter also traces how scientific visualizations become tied closely to computers, but shows how similar issues in creating and interpreting visualizations remain, despite the changing technologies for producing them. Chapter 3 deals with a core issue for the volume—how contemporary theorists conceptualize visualization. The first two questions we address in the book are answered: (1) How is visualization defined in the literature? (2) What constitutes a good visualization, and what is necessary for individuals to interpret and evaluate them? The chapter also outlines the data sources and methods that were examined in answering all five questions. Twenty-eight distinct definitions of visualization were identified in the literature. However, these definitions pointed to a more parsimonious three-fold distinction between visualization objects, introspective visualizations, and interpretative visualizations that simplifies the discussion. Also, we found several useful guidelines, rather than clear-cut rules for dealing with colour, realism, relevance, interactivity, animation, and other characteristics of visualizations that can affect their quality and effectiveness. Chapter 4 looks at the basic mechanisms at work in visualization and shows where there is agreement and where there is disagreement in our understanding of how visualization can work in human cognition. Three alternative theories are presented and discussed and some of their implications for the production of visualization objects are explained.

Chapter 1
A Commonsense View and Its Problems

We introduce some commonsense notions of visualization for two reasons. First, we establish some basic ideas and vocabulary by looking at everyday examples of visualization in learning. Second, we establish a baseline for the sort of activities and objects that are the main focus of this book. Let us begin by conceiving of a *visualization object* as any object that a student observes to assist in the learning or understanding of some topic of educational importance. A visualization object could be a picture, a schematic diagram, a computer simulation, or a video. The student who uses the visualization object we will say is *visualizing*. The student who uses visual imagery in the absence of visualization objects we will say is *introspectively visualizing*. These terms will undergo refinement as the book proceeds, but these general notions will be sufficient to introduce our main themes.

Mathematics

There is a long tradition of using diagrams as visual aids to learning geometry. There is good evidence that diagrams were integral to mathematics in much of ancient geometry in India (Swetz, 1995; van der Waerden, 1983), China (Swetz, 1995; Swetz & Kao, 1977), and the Near East (Netz, 1998; van der Waerden, 1983). Modern mathematicians, however, have been suspicious of diagrams, suggesting that the universal mathematical essence that is to be abstracted from a proof cannot be captured by the particularity of a diagram. Barwise and Etchemendy (1996) provide a trenchant critique of this suspicion. If Barwise and Etchemendy are correct, then mathematical visualization objects may have important contributions beyond the introduction of ideas to beginning students. We need not go into the deep and difficult domain of mathematical proof to see how visualizations are important in mathematics. Visualization objects plausibly can be used to assist in the interpretation of mathematical problems, to show how quantities change over time, and to show relationships between one mathematical concept and another related one. From the early grades, the static diagram is likely the simplest and most pervasive visualization object in the mathematics classroom.

Some of the most familiar mathematics diagrams are used in the study of geometry. The geometrical diagram is an unusual thing in that it is not an abstraction

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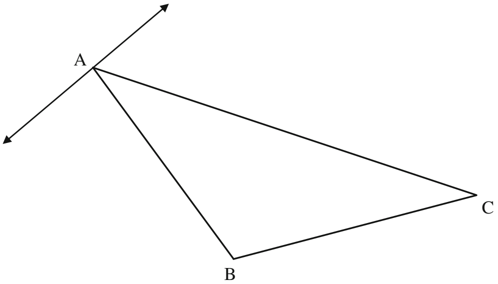

Fig. 1.1 Triangle ABC has a line passing through point A. Students are expected to abstract only the general features of this situation. The angles could be different, as could the lengths of the sides of the triangle

of an experienced object. Rather, it is an attempt to take an abstract concept and make it concrete. In Fig. 1.1, a geometrical diagram shows a triangle ABC and a line through point A. What exactly is this picture depicting? It is standard practice in geometry to insist that a diagram such as Fig. 1.1 not represent any particular triangle. It represents any triangle that could satisfy the conditions set out in a given argument or problem. Triangle ABC is intended to be a generic representation of any conceivable plane triangle: the relative side lengths could be different from what appears on the page, the angles could be different from what is shown, and so on. The usefulness of this visual in geometry is to indicate to students that a triangle and a line through one vertex could be said to exist, but that whatever will be discussed about the triangle and line will be only a small part of the relevant information captured in the diagram. Students must be taught to recognize which features of a diagram such as Fig. 1.1 are particular to the diagram and which are universally applicable to the range of possibilities implied by the accompanying text. It would be incorrect, for example, for a student to place a protractor on the diagram and claim to know the angle measure of every triangle ABC with a line passing through vertex A.

A second common use of visualization in school mathematics is in the drawing and interpretation of graphs. Students have been sketching graphs since Descartes introduced them in the seventeenth century. A simple 2D graph is a geometrical representation of the relationship between two variables. Figure 1.2 depicts a graph of the function $y = x^2$. High school students typically are expected to understand that the polynomial formula $y = x^2$ and its graph encode the same mathematical information; the symbolic form and the graphical form both represent the function. The function, presumably, has an existence independently of either the formula or graph because both are said to be representative of it. The curriculum-makers, then, have to make some important decisions about what is being studied. Are students to learn the properties of the function only, with the formula and graph as learning aids? Or are students to learn the properties of the polynomial formula or of the graph, each of which presents interesting mathematical properties in its own way? Does the availability of graphing software have an effect on this choice? It seems likely that the ease of creating visualizations in mathematics has led to an increased value for the study of graph properties in recent years. This conclusion is supported within the most recent principles and standards for school mathematics documents from the National Council of Teachers of Mathematics (NCTM, 2000).

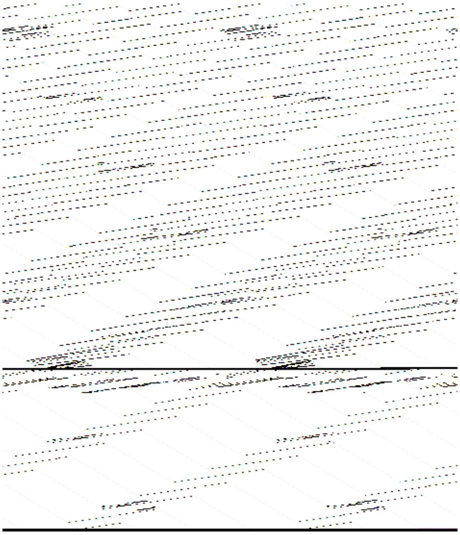

Fig. 1.2 A graph of the function $y = x^2$. The graph has features that have equivalent interpretations to features of the equation, but the graph's features are presented in a forceful way. The graphic object invites talk of increasing or decreasing slope, of curvature, etc

The examples of geometry and graphing highlight a difficulty in assessing the impact of visualizations in education: sometimes comparisons are difficult because visualization can bring new activities and new values into educational practice and assessment. If a teacher wishes to assess students' understanding of the function $y = x^2$, the examination's and the students' choices of representation may shape the response in unpredictable ways. Does analysis of the graph, for example, show understanding of the function itself or does it show understanding of the visual artefact? This distinction may not always be simple to make.

Reading

Roughly, the number of pictures in children's books varies inversely with the grade level of the book. Books for beginning readers have more space allocated to pictures than to print; the ratio of pictures to print decreases until young adult novels either have no pictures at all or have only cover illustrations and small pictures at the chapter headings. One possible explanation for this relationship is that illustrations somehow help younger readers to read, and that as the readers mature the pictures are somehow less helpful. But what is it that the pictures are supposed to be helping the reader to do?

Plausibly, the picture provides some important visual clues about the content of the text. That is, the beginning reader may have difficulty interpreting details about characters, setting, or action, and the visual representation points the reader in a helpful direction. If this is the case, then part of the thinking that the child is supposed to be learning to do is being done for them. Part of reading text, presumably, involves interpreting information and constructing a mental picture of character, time, and place as depicted in the story. It would seem, then, that the provision of visual clues to the beginning reader, if they are not to be a hindrance to the acquisition of reading skills, unburdens or assists the reader in some important way. Perhaps the reader can check suppositions against the illustration(s). Perhaps by removing the task of reading some parts of the text, the developing reader can give further attention to other parts. Of course, all these point to a potential danger of providing visualization objects to the beginning reader. It would not be desirable to have the object replace the print for the reader when the desired outcome is that the reader learns to read print as well as illustrations.

Another possibility is that the visualization object that accompanies the print is not a conceptual aid, but that it is motivational. What reason does a young reader have to go through the difficulty of reading, if it is necessary to first read the story to discover that it is worthwhile? Pictures may provide a promise of a later payback if the story is read.

Science

Science classrooms abound with visualizations: realistic diagrams, photographs and simulations, astrophotographs, scale drawings of equipment, and the like. Non-realistic visualizations are probably more common than realistic ones. Schematic diagrams or bodily systems are drawn to illustrate relationships, but do not show true physical appearance. Similarly, many diagrams show a relationship between physical phenomena and mathematical abstractions. Diagrams of vector addition, for example, encode both a mathematical process and a depiction of physical movement. Electrical circuit diagrams bear no physical resemblance to electrical circuits and are not realistically representative of the physical flow of electricity, but, rather, abstract the ideas of current and voltage, and visually represent them in a way that makes calculation possible.

Why Visualization Might Be Useful

After looking at these common instances of visualization in education, it might seem that visualization is obviously of use in education, and that there need be little else said about the matter. It appears that this has, by and large, been the attitude of the educational community. It is neither clear, though, that all visualization objects are valuable nor that all acts of visualization accomplish what they are intended to accomplish.

Our visual perceptions are rarely sufficient for educational purposes. In early reading, for example, the purpose of the visualization is not to be a substitute for a visual experience outside of the reading experience; it is to draw attention to particular features of visual experience. That is, the point of an illustration of a horse is not to replicate the experience of seeing a real horse; it is to draw the reader's attention to some selected features of a horse that are relevant to the print. To put it another way, if the reader's experiences were already sufficient to serve the purpose of interpreting the print, then the illustration would not be necessary. The illustration calls the reader to make conceptual connections to the print, not to make another visual reference. The illustration may serve only as a reminder of a previous visual experience. If so, it is difficult to see how the pictorial reminder could be superior to any other reminder, including the word " horse".

Other visualizations can be useful in depicting trends over time in a more striking fashion than words. For instance, a view of the planet with areas colour-coded for average yearly temperature can be quite effective when shown as a time-lapse for the past 150 years.

Visualizations in science can be used to help imagine the unseen, for instance, the molecular, atomic, and sub-atomic worlds. Sometimes, such visualizations break down when the objects to be visualized defy such a physical operation, as for instance in attempting to portray the electron probability cloud around an atom. However, simple box diagrams with arrows between boxes representing changes in category can be effective in representing how to map mathematics onto physical systems, such as the spread of a disease among members of a population.

It is tempting to believe that visualizations assist learners through realistic depictions of some features of the world. As almost all the above examples suggest, however, that is often not how visualizations are utilized. In the case of electrical schematic diagrams, for example, the purpose is just the opposite of this. The diagram assists the student to understand properties of electrical circuits by deliberately misrepresenting visual reality and instead depicting non-visual properties in a visual way. The same is true of the vector diagrams, geometrical figures, and isotherms on maps.

Another theme implicit in our examples is that visualizations are used for two main families of activities. In some cases, the visualization is intended to be a supplement to another activity; the visualization is supposed to assist in the development of understanding. The educational point is that the visualization provides information that other means of instruction do not, allowing the student to develop deeper and richer concepts than they otherwise might. In other cases, the visualization activity is intended to serve as an aid in the solution of problems. The electrical circuit diagram, for example, allows the student to quickly and easily write equations to calculate voltages and currents. This is not to suggest that visualization cannot accomplish both of these feats simultaneously; rather it highlights the important point that the purpose of an educational activity should have a bearing on the type of visualization that is chosen and on how it is used.

As this book progresses, a number of key findings will emerge. First, we note numerous instances where the research is inconclusive or contradictory; there is still much that is poorly understood about educational visualization. Second, there are times when visualization objects hinder legitimate educational goals. Third, visualization objects must be carefully chosen to provide a good match between what the student already knows and the desired outcome of the visualization.

Chapter 2
A History of Visualization in Psychology and Science

Visualization as a psychological phenomenon has been studied for little more than a century. Nineteenth century studies opened the important and interesting question of whether visual thinking involves a reproduction of the object of the visualization or whether it is something else altogether. Despite considerable progress in psychological understanding of the mechanisms of visual perception and visual thinking, that question and others are still open. In what follows, we try to show where the main issues lie.

We trace an historical path looking at the use of visual representations in scientific writings since Galileo. This survey illustrates the possibility of effective use of visualizations in the absence of conclusive evidence of the psychological mechanisms by which they work. In addition, it highlights a theme first developed in the opening chapter of this book: Visualizations can be realistic or schematic and may depict the directly visualizable or the non-visualizable. Further, the effectiveness of visual representations is related to the contexts in which they are used; there is no direct path from visualization to understanding.

Early Psychological Research

Use of the term "visualization" appears to date to the late nineteenth century (Simpson & Weiner, 1991). Being convinced of the power of mental images and interested in determining "the degree to which this quality was inherited" (Gillham, 2001, p. 222), Galton developed his "breakfast table questionnaire" sometime before 1880. The questionnaire was so called because it asked the subject to "think of some definite object—suppose it is your breakfast table as you sat down to it this morning" (Galton, 1880b, p. 301). The questionnaire contained 19 questions intended to detail the completeness, vividness, and types of visualizations his respondents would report having had. Through persuading friends and acquaintances including members of the Royal Society, the Royal Institution, the Royal Geographical Society, and the Birmingham Philosophical Society to answer his questions, Galton was able to collect completed questionnaires from 107 men, 180 women, and numerous school boys. He limited his published analysis of participants' use of mental

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imagery to 100 adult males and 172 school boys at Charterhouse School. Galton expressed surprise to learn that the great majority of scientists who completed the questionnaire reported that mental imagery was unknown to them. He did not seem to consider the possibility that these scientists had no need for mental imagery, but he claimed that the scientists "had a mental deficiency of which they were unaware" (1880b, p. 302). Galton was convinced that mental images were roughly identical with visual images, but that the recollection of visual events would necessarily be reconstructed in an order that reverses the chronology of the visual experience (1880a, p. 312). Further, Galton claimed to have shown that there is a hereditary link to the ability to construct mental images and he conjectured that the ability had a relationship to race as well, citing the Bushmen, the Eskimos (as he called the Inuit), and the French as particularly well endowed with the ability to visualize. Galton argued that although visualization is largely an inherited ability, it is a trainable skill that is of great potential in education (1880b).

While Galton was exploring visualization in Britain, a number of European psychologists independently were studying visual imagery and the relationship between images and thought. Their research was challenged by a group of German psychologists at Würzburg, led by Karl Marbe and Oswald Külpe. The Würzburg group claimed that many of their own subjects reported "imageless thought" and took the claims much more seriously than did Galton. In America, Edward Titchener challenged the Würzburg results and claimed to have shown that all thought was accompanied by imagery (Johnson-Laird, 1998). The debate lasted into the twentieth century, only to be declared irrelevant by the ascendant behaviourist movement. Whereas the nineteenth and early twentieth century psychologists had based their conclusions on first-person reports of introspection, the behaviourists looked at humans from the outside, restricting their theory to third-person accounts of behaviour. Questions of the phenomenal experience of visualization were revived in the second half of the twentieth century with the rise of cognitive psychology (Reisberg, 2006; Willingham, 2006/2007). Cognitive psychology not only is now dealing with the experience of visualization, it also deals with the structure of mental images, reviving the nineteenth century question of whether image-based thought is different from other types of thinking. The distinction, if any, between image-based and imageless thought remains a significant and unresolved problem (Johnson-Laird, 1998).

Recent Theories of Visualization in Cognitive Psychology

In defining a set of terms he would use in his article on visuospatial thinking, Mathewson (1999) wrote, "visualization retains its usual meanings in cognitive science" (p. 34). A search for this "usual meaning" in a set of books on cognitive science produced very little, as the term "visualization" appeared in the index of only 2 of the more than 30 books we examined. In one book, *The Encyclopedia of Cognitive Science* (Nadel, 2003), "visualization" was found under the heading "Literacy: Reading" and referred to visualization ability as "the ability to store and retrieve representations defining the visual characteristics of environmental stimuli, including the graphic symbols used to represent written words" (p. 923). In the second book, Johnson-Laird (1998) reviewed research in the field of visual imagery in a chapter entitled "Imagery, visualization, and thinking".

A further search through a second set of approximately 30 books (these focused more specifically on visual cognition) resulted in locating the term "visualization" in the indexes of two additional books. In one of the two books, Barry (1997) wrote, "the understanding of the power of visualization gained wide popular acceptance in the 1950s with the publication of Norman Vincent Peale's *The Power of Positive Thinking*, which uses visualization to create a positive mental picture of achievement" (p. 90). Barry also described as significant the positive impact that introspective visualization has had on athletic performance and on restoring health, both from injury and from disease. The latter results, she explained, are due to the fact that "visualization can be thought of as a process of neurocommunication" that is able to activate and direct the immune system (p. 92). For example, Barry claimed that cancer patients who visualize their tumour and cancer cells being attacked and destroyed and themselves as healthy and well extend their survival rates. In a chapter in the second book on mental images in human cognition, Antonietti (1991) explored the question of why the use of mental visualization facilitates problem solving. In addition to these books, this second search identified the book, *Seeing and Visualizing: It's Not What You Think* (Pylyshyn, 2003). In this volume, Pylyshyn outlines his views on the independence of vision and cognition and develops a theory of how vision and visual imagery are accessed and utilized in cognitive processes. Central to Pylyshyn's thesis is the claim that neither language nor visual imagery is sufficient to account for the content of thoughts; there must be some other form that thoughts take beyond language and image. Pylyshyn's book ends with a fascinating chapter outlining a plausible account of how visual and mental imagery can be useful in assisting learning in some contexts. We explore his account in Chapter 4.

Despite the fact that the term was not listed in the index, "visualization" is occasionally found in the text of books on cognition in sections addressing such topics as visual imagery, visual perception, or visual processing. Enns (2004), for example, raised the issue of "how we can distinguish between the two forms of visualization" (p. 321), that is, between imaging and seeing. This is possible, he explained, for two reasons. First, although there is an estimated two-thirds overlap in the brain regions active in both imagery and perception, this overlap is by no means complete. Second, he reported that studies have indicated mental imagery to be "considerably more inflexible and limited than actual perception" (p. 321).

Johnson-Laird (1998) divides theories of mental operations into two groups: syntactic propositional theories and semantic model theories. Syntactic theories depict reasoning as a series of formal operations on a single type of propositional representation. Johnson-Laird acknowledges some plausibility for the syntactic view, but prefers the semantic. Semantic theories depict reasoning as a construction of meaning-rich models that bear structural resemblance to their referents. That is, there is a direct mapping of some features of the object of the model to the model itself. Thus, if one had a semantic model of a cat, then features of the model would correspond directly to the related features of the cat— four-leggedness, for example. In addition, semantic models can represent non-visual information. According to Johnson-Laird, even though semantic models can "embody abstract predicates that are not visualizable. . .images represent how something looks from a particular point of view. They are projected from the visualizable aspects of underlying models" (p. 464). He gives the ownership of property as an example of a non-visualizable concept that is nonetheless modelled in the brain: "one cannot perceive the relation between owner and owned, only evidence for ownership" (p. 457). He maintained, however, that images may be used symbolically, as when data are translated into a data display capable of capitalizing on the ability of the visual system to extract high-level patterns from low-level data. Further, he claimed that although people can construct novel images out of given components it is doubtful that visualization can lead to "profound innovations and novel scientific concepts". Instead, "visualization can help thinkers to envisage possibilities, and it may help them to imagine certain spatial and physical properties and operations. They cannot, however, directly visualize abstract concepts or conceptual relations" (p. 464). This, he wrote, requires mental models representing complex abstract propositions.

If it is reasonable to equate visualization with visual imagery, then many major functions of visual imagery identified by research would hold true for visualization—for example, memory (Hertzog & Dunlosky, 2006; Paivio, 1986; Reisberg, 2006; Willingham, 2006/2007), problem solving (Antonietti, 1991; Willingham, 2006/2007), and visuospatial relationship functions (Jacob & Jeannerod, 2003; Reisberg & Heuer, 2005; Tversky, 2005). Willingham (2007), for example, wrote

> Imagery serves a memory function (making the visual properties of objects available under some conditions) and a problem-solving function (allowing us to try out changes in the positions of objects or our bodies by moving them in our mind's eye before we move them physically). These two functions both imply that mental images are pictorial representations; images are a way of representing information in the mind that is different from verbal representations. (p. 272)

The pattern of research evidence points to explicit functions for multiple representations such as a memory aid, a mnemonic for verbal associative learning, and a cognitive process but with limits to visual cognition.

Jacob and Jeannerod (2003) noted that "in particular, perceptual representations formed by the visual system constitute an important source of knowledge about the spatial relationships among objects in one's environment" (p. xiii). For example, in viewing a picture of a banana and an apple, one is quickly aware of their spatial relationship, sizes, and shapes. These can, of course, be discerned from a verbal description, but not as readily. Reisberg and Heuer (2005) differentiate between depictions and descriptions, explaining that depictions represent both content and the spatial outlay of the parts of this content. They give as an example of a depiction a picture of a mouse that shows the mouse's head and its tail and their relationship to each other. Descriptions do not bear a direct correspondence between an object and its image. There is no spatial correspondence in a description as "no part of the word 'mouse' represents a particular bit of the mouse's anatomy" (p. 37). This distinction is likely important in educational visualization, as students often work with descriptions in the form of words and icons while simultaneously working with realistic depictions.

Nonetheless, there are many that doubt that mental images have the same educational properties as do visual percepts of graphical representations. As Pylyshyn (2003) suggests, there are solid theoretical and empirical grounds to doubt that mental images are equivalent to visual percepts in general, even if they have similar phenomenal characteristics. He notes that mental images do not preserve the realistic geometry of visual percepts, often allowing imaginary operations that would quickly be seen to be impossible in the visual image. For example, the imagination allows the construction of a house starting with the roof and proceeding to the installation of the walls supporting the roof and then to the foundation supporting the walls. Pylyshyn argues that syntactic or propositional models are more plausible models of thinking than are semantic models. In particular, Pylyshyn argues that the syntactical "language of thought" (Pinker, 1997, p. 70) cannot be equated with either visual or natural language semantics (p. 431).

There is much at stake in the semantic/syntactic debate. The design and use of visualization objects is likely to be improved with an improved understanding of how they are processed by the brain. If the semantic model thesis proves to be correct, then it is likely important to find out which visual objects are most efficiently and accurately processed as they are stored. Should syntactic theory hold the day, then other features of visual objects will become important. On the syntactic view, the visual object is useful insofar as it can be used to assist or to organize other thoughts. On this view, a geometrical diagram is seen to be useful only insofar as it allows the thinker to organize and catalogue relevant relationships in the problem to which the diagram relates. Until such time as this theoretical debate is resolved, educators and educational researchers will continue to explore visualization on the basis of student performance.

The Development of Visualization in Science

Psychological research in visualization may be less than a century and a half old, but the use of visual representations has a much longer history. Although the majority of scientists who filled out Galton's questionnaire reported that they did not make use of mental images in their research, scientists have used and continue to use visualizations to think about and communicate data and data interpretation (for example, Giere, 1996; Gooding, 2004; Miller, 1986; Ruse, 1996). Although visualization was not often explicitly defined, Miller (1986) called it "an act of cognition" (p. 154) and Baigrie (1996) wrote that it "involves the fabrication of mental images which are then exhibited by means of pictorial devices" (p. 86). The development of both the new science of perspective and the printing press contributed to the emergence of scientific visualizations in various scientific disciplines (Kemp, 1996). In the seventeenth century, examples of early visualizations include Gilbert's (1600) drawing of the earth's magnetism and many of Galileo's depictions. According to Kemp (1996), Galileo's advanced understanding of the principles of perspective, including his systematic understanding of cast shadows, undoubtedly informed his interpretation of the phenomena he was able to observe and his drawings of those phenomena.

Despite expressing reservations about the use of perceptual objects in scientific reasoning, Descartes' scientific treatises are filled with illustrations of imperceptible phenomena—for example, drawings of magnetic lines of force, whirlpools of matter, and the optics of the human eye (Fig. 2.1). Baigrie (1996) has argued, however, that these visualizations were "not meant to depict a world but are designed to help us conceive of how it might work. . .as resources that can enhance human cognition" (p. 87).

Newton, too, included numerous drawings in his works with those found in *Philosphie naturalis principia mathematica* (published in 1687) having gained particular fame. Massaroni (2002) commented that although "the pictures are completely detached from any constraint having to do with visual verisimilitude. . .[the] graphic elements used by Newton correspond rigourously to specific physical states of affairs. . .. Newton's is a graphic model built to permit rigourous simulations and the computation of precise solutions to problems involving the action of several forces" (p. 152). Baigrie (1996) concluded, "in the shadow of Newton's *Principia*, Descartes' pictorial devices seemed a lot less like science and more like works of art—symbolic renditions of natural things that bore little connection with reality" (p. 129). Both Descartes and Newton, then, used the visual to express both structure and relationships among phenomena under examination. Descartes' pictures

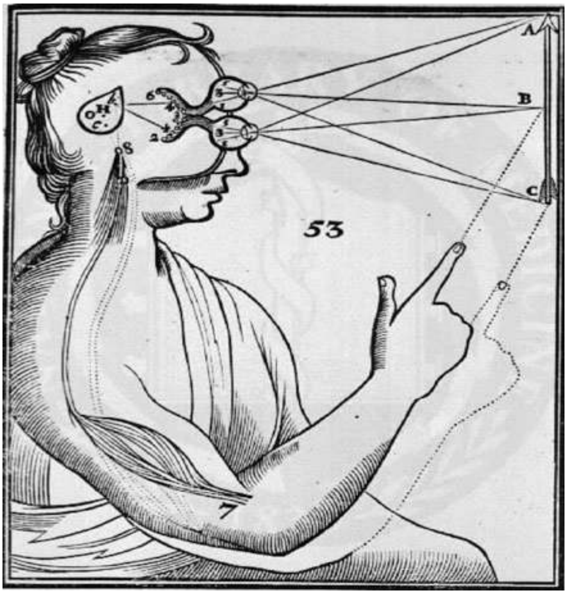

Fig. 2.1 Descartes' depiction of the workings of human vision. Descartes takes liberties with the geometry of the face, but the diagram retains many realistic features nonetheless

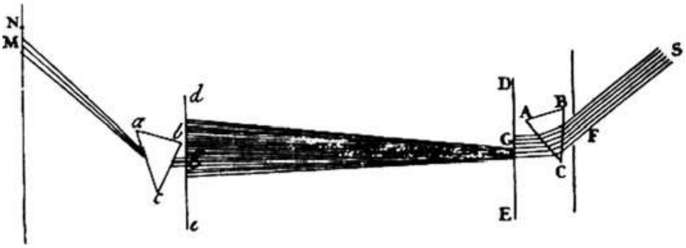

Fig. 2.2 Newton's depiction of the separation of the light spectrum with a prism. Note that the diagram is entirely schematic, with none of the realistic features of Descartes' diagram present

encoded basic ideas in a symbolic fashion, not unlike religious paintings that rely on pictorial conventions to express the non-sensible in visual terms. Newton 1730 stripped away much of Descartes' symbolic and stylistic material, leaving a more idealized visual aid for the reader to focus more on the phenomena being described and less on its cosmological context. Thus, there had been an evolution in what was considered to be scientific in visualizations: Newton's visualization reduced the phenomena to the objects of study by minimizing the non-scientific content (Fig. 2.2).

Maxwell's (1873) drawing of the distribution of magnetic forces in space and Rutherford's (1911) depiction of atoms as small planetary systems illustrate the continuing tradition of pictorially representing data not observable through the senses. However, as Miller (1986) and others have explored, the rapid development of atomic theory in the 1920s brought the efficacy of visualization into question. Miller explained this decline in reliance on visualizability as a consequence of physicists' coming to accept the dual nature of the electron. In accepting that an electron could behave both as a particle and as a wave, scientists realized the impossibility of visually representing such discontinuity. According to Massironi (2002), in fact Heisenberg was adamant that it was impossible to extend classical, visualizable explanations into the atomic domain. However, lacking reference to a visualizable entity, scientists were left grasping for a means by which to discuss the new theories. As Bohr (1928) observed, "hindrances. . .originate above all in the fact that, so to say, every word in the language refers to our ordinary perception" (p. 590). This problem of language was partially resolved through scientists' increasing ease in using mathematical expressions to describe and discuss the unvisualizable.

In the 1940s Feynman produced a set of diagrams that schematically represent particle interaction, visualizations that even Heisenberg was willing to accept (Massironi, 2002). Drawn to help him keep track of the complex calculations he was carrying out (Brown, 1996), these diagrams show particles as if they had left a trail delineating their passage (Massironi, 2002). Brown emphasized that these diagrams cannot be considered to be pictures of physical properties. They are, instead, geometric representations of probability functions (Fig. 2.3). In this, they are very different from earlier visualizations that attempted to represent invisible phenomena.

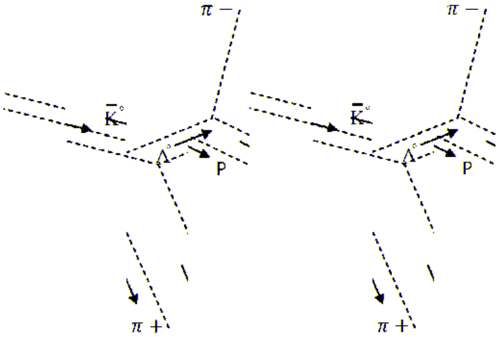

Fig. 2.3 K^o meson interacts with a proton producing a π+ meson and a Λ^o particle, which itself then decays

In his exploration of the basis of modern scientific culture, Latour (1990) afforded visualization a major role in advancing scientific understanding. For Latour, visualizations (which include such visual displays as diagrams, lists, drawings, bands, columns, maps, graphs, and compilations of files) are essential to science and technology as they are relatively easy to manipulate and to use to convince others of the correctness of one's explanations. Schnotz's (2002) view that visual images support communicating, thinking, and learning parallels this perspective, although Schnotz focused on how visual displays support the communication, thinking, and learning of students and Latour on how they support scientists' activities.

The Introduction of Computers to Scientific Visualization

In the mid-1980s when it was becoming increasingly apparent that burgeoning amounts of data were outstripping scientists' and engineers' abilities to interpret, the National Science Foundation (NSF) formed a panel of researchers from academia, industry, and government. After analysing this problem, the panel issued a report in 1987 entitled "Visualization in Scientific Computing", a report credited with laying the basis for the discipline of scientific visualization (Rosenbaum et al., 1994). In that report scientific visualization was defined somewhat cryptically as "a method of computing. It transforms the symbolic into the geometric, enabling researchers to observe their simulations and computations... [and] offers a method for seeing the unseen" (NSF Special Report, 1987, p. 63). Since that time, numerous other definitions, varying in explanatory power, have been offered (considerably more than for the areas of visualization reviewed thus far), including "the binding (or mapping) of data to a representation that can be perceived" (Foley & Ribarsky, 1994, p. 104); "a tool or method for interpreting image data fed into a computer and for generating images from complex multi-dimensional data sets" (Definitions and rationale for visualization, 1999, p. 1); and "the process of transforming information into a visual form, enabling users to observe the information. The resulting visual display enables the scientist or engineer to perceive visually features which are hidden in the data" (Gershon, 1994, p. 129).

Scientific visualization, as this process is commonly called, is widely used in a number of science and engineering fields that benefit from having access to "computer-generated pictures to gain information and knowledge from data (geometry) and relationships (topology)" (Hagen, Nielson, & Post, 2000, p. ix). The table of contents of three scientific visualization conferences gives an indication of the breadth of studies that use visualizing techniques: "Computer visualization in spacecraft exploration", where visualizations are used for such applications as the planning of trajectories and orbital tours and the communication and analysis of data collected in space (Thompson & Sagan, 1991); "Shapes and textures for rendering coral" (Max & Wyvill, 1991); "A new color conversion method for realistic light simulation" (Naka, Nishimura, Taguchi, & Nakase, 1991); "Reconstructing and visualizing models of neuronal dendrites" (Carlbom, Terzopoulos, & Harris, 1991); "Research Issues in modeling for the analysis and visualization of large data sets" (Nielson, 1994); "Fractal geometry and its applications in visualization" (Novak, 1994); "Solid fitting: Field interval analysis for effective volume exploration" in which visualizations are used to represent volume (Fujishiro & Takeshima, 2000); "Scattered data techniques for surfaces" (Lodha & Franke, 2000); and "Visualization of complex physical phenomena and mathematical objects in virtual environment", including visualization of "topically non-trivial objects" such as string theory and problems encountered when attempting to map textures onto topologically complex surfaces and to render "self-crossing transparent surfaces" (Klimenko, Nititin, & Burkin, 2000, p. 159).

Related to scientific visualization, but broader in scope, is information visualization, which is described as "a process of transforming information into a visual form enabling the viewer to observe, browse, make sense, and understand the information. It typically employs computers to process the information and computer screens to view it using methods of interactive graphics, imaging, and visual design. It relies on the visual system to perceive and process the information" (What is visualization? n.d., p. 1). Additionally, Chen (2003) asserted that "the goal of information visualization is to reveal patterns from abstract data. Information visualization brings new insights to people.... The greatest challenge is to capture something abstract and invisible and transform it into something concrete, tangible, and visually meaningful" (p. 101). In the ensuing chapter he demonstrates in text and graphics how this type of visualization can be, and has been, accomplished. Information visualization, thus, extends beyond the needs of scientists and engineers and includes, for example, visualizations produced for business purposes.

Tufte (1990) claimed that "we envision information in order to reason about, communicate, document, and preserve that knowledge" (p. 33). In his books, Tufte has presented and analysed an additional set of data representations that are occasionally referred to as visualizations—graphic representations that are not necessarily computer designed. These include the geographical maps, diagrams, and charts used to help people "extract high-level patterns from low-level data" (Johnson-Laird, 1998, p. 464).

Concluding Comments

In spite of the currency of the technical vocabularies in scientific and information visualization, the core ideas are old. Many well-known diagrams, tables, and graphs fit the above definitions in that they are visual representations of data that provide information access through their physical structures. Galileo (1632/1953) differentiated between what "the eye of the forehead" (p. 157) reveals and what "that of the mind" (p. 157) reveals—between seeing and visualizing. There has been increasing sophistication in scientists' ability to create visualization objects that amount to much more than reminders of how things look. Many of these objects are deliberately non-realistic because their usefulness is a function of their logical form, not merely their verisimilitude to nature. Many of these attempts have been highly successful. As Tufte (1990) has made clear, the design of the graphic representation is important. So, too, as shown by cognitive psychologists, are the background knowledge and interpretive abilities and skills brought to visualization by the viewer. Thus, the efficacy of any visualization to communicate and teach lies very much in the eyes, and the brain, of both the creator and the beholder.

In the end, the term visualization certainly has no "usual meaning". It was used in the literature reviewed as a noun to describe a graphical representation, as a verb to describe the process of creating a graphical representation, and, commonly, as a synonym for visual imagery. We take up these issues of meaning in the following chapter.

Chapter 3
The Concept of Visualization

Perhaps the most defining feature of the current state of empirical research on visualization is the lack of consensus about the most elemental issues that surround it, including

1. settling on a definition for visualization,
2. clarification of the underlying presumptions, and
3. deciding how to document both short-term and long-term effectiveness.

The task of untangling these issues is complex. The status of terms, often used interchangeably, such as “visualization”, “visual representation”, “visual media”, “media literacy”, “visual communication skills”, “visual literacy”, “illustrations”, and “media illustrations”, is yet to be clarified. Furthermore, the routine confusion between pictures/visual images and reality is a fundamental and persistent problem (Griffin & Schwartz, 2005).

The main objective of this chapter is to answer two questions:

1. How is the term “visualization” defined in the literature?
2. What constitutes a good visualization, and what is necessary for an individual to be able to interpret and critically evaluate visualizations?

Methods

We followed a series of five steps in answering the two questions addressed in the chapter and the three additional questions addressed in the subsequent chapters. Step one involved a methodical search of all relevant sources, the identification of vocabulary, and the mapping of the citations on visualization. The data systems used for this review included CBCA Ed, ERIC, SAGE, Education Abstracts, ProQuest, Psych Info, Academic Search Premier, Google Scholar, and Web of Science. Step two required the classification of the types of research into explanatory, exploratory, descriptive studies, and “other”. The third step involved analysis and evaluation of claims made. Step four organized the reviews through repeated comparisons and

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contrasts of the literature in order to identify areas of difference and similarity in data, methodology, and epistemology. Step five moved to mapping the information collected and analysing it on the basis of several categories: date published, objectives sought, questions and concerns raised, materials and evidence cited, arguments advanced, concepts and forms of analysis applied, and conclusions reached.

We evaluated 247 articles for this review, ranging in publication year from 1936 to 2009 (July). Of those 247 articles, 140 were empirical studies and 107 were discussion articles. We organized the articles by subject area: literacy, mathematics, science, teaching, technology, and a miscellaneous category that contained articles examining learning theories and the value of visualizations, among other things. The subject area with the most articles was science, as can be seen in Fig. 3.1. We also examined articles for characteristics of the studies, including the number of participants (Fig. 3.2) and the educational level and employment of the subjects in the study (Fig. 3.3). We saw a marked increase in the number of studies with university students, with a peak in the 1970s due to a series of studies Francis Dwyer conducted at Pennsylvania State University, and then continuing in a linear fashion starting from the early 1990s and into the new millennium. This pattern is in contrast to the number of studies with primary school students, which reached its peak in the 1970s and has decreased since then (see Fig. 3.4). There were six studies which examined teachers' use of, or training to use, visualizations in their classrooms. There was no significant difference in the number of studies with male or female students; most studies used an equal or nearly equal number of both genders, although four studies used males only, and four studies used females only.

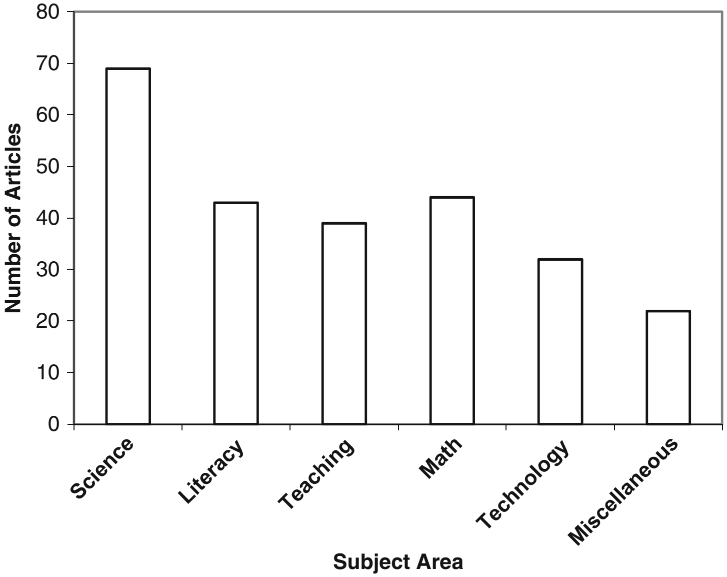
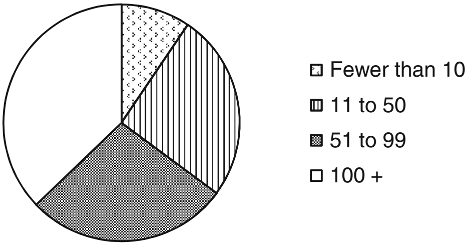


Fig. 3.1 The number of published articles by subject area

Fig. 3.2 Proportion of studies by the number of participants involved



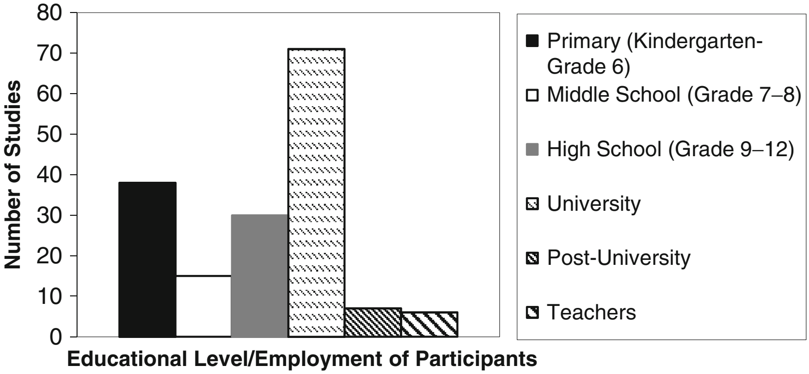


Fig. 3.3 The number of studies by the educational level/employment of participants in them

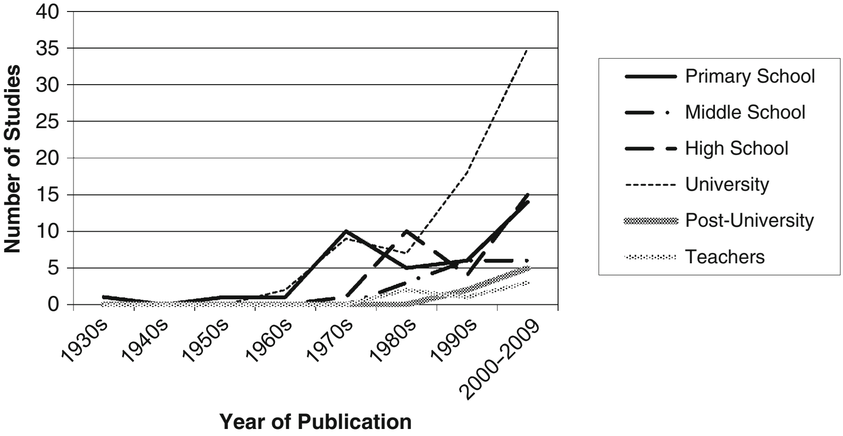


Fig. 3.4 Publication trends by educational level/employment of participants

The Definition of Visualization

In an attempt to define “visualization”, we found that many terms—including visualization, visual aid, image, and visual literacy—are used frequently and interchangeably throughout the literature. We decided to seek clarification from the *Merriam-Webster Online Dictionary* (2007). See Table 3.1 for a specification of the meanings found.

Even though the definitions in Table 3.1 do little to clarify what “visualization” means in the context of education or educational research, they are provided to illustrate the need for explicit clarity in the conduct of research. There are multiple usages for the same term, expressed as verbs and nouns. Bishop (1989) noted the important distinction between the noun and verb forms of “visualization”. The noun “directs our attention to the product, the object, the ‘what’ of visualization, the visual images. The ‘verb’ of visualization on the other hand makes us attend to the process, the activity, the skill, the ‘how’ of visualizing” (p. 7). In our review of approximately 250 articles, books, and chapters, we found 28 explicit definitions of visualization, and those dated from 1974 onwards. The first explicit definition is provided by Allan Paivio in 1974, who stated that imagery is “a dynamic symbolic system capable of organizing and transforming the perceptual information that

Table 3.1 Definitions of terms from *Merriam-Webster Online Dictionary* (2007)

Visualization (noun)	1. formation of mental images 2. act or process of interpreting in visual terms or of putting into visible form
Visualize (transitive verb)	To make visible: as to see or form a mental image of
Image (noun)	1. a reproduction or imitation of the form of a person or thing; 2. a: the optical counterpart of an object produced by an optical device (as a lens or mirror) or an electronic device; b: a visual representation of something: as (1): a likeness of an object produced on a photographic material, (2): a picture produced on an electronic display (as a television or computer screen) 3. a: exact likeness: semblance; b: a person strikingly like another person 4. a: a tangible or visible representation: incarnation; b: an illusory form 5. a(1): a mental picture or impression of something; (2): a mental conception held in common by members of a group and symbolic of a basic attitude and orientation 6. a vivid or graphic representation or description
Image (transitive verb)	1. to call up a mental picture of 2. to describe or portray in language especially in a vivid manner 3. a: to create a representation of; also, to form an image of; b: to represent symbolically
Visual literacy (noun)	The ability to recognize and understand ideas conveyed through visible actions or images (as pictures)

we receive" (p. 6). The 23 explicit definitions starting with Paivio's are shown in Table 3.2. We have included definitions of related terms, such as "imagery" and "visual aid", in this total. The definitions given make explicit which term is used in the original works.

Table 3.2 Explicit definitions of "visualization" in chronological order provided in research literature

Year	Author(s)	Explicit definition
1974	Paivio	". . .the conception of imagery as a dynamic symbolic system capable of organizing and transforming the perceptual information that we receive" (p. 6)
1982	Hortin	"visual literacy is the ability to understand and use images and to think and learn in terms of images, i.e., to think visually" (p. 262)
1983	Nelson	"Visualization is an effective technique for determining just what a problem is asking you to find. If you can picture in your mind's eye what facts are present and which are missing, it is easier to decide what steps to take to find the missing facts" (p. 54)
1985	Sharma	"Visualization (mental imagery) serves as a kind of 'mental blackboard' on which ideas can be developed and their implications explored" (p. 1)
1986	Presmeg	". . .a visual image was defined as a mental scheme depicting visual or spatial information" (p. 297)
1989	Ben-Chaim, Lappan, & Houang	"Visualization is a central component of many processes for making transitions from the concrete to the abstract modes of thinking. It is a tool to represent mathematical ideas and information, and it is used extensively in the middle grades" (p. 50)
1989	Bishop	"Visual processing ability was defined as follows: 'This ability involves visualization and the translation of abstract relationships and non-figural information into visual terms. It also includes the manipulation and transformation of visual representations and visual imagery. It is an ability of process and does not relate to the form of the stimulus material presented' (Bishop, 1983)" (p. 11)
1989	DeFanti, Brown, & McCormick	"Visualization is a form of communication that transcends application and technological boundaries" (p. 12)
1991	Arnheim	"Visualization refers to the cognitive functions in visual perception. In visualization, pictures combine aspects of naturalistic representation with more formal shapes to enhance cognitive understanding" (p. 2)
1994	Lanzing & Stanchev	"Presenting information in visual, non-textual form is what is meant when we speak of visualization. The non-textual symbols, pictures, graphs, images and so on conveying the information will be called visuals" (p. 69)

Table 3.2 (continued)

Year	Author(s)	Explicit definition
1995	Rieber	"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). Visualization includes both internal (for example, mental imagery) and external representations (for example, real objects, printed pictures and graphs, video, film, animation)" (p. 45)
1996	Zazkis, Dubinsky, & Dautermann	"Visualization is an act in which an individual establishes a strong connection between an internal construct and something to which access is gained through the senses. Such a connection can be made in either of two directions. An act of visualization may consists of any mental construction of objects or processes that an individual associates with objects or events perceived by her or him as external. Alternatively, an act of visualization may consist of the construction, on some external medium such as paper, chalkboard or computer screen, of objects or events that the individual identifies with object(s) or process(es) in her or his mind" (p. 441)
1999	Antonietti	"Imagery is a kind of mental representation which can represent objects, persons, scenes, situations, words, discourses, concepts, argumentations, and so on in a visuospatial format. Mental images can refer to entities that a person: (a) is perceiving at present, (b) has perceived previously, or (c) has never perceived. Mental images can represent either concrete or abstract, either real or imaginary entities and may be either like photographs or motion-pictures or like diagrams, schemas, sketches, symbols. Finally, mental images either may be static or may represent movements and transformations" (p. 413)
1999	Habre	"Visualization is the process of using geometry to illustrate mathematical concepts" (p. 3)
1999	Mathewson	"Visualization retains its usual meanings in cognitive science, but also has been arrogated by science and technology to mean computer-generated displays of data or numerical models" (p. 3 footnote)
1999	Liu, Salvendy, & Kuczek	"Visualization is the graphical representation of underlying data. It is also the process of transforming information into a perceptual form so that the resulting display make[s] visible the underlying relation in the data. The definition by McCormick, DeFanti, and Brown (1987) of visualization is 'the study of mechanisms in computers and humans which allow them in concert to perceive, use and communicate visual information (p. 63)'" (pp. 289–290)

Table 3.2 (continued)

Year	Author(s)	Explicit definition
2001	Presmeg & Balderas-Canas	"The use of visual imagery with or without drawing diagrams is called visualization" (p. 2)
2001	Strong & Smith	". . .spatial visualization is the ability to manipulate an object in an imaginary 3-D space and create a representation of the object from a new viewpoint" (p. 2)
2002	Schnotz	"Visual displays are considered tools for communication, thinking, and learning that require specific individual prerequisites (especially prior knowledge and cognitive skills) in order to be used effectively" (p. 102). "Representations are objects or events that stand for something else (Peterson, 1996). Texts and visual displays are external representations. These external representations are understood when a reader or observer constructs internal mental representations of the content described in the text or shown in the picture" (p. 102)
2002	Stokes	". . .visual literacy defined as the ability to interpret images as well as to generate images for communicating ideas and concepts" (p. 1)
2003	Linn	"Visualization for the purposes of this paper refers to any representation of a scientific phenomena in two dimensions, three dimensions, or with an animation ". "Visualizations. . .test ideas and reveal underspecified aspects of the scientific phenomena. . .display new insights and help investigators compare one conjecture with another. . .illustrate an idea that words cannot describe" (p. 743)
2004	Zaraycki	". . .visualization is the process of using geometrical illustrations of mathematical concepts. Visualization is one of the most common techniques used in teaching mathematics" (p. 108)
2005	Piburn et al.	"visualization. . .('the ability to manipulate or transform the image of spatial patterns into other arrangements')" (p. 514)
2007	Garmendia, Guisasola, & Sierra	"Part visualization is understood to be the skill to study the views of an object and to form a mental image of it, meaning, to visualize its three-dimensional shape (Giesecke et al., 2001). . ..visualization is mental comprehension of visual information" (p. 315)
2008	Gilbert, Reiner, & Nakhleh	"Visualization is concerned with *External Representation*, the systematic and focused public display of information in the form of pictures, diagrams, tables, and the like (Tufte, 1983). It is also concerned with *Internal Representation*, the mental production, storage and use of an image that often (but not always. . .) is the result of external representation" (p. 4). "A visualization can be thought of as the mental outcome of a visual display that depicts an object or event" (p. 30)

Table 3.2 (continued)

Year	Author(s)	Explicit definition
2009	Deliyianni, Monoyiou, Elia, Georgiou, & Zannettou	"Particularly, in the context of mathematical problem solving, visualization refers to the understanding of the problem with the construction and/or the use of a diagram or a picture to help obtain a solution (Bishop, 1989)" (p. 97)
2009	Korakakis, Pavlatou, Palyvos, & Spyrellis	"'Spatial visualization', the ability to understand accurately three-dimensional (3D) objects from their two-dimensional (2D) representation" (p. 391)
2009	Mathai & Ramadas	"Visualisation is defined in terms of understanding transformations on structure and relating these with function" (p. 439)

The definitions and statements in Table 3.2 point to a three-fold distinction between physical objects serving as visualizations (geometrical illustrations, animation, computer-generated displays, picture-like representations); mental objects pictured in the mind (mental scheme, mental imagery, mental construction, mental representation); and cognitive processing in which visualizations, either physical or mental, are interpreted (cognitive functions in visual perception, manipulation and transformation of visual representations (by the mind), concrete to abstract modes of thinking, and picturing facts). The three distinctions follow:

1. *Visualization Objects*. These are physical objects that are viewed and interpreted by a person for the purpose of understanding something other than the object itself. These objects can be pictures, 3D representations, schematic representations, animations, etc. Other sensory data such as sound can be integral parts of these objects and the objects may appear on many media such as paper, computer screens, and slides.
2. *Introspective Visualization.*These are mental objects that a person makes that are believed to be similar to visualization objects. Introspective visualization is an imaginative construction of some possible visual experience.
3. *Interpretive Visualization.*This is an act of making meaning from a visualization object or an introspective visualization by interpreting information from the objects or introspections and by cognitively placing the interpretation within the person's existing network of beliefs, experiences, and understanding.

We have chosen these terms not because they are common in the literature—they are not—but because they are useful for capturing most of the important distinctions that are represented in Tables 3.1 and 3.2. The distinction between physical visualization objects and mental introspective visualization is an obvious one; most writers at least make this clear through context. The distinction between the visualization itself whether physical or mental and the thinking involved in interpreting that visualization is also important. As was noted in Chapter 2, it is not fully known how visual imagery is processed in the human brain. It may be the case, for example, that introspective visualizations do not undergo interpretation in the same way as visualization objects. If so, our distinction will need to be changed in the light of future research. For now, we believe it is prudent to assume that the two types of visualization undergo similar need for clarity and processes of interpretation.

What Constitutes a Good Visualization?

Insofar as visualization involves the interpretation of pictures, it seems a suitable theory of picture meaning is required to know whether or not a visualization is a good one. If pictures are to be used to assist or enable certain types of learning, then some idea of how information is encoded in pictures is likely to be useful. It also seems that a workable theory of pictures as abstractions is necessary to pave the way for relating picture making to our desire to find resolution, coherence, and unity in the world around us (Arnheim, 1966; Gregory, 1970; Zettl, 1990). After all, visualization plays a central role in the cognitive processes scientists and mathematicians engage (Arcavi, 1999; Buckley, Gahegan, & Clarke, 2000); Duval, 1999; Gilbert, 2005; Kaput, 1999). Unfortunately, if a comprehensive theory of pictures and picture meaning is not currently available, then research on visualization must proceed based on intuitions about picture usefulness rather than on informed judgement.

Thinking intuitively, what must a student do to use a visualization object? It seems clear that even a trivial interpretation of visualization objects requires that the student utilize attributional and inferential strategies. This is so because, in the absence of human cognitive engagement, visualization objects are merely sources of optical data. The person viewing the image must have at least some repertoire of experiences, mental skills, and volitions even to begin the process of interpretation. Some cognitive action must be made to move from what is on the page (or screen, etc.) to some internalized conception of what it represents before interpretation, manipulation, or prediction can occur. The failure to recognize the processes of mediation between what is visualized in the mind's eye and the visualization object itself involves much more than just the confusion of the object and what it stands for (Presmeg, 1999). The use of visualizations in any mode or style involves not only an awareness of the properties of the object itself, but also a familiarity with the forms of symbolization that appear in the object as proxies for reality. Recall Fig. 2.1, Descartes' diagram of human vision. Without some familiarity with the central ideas, it is not obvious which features of Descartes' illustration are relevant to the understanding of what. Are the eyes important? Does the gender of the subject matter? What are those lines piercing her eyes? What is she pointing at? Helping students attain a range of interpretive and evaluative skills in order to recognize and understand the manipulations possible with visualization and also how to interpret a representational symbolic system are just a few of the factors to be considered in teaching with visualization objects. Thus, a thorough understanding of the nature of

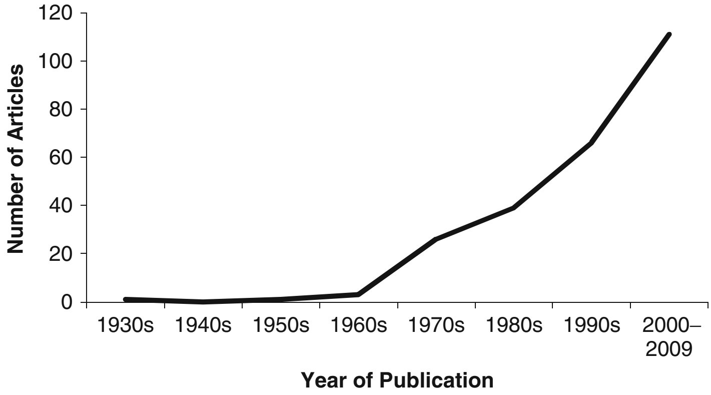


Fig. 3.5 Number of published articles about visualization by year

visualization objects, their functions (Ainsworth, 1999), and the interpretive skills essential to assess the plausibility, validity, and value of visual images is critically important.

Much research has focused on which characteristics of visualization objects are significant in making them maximally effective in conveying information to a learner. The earliest known studies on visualization for the purposes of teaching and learning appeared in 1936, and since that time there has been a more or less steady increase in the number of studies. Figure 3.5 shows a timeline of articles focused on visualization. From the 140 empirical studies examined in this review, five characteristics emerged as important features of visualizations: colour, realism, relevance, level of interactivity, and animation. The number of studies focused on each characteristic can be seen in Fig. 3.6.

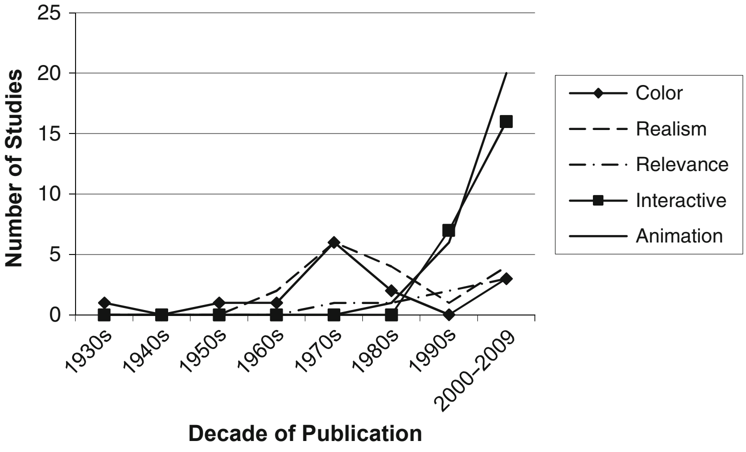


Fig. 3.6 Number of published studies about characteristics relating to a good visualization by decade

Colour

Studies in the first half of the twentieth century focused primarily on the presence or absence of colour in illustrations for children's books. Miller's (1936) study presented 300 primary school children with photographs copied in five different ways: line drawing, black and white, full colour with three primary colours, colour with red as the predominant colour, and colour with blue as the predominant colour. The majority of children in grades four to six stated a preference for the full colour picture, followed by the picture in which red was predominant, and then in which blue was predominant. Rudisill did a similar study in 1952 with approximately 1,200 children in kindergarten up to grade six. She presented five types of illustrations (all with the same content) that were commonly found in children's books: an uncoloured photograph, a coloured photograph, a coloured drawing realistic both in form and in colour, an outline drawing realistic in form but with an outline that is coloured without regard for realistic effect, and a coloured drawing that is conventional in form but unrealistic in colour. She concluded that children first look at an illustration for content that is lifelike and real, including colour, which adds to the realism. Given the different sorts of books and visual images that today's children experience compared to those studied by Miller and Rudisill, it is difficult to say how much validity these results would continue to have.

In 1960, Amsden extended the studies on the impact of colour. She examined the amount, value, and kind of colour 60 children, aged 3–5 years, preferred in illustrations. To determine the amount of colour preferred, she provided a black and white line drawing, one with one colour, one with two colours, one with three colours, and a drawing with four colours, which she said represented the most realistic of them all. To determine the value of colour, she provided drawings with lighter and darker shades. To determine preference, she provided a black and white photograph as well as a line drawing. And lastly, to determine the style of drawing, she provided a realistic drawing and a fanciful drawing. Amsden found that illustrations with more colours were significantly more preferred to those with fewer colours, but when a black and white photograph was compared to a line drawing with one colour there was no significant difference in the children's preferences. In his studies in the 1960s and 1970s, Dwyer asked, among other things, if colour was an important variable in facilitating university undergraduate student achievement. Based on his studies comparing illustrations of the human heart, he concluded that colour was important in visuals but only with reference to certain instructional objectives, such as those focused on realistic features of objects, those requiring identification of parts of a diagram, and those focused on overall concept understanding (1970, 1971).

In a study of the literate and illiterate population of Olhao in Southern Portugal, Reis, Faísca, Ingvar, and Petersson (2006) compared object recognition in coloured and black and white depictions of physical objects. When 38 participants divided equally into literate and illiterate groups were compared, they found that "color, independent of the presentation mode, does make a difference for the illiterate subjects" (p. 52) on object recognition. Based on this result the authors concluded that "color has a stronger influence on performance than photographic detail for the non-literate subjects" (p. 53), thus suggesting that "it is the presence of color attributes…which facilitates the access to stored structural knowledge about objects" (p. 53).

From our perspective, there is a great difference between studies that focus on interest as the dependent variable and those that focus on understanding, or literacy achievement. Children's preferences are not necessarily of sufficient educational value to justify the choice of picture style or colour based upon them. If the only effect is increased interest with no concomitant effect on understanding or achievement, then other factors such as time, efficiency, and expense can play a larger role in decisions about the use of colour.

Realism

Francis Dwyer carried out numerous studies focusing on realistic detail in illustrations. His 1967 study examined how 108 university undergraduates interpreted information about the human heart when it was presented in various ways: orally with no accompanying illustrations but with text naming parts of the heart projected on a screen; orally and with abstract linear representations of parts of the heart; orally and with more detailed, shaded drawings representing parts of the heart; and orally with realistic photographs of the parts of the heart. Dwyer found that a reduction in realism did not necessarily reduce the instructional effectiveness, and sometimes even improved it. He also noted that there were different levels of effectiveness with the different types of instruction for different educational objectives. Dwyer followed his 1967 study with a similar study in 1968, which again examined levels of realistic detail required for educational objectives related to teaching undergraduate students about the human heart. The same presentation sequence was followed in 1968 as in the 1967 study, with five groups of students hearing and viewing information in the same five conditions. After listening to the presentation sequences, the 269 students were given four post-tests with questions on identification of parts of the heart, terminology, and heart functions coupled with the requirement to draw a diagram of the heart. Scores for each of these four tests were combined and a total composite score was determined. Dwyer found that the oral presentation of information complemented by printed text without pictures was the most effective condition for learning the identification of parts of the heart, terminology, and understanding heart function. Students in this control group (oral with printed text only) also had the highest composite scores compared to all of the treatment groups. However, students who had viewed abstract line or shaded diagrams during the oral presentation scored better than the control group on drawing a diagram of the heart. Dwyer concluded that the realistic details in certain illustrations were distracting students from the important information in the text, and that students took too long to study and comprehend the information in the diagram. This suggests that it is very important that the designers and implementers of visualization objects and activities pay close attention to the structure of the objects and be careful not to include unneeded detail. This is reminiscent of the differences between Descartes' elaborate and Newton's austere diagrams depicting optical phenomena (Figs. 2.1 and 2.2).

Haring and Fry (1979) concurred with the finding that pictures do not need to be detailed or colourful to be effective for increasing recall. Their study with 150 fourth and sixth graders broke a story into sections, and then added two sets of redundant pictures. They found that even unimaginative pen and ink drawings helped with recall of main ideas presented in the text. Readence and Moore (1981) questioned the effect of adjunct pictures on reading comprehension in their review of previous studies. They examined several variables, including realism in illustrations, and they differentiated between line drawings, shaded drawings, and photographs. They found that line drawings alone were able to provide the proper spatial perspective necessary to facilitate reading comprehension.

Relevance

In 1989 when Norma Presmeg examined previous research that challenged students with mathematical problems and interviews asking about their use of visualizations in solving problems, she found that when the medium of instruction is in a language that is not the home language of the student, having visual elements included in the lesson can help comprehension of the material. Presmeg suggested that comprehension as a result of the inclusion of visual elements in the lesson is particularly increased if the visuals are meaningful to the students' frame of reference. For example, she suggested that the Rangoli patterns that are commonly used by Hindu and Sikh families to decorate their homes have a geometrical basis that can be referenced by a teacher to discuss shape and space in the classroom, helping some students to solve some mathematical problems.

Booth and Thomas (1999) studied the relationship between problem solving and spatial ability in 32 mathematics students aged 11–15 years. They used the New Zealand-developed Progressive Achievement Tests, which measure recall ability; accuracy and efficiency at calculating; comprehension of terms, symbols, formulas, concepts, and principles; ability to apply knowledge; and ability to select processes necessary to provide solutions. The information was provided in diagram and picture format, and the researchers found that the diagrams required more time and a higher level of visual skill to interpret and relate to the problem than did the pictures. When a student must relate a visual to a model of reality presented in a mathematical problem, the relationship requires interpretation and spatial skill that some students may not possess. Healy and Hoyles' (1999) study examined how 20 students aged 12 and 13 years used visual reasoning in mathematical activities. They used computer-integrated tasks and computer-added tasks to document the influence of computer use on patterns of reasoning and found that computer work needed to be carefully planned so that it would be relevant and transferable to the curriculum. They maintained that improving visual and symbolic reasoning in mathematics through using computers required a strong and precise connection between reasoning and the tasks on computers.

Vekiri (2002) has cautioned against assuming that graphic displays in and of themselves can enhance learning. To be effective, visual representations must first be well designed: for example, she argued that Gestalt principles of perceptual organization such as connectedness and proximity should be employed. In addition, if it is to enhance learning, then a visualization object must effectively communicate information to a viewer. This means that what the learner brings to the task is extremely important. That is, the viewer's background knowledge and interpretive ability and skills play a major role in determining the teaching effectiveness of any visualization.

Further, Richardson (1994) has advised that for some cognitive tasks "imaginal elements may be either irrelevant or detrimental to performance" (p. 70), explaining that "a vivid image will have no special virtue if a task can be performed equally well without its presence". Citing research by Reisberg and Leak (1987), Richardson continued, "it may be that vivid imagery is a disadvantage in some situations in which, for example, perceptual judgments are required" (p. 121). In their research, Reisberg and Leak (1987) found that subjects they described as "high vividness imagers" (p. 521) were less accurate than "low vividness imagers" (p. 521) when faced with a task requiring the comparison of imaged faces of famous people.

So, while it appears to be widely accepted that visualization objects can support communication, thinking, and learning, Schnotz (2002) also cautioned that this is true "only if they interact appropriately with the individual's cognitive system" (p. 113). That is, the strategies a learner has developed for visualizing are essential, as is the individual's prior content knowledge, cognitive abilities, and learning skills. Furthermore, Schnotz emphasized that effective learning from graphics is also dependent on the instructional design of the visuospatial text, listing many of the same design characteristics and justifications that Vekiri (2002) had.

Interactivity

Researchers of computer animations as visualization objects have noted that the high level of interactivity between object and learner appears to facilitate greater levels of interpretive visualization than do other types of visualization objects. Milheim (1993) discussed previous research on the use and effectiveness of animation in instruction and summarized it into guidelines and suggestions for implementing animation. He stated that animation in computer-based instruction is uniquely beneficial because the learner can control and manipulate parts of the presentation, can test hypotheses, and can witness consequences through programme feedback. Bennett and Dwyer (1994) stressed the same point when they said that "interactive visuals [in this case, drawing lines to emphasize shape and location of critical information of the question] which allow the learner to take an active role in the learning process can influence the learner's ability to select, acquire, construct and integrate concepts" (p. 23). Their study tested 178 college-level students' abilities to read text and to refer to visuals to reinforce information. Students participated in the instructional presentation and immediately afterwards had a drawing test that evaluated their ability to construct and reproduce items from the presentation. They also completed an identification test, a terminology test, and a comprehension test. Bennett and Dwyer found that interactive visual strategies were effective in facilitating student achievement, but that students need an explanation of how the interactive strategy is going to help achieve the specific learning objective in order to help them organize the information for acquisition and retrieval.

In their review of previous research, Scaife and Rogers (1996) stated that "virtual reality and visualization, as means of representing and interacting with information, are very much at the forefront of technological development" (p. 3). They found that being immersed in the experience of a visual aid is a major motivating factor for learning and that animated diagrams were more effective at facilitating cognitive tasks than static, non-interactive graphics (p. 3). Taking interaction with visualization further is LaViola Jr.'s (2007) Tablet PC-based application, MathPad^2. (Note that the superscript "2" is an exponent, not a reference to a footnote.) LaViola Jr. explains the work already done on MathPad^2 as well as recent advances in the use of mathematical sketching. He states that "an important goal of mathematical sketching is to facilitate mathematical problem solving without imposing any interaction burden beyond those of traditional media" (p. 38). In other words, LaViola Jr. has aimed to create a programme that is better than pencil-and-paper drawings but not more cumbersome to use. The potential of MathPad^2 was affirmed in a preliminary evaluation when it was reported that "subjects thought the application was a powerful tool that beginning physics and mathematics students could use to help solve problems and better understand scientific concepts" (p. 8).

Lurie and Mason's (2007) discussion paper explored the use of interactive visualization tools in consumer marketing. They argue that "by mimicking the act of touching and feeling products, interactive virtual reality visualizations may be better substitutes for haptic experiences than textual information" (p. 163). The authors posit that such virtual reality has the ability to "increase consumers' confidence in their choices and lower the proportion of physical search relative to online search" (p. 163). Companies such as those selling houses, cars, telephones, and furniture use these virtual reality visual representations to allow their customers an opportunity to explore products through sound, motion, and other effects.

Animation

Since the early 1990s, computer-generated animation has taken an increasing role in the discourse of visualization. Lloyd Rieber (1990a) reviewed the extant literature and claimed that "animation has been used in instruction to fulfill or assist one of three functions: attention-gaining, presentation, and practice" (p. 77). He noted that the "use of animation must be evaluated carefully, however, to avoid inadvertently reinforcing wrong responses" (p. 78). Rieber made three main suggestions for using animations:

1. Use them only when the attributes of the animation are compatible with the learning task (that is, when completing the task successfully involves the need for visualization, motion, and/or trajectory).

2. Make animations simple enough so that the relevant cues provided by the animation are understood (that is, decompose the information into chunks so that each important point is emphasized).
3. Use interactive animation in a way that students can perceive the differences in the feedback from the graphics (that is, allow students to take control of their learning by manipulating the "game").

It is clear that animated visualization objects are able to show time-domain changes in a way that static diagrams and drawings cannot. Many of the same issues that have been raised for static objects transfer to animations. These points are explored more deeply in Chapter 7.

Concluding Comments

What we have seen in this chapter is that there is general support for the hypothesis that various sorts of visualization objects are helpful for students to learn in a variety of contexts. There are no clear-cut rules for how to create the most effective visual aid. However, there do seem to be some general guidelines that can be extracted based on our review. First and foremost, visual aids must be relevant to the lesson objectives. If a visual aid is being used simply for sensational or attention-getting purposes, it will distract from the learning and inadvertently cause the students to recall the wrong information. Second, the content of the visual aid is more important that the presence or absence of colour or the simplicity of line drawings versus the depth of realism. Third, visual aids should be used as a supplement to and not a replacement for text. Combining visuals and printed information enables students with different learning styles to receive the information through either the text, the visual, or both. Fourth, animation should be used only when the knowledge to be gained is related to movement or can be better understood if a 3D visual is shown (for example, trajectory of movement, chemical bonds, layers of epidermis on a cadaver). Animations should be short, simple, and obvious in terms of what is being demonstrated. Fifth, interactive/dynamic visuals are beneficial to learning, but only if there is a component of immediate feedback (Levin, Anglin, & Carney, 1987); Mayer, 1997 ; Scaife & Rogers, 1996.

Chapter 4
Cognitive Theory

This chapter examines basic mechanisms of visualization. An important question is whether visual images and language are coded and processed simultaneously or separately. If it is determined that linguistic and visual modes are coded and processed separately then the possible level of interaction between the modes becomes an issue. The question of interaction is particularly important in the use of multimedia or interactive visualization objects, and thus the theoretical problem becomes real: How are learners able to relate their visualization experiences with other contents and products of their cognitive experiences? Visualization will be useful for learning if it can assist students to acquire educationally desirable knowledge. That is, students are expected to acquire reasonable or defensible knowledge as a consequence of their engagement with visualization objects, perhaps in conjunction with other experiences such as direct teaching, reading text, and performing experiments.

The visual information that first comes to the brain is surprisingly sparse. It turns out that even though our visual experience has the phenomenal appearance of being complete and continuous, at the level of the eyes and the basic electrical information it is not. Somewhere in the human brain this sparse data is processed in such a way as to make our visual experience the rich and continuous thing that it is. The mechanisms by which this occurs are the subject of deep theoretical disputes that stand in the way of a full understanding of visualization as a process. At some stage in the processing of raw data into a meaningful phenomenal experience, the contents of our thoughts enter into visualization.

This chapter will provide an overview of three theories of how images are coded by the brain: dual coding theory, the visual imagery hypothesis, and the conjoint retention hypothesis. We shall then examine what these theories say about the design of effective visualization objects.

Cognitive Coding of Visual Images

In her review of the value of graphical displays in learning, Vekiri (2002) paid particular attention to three theoretical perspectives: dual coding theory, the visual imagery hypothesis, and the conjoint retention hypothesis. The dual coding theory

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(for example, Clark & Paivio, 1991; Paivio, 1986; Sadoski & Paivio, 2001) has gained widespread recognition as a plausible, though partial, explanation of how visual perception affects memory. Very briefly, this theory proposes that there are both verbal and nonverbal mental systems for processing linguistic and imagery information and that words and sentences are processed and encoded in the verbal system, while images are processed and encoded in the nonverbal system. These systems process independently, but their products are accessible either separately or in combination, allowing material stored in each system to be associated, and these referential connections aid memory and the retrieval of information (Clark & Paivio, 1991; Paivio, 1986; Sadoski & Paivio, 2001).

Paivio (1974) argued that when verbal information and visual information are presented simultaneously, the information is coded in the learners' brain using multiple senses, which allows for the option of retaining and accessing the information using one or more modalities (for example, verbal and/or visual). According to Paivio, "the imagery system organizes elementary images into higher-order structures so that the informational output of the system has a synchronous or spatial character, whereas the verbal system organizes linguistic units into higher-order sequential structures. . .both systems are capable of functioning in a dynamic and flexible way to reorganize, manipulate or transform cognitive information" (p. 8). Paivio's theory has led many researchers to explore the benefits and drawbacks of providing verbal and visual cues simultaneously, in order to encourage learners to use all sensory modalities while interpreting and evaluating visualizations.

Vekiri (2002) has cautioned, however, that the studies foundational to this theory "involved very simple cognitive tasks and performance outcomes, which severely limits the application of dual coding theory" in more complex learning situations (p. 270). Hertzog and Dunlosky (2006) have also cautioned

> What is critically important is that imagery use in and of itself is not effective for learning new materials. Instead, an interactive image must be formed in which imaginal tokens of the concepts represented by the two words are actively engaging one another—in other words, the critical encoding activity is relational processing. . .. One realizes relatively little learning benefit from forming separate images of a clown and a spoon, but imagining a clown interacting with a spoon. . .results in greatly enhanced paired-associate recall. (pp. 259–260)

The second perspective, the visual imagery hypothesis, is not necessarily incompatible with dual coding theory, but stresses that graphical representations are effective because their visuospatial structure allows individuals to process information more efficiently, that is, with fewer cognitive transformations (Vekiri, 2002). This efficiency, in turn, reduces the load on working memory. Johnson-Laird's (1998) model theory would be an example of a visual imagery theory, as would Pylyshyn's (2003) syntactic theory. Pylyshyn argues that the content of thought is greatly underdetermined by the information that could be encoded by visual imagery or by natural language. Much of what must be taking place in thinking must be inaccessible to conscious thought most of the time. If thinking involves inner dialogue or imagery, he argues, it does so only partially. Simple acts of reference, for example, "I am using this pen for that project, not that pen", contain too much information, embedded in presuppositions and assumptions, to be fully disclosed by either an image or by language. Whatever it is that the brain is doing while thinking, he argues, it cannot be fully disclosed by the dual coding theory. On this view, visual imagery can be helpful to the learner not because it encodes a thought or series of thoughts, but because it has other semantic properties that allow the learner to order, to compare, or to manipulate some information extracted from the image.

Larkin and Simon's (1987) research, for example, has contrasted the computational efficiency of diagrammatic representations and sentential representations in solving different kinds of problems (for example, in physics, geometry, and economics). They concluded that diagrams can be superior to verbal descriptions in solving certain types of problems because diagrams can organize relevant information in close proximity, allowing operators to search, compare, and make inferences more easily than with sentential text. However, they also concluded that this possibility of the superiority of diagrams does not mean that a diagram can be so constructed in every case, which helps to explain why some diagrams are much better than others in aiding problem solving and sometimes worse than verbal descriptions.

The third perspective, the conjoint retention hypothesis, draws strongly on both dual coding and visual imagery to explain how learning takes place when graphics (predominantly different types of maps, including geographic, thematic, and concept maps) are combined with text (Vekiri, 2002). Kulhavy, Stock, Peterson, Pridemore, and Klein (1992) who coined the phrase "conjoint retention hypothesis" put forward the idea that both map and text elements are represented conjointly in memory. They further explained that this hypothesis was based on two assumptions, both contained in Paivio's (1986) dual coding theory: first, spatial and verbal stimuli are located in distinct memory codes that are accessible to one another; and, second, maps can be "efficiently searched with relatively low processing cost to the active memory system" (p. 57). This second assumption reflects the visual imagery hypothesis that emphasizes the computational efficiency of graphics.

Using Cognitive Theories to Design Effective Visualization Objects

It is beyond the scope of this book to attempt to adjudicate the debate over the form of visual content in the brain. The fundamental question is whether visual information and verbal information are processed in a similar fashion or whether they are handled differently. There is an easily discerned phenomenological difference between the two—introspection indicates that the experience of language and the experience of image are rather different. The current consensus is that Galton was mistaken: no amount of introspection can lead a subject to discern the similarities and differences in the way or ways that linguistic and imagistic experiences and information are processed, phenomenology notwithstanding. As we will see in Part

II of this book, it is not necessary to have solved the cognitive issues in order to effectively use visualization in education.

In 1997, Mayer reviewed his own previous studies examining multimedia presentations and the way in which people integrate verbal and visual information during learning. Students were given multimedia instruction on the basics of scientific phenomena and were asked to generate creative solutions to applied "transfer problems" related to the basic material. He found that "overall, students who received visual explanations coordinated with verbal explanations produced approximately 75% more creative solutions [that is, their number of solutions was 75% greater] to transfer problems than did students who received the explanation presented only in verbal form" (p. 8). Mayer also established that students who had low prior knowledge greatly benefited by receiving integrated instruction for problem-solving tests. He concluded that the most effective way to present visual and verbal material together is "when the material is a cause-and-effect explanation of a simple system, when the learners are inexperienced, and when the goal is meaningful learning" (p. 18). Mayer stressed that visual objects, no matter how cleverly they are animated, are not beneficial without explanatory narration. He interpreted his results as supportive of dual coding theory.

In her assessment of extant research supporting dual coding theory, Vekiri (2002) noted that research "has shown that diagrams can provide a valuable contribution to students' learning, but their effects are contingent upon two important factors: the characteristics of the displays themselves and the characteristics of the learners who use them" (p. 275). Her main points were the following:

1. Displays need to address the goal of the task.
2. Displays should be provided along with explanations and guidance.
3. Displays need to be spatially and timely coordinated with text.
4. Students' prior knowledge affects their style and ability in interacting with displays.
5. Students' visuospatial ability affects their ability to use the display (pp. 275–279).

Vekiri (2002) claimed that there is strong research support for the first three points. The first aligns with the commonsense notion that extra material can be distracting or confusing. This is a challenge for teachers because many visualization objects such as films are not custom-made for the task at hand. The second point is less obvious. There is a strong tradition of self-guided learning in education, and students are often expected to figure things out on their own. Citing Rieber (1990a, 1990b, 1991), Vekiri argues that "adding visual displays to verbal material can enhance student understanding but displays are not effective when used without guidance or explanations" (p. 275). On the third point that spatial and temporal ordering of visual object and text is important, Vekiri says that if text and image are separated by space (for example, a diagram is on a page different from the text referring to it) or time (for example, narration and image are not together in an animation), then students have difficulty constructing rich and coherent mental models. Mayer and Anderson (1991) call the third point on Vekiri's list the contiguity principle.

The fourth and fifth points are vaguer and less well established than the first three, Vekiri admits. There are contradictory results regarding whether increased content knowledge leads to greater or lesser benefit from visualization objects (see Fig. 4.1). It does appear that higher prior content knowledge helps "readers to make more strategic use of text and diagrams and to integrate information successfully" when text and visual are combined, but there may be cases where "they benefit more when their knowledge is not too advanced" (p. 278). The exact function of prior visuospatial ability is unclear. Mayer and Simms (1994) found that students measured to have low spatial ability were less successful in using diagrams than were students with higher spatial ability. Further investigation of this phenomenon and its consequences will perhaps lead to a stronger theoretical sense of why spatial ability has the effect, and whether the ability can be improved.

In sharp contrast to dual coding theory research, the visual imagery hypothesis has led to research that focuses on the structure of visualization objects as computational aids. The hypothesis suggests that visualization objects are best understood as useful ways of storing information so that it can be accessed by sight as well as by introspection. This hypothesis has led a number of researchers to look at graphic organizers as useful tools for showing relationships. Tversky (2001) observed that graphic displays, through externalizing representations, reduce demand on memory and facilitate information processing, and that "effective graphics make it easy for users to extract information and draw inferences" (p. 111). Graphics are able to do this to the extent that information is spatially organized so it can be accessed, integrated, and operated on easily; essential features are abstracted and emphasized; and causal chains of events "over and above the parts of the system and their interconnections" (p. 110) are illuminated. Like Larkin and Simon (1987), she warned that poorly designed graphics do not facilitate learning.

An example of a logical system that exploits visual operations would be a Venn diagram. In Fig. 4.2, the diagram pictures all of the whole numbers less than 20 that are both square and odd. The structure of the diagram permits the observation of logical relationships at a glance—to the tutored beholder. The second point simply refers to the use of visual aids in a bookkeeping role. Often partial results are kept in graphic form for easy reference later in the work. By the third point, Pylyshyn claims that often by looking at a particular instance, the visual system leads a person to see what must be the case in general. By looking at a wheel roll

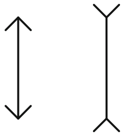


Fig. 4.1 Knowing that the line segments are the same length is not sufficient for the illusion to be broken

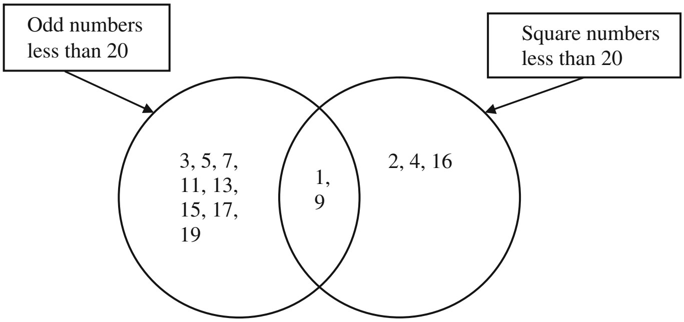


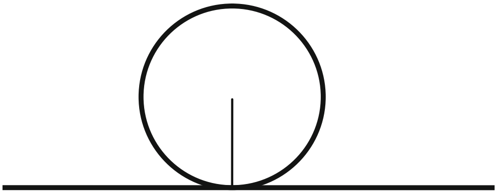
Fig. 4.2 The *left* circle contains all whole numbers less than 20 that are odd, and the *right* circle contains all whole numbers less than 20 that are squares. The *central* region contains numbers that are both odd and square and less than 20

along the ground, for example, a student can correctly see that the floor is tangent to the wheel and that the floor is perpendicular to a line drawn from the point of contact to the axle (see Fig. 4.3). In this example, verbal prompting is likely to be necessary.

To see how a visualization object can be used to track instances, consider the problem of seating four people on a bench: How many seating arrangements are possible? Figure 4.4 shows a simple way of using a visual aid to enumerate all possibilities. The fifth use in the list is to enumerate logical possibilities and impossibilities. This is easily illustrated with problems of the following sort: Alan is taller than Betty but Betty is shorter than Susan. Who is the tallest? While many people can solve this problem without the visual aid, many would find a picture such as Fig. 4.5 helpful in showing that the problem does not have a unique solution. In each case, the visual imagery hypothesis suggests that the usefulness of visualization lies in relieving the brain of some of its load.

Finally, the conjoint retention hypothesis is consistent with either the dual coding theory or the visual imagery hypothesis. According to Vekiri (2002), experimental results supporting the conjoint hypothesis could be used to support one or both of the other two theories. That said, there are no recommendations for the creation and use of visualization objects that are derived solely by virtue of this view.

Fig. 4.3 The wheel's radius is perpendicular to the surface on which the wheel rolls. Can you imagine this not being the case?



ABCD	BACD	CABD	DABC
ABDC	BADC	CADB	DACB
ACBD	BCAD	CBAD	DBAC
ACDB	BCDA	CBDA	DBCA
ADBC	BDAC	CDAB	DCAB
ADCB	BDCA	CDBA	DCBA

Fig. 4.4 A systematic list for accounting all possibilities when seating four people on a bench. The lists release the load on working memory by dividing the problem into smaller pieces and leaving artefacts for later counting

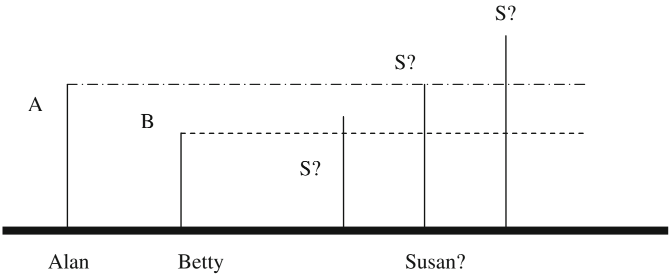


Fig. 4.5 Alan is taller than Betty and Betty is shorter than Susan. A diagram makes it clear that there are three possibilities for the relationship between Alan's and Susan's heights

Concluding Comments

A surprising consequence of this survey is the narrowness of the research within both the dual coding and the visual imagery camps. Dual coding theorists focus exclusively on research that indicates that students can acquire knowledge from combining linguistic and visual representations of the same or closely related phenomena. Visual imagery theorists focus on visual imagery that is used entirely as an external reference. Neither group seems to be interested in the others' research. The results suggest that both groups have found important educational uses for visualization. Well-designed visualization objects are useful computational aids when they are used to relieve the student's working memory of some of its load. Other well-designed visualization objects are useful as an adjunct to other means of acquiring knowledge, such as reading text or listening to language. It remains unclear how this is accomplished in the brain, but it is clear from the extant research that educators have two powerful theoretical bases for utilizing visualization in the classroom.

Part II
Current Educational Research

Although solutions to the many unanswered problems of cognitive psychology would assist educational researchers to refine their work on visualization, important research can still be done in their absence. Acknowledging the many unknowns, educationalists have forged ahead and have produced many important results regarding the use of visualization in mathematics, reading, and science education, though there appear to be fundamental differences in the ways that visualization is currently used in these three areas. These differences are largely due to the different purposes to which visualization is put in these subject areas. In mathematics, as shown in Chapter 5, the bulk of the research is aimed at visualization as a computational aid, as suggested by the visual imagery hypothesis. In mathematics, such visualization often leads to the creation of new mathematics. One could use a visualization object to assist students to understand a mathematical object, which could lead to the creation of another object that is mathematically interesting in its own right. For example, a graph might be used to help a student to understand a function. The graph itself, however, is a new mathematical object with its own properties. It is then possible for the educator or educational researcher to take an interest in graphs that is independent of the original aim of the graph's introduction. The role and effectiveness of visualizations in mathematics is both contentious and ambiguous. The contention arises from the belief by many mathematicians that visualizations tie universal mathematical concepts and thoughts inappropriately to specific objects, thereby misleading students about the significance of the mathematical results. The ambiguity arises because the best mathematicians often are not the best visualizers. The question arises whether it is the nature of the curriculum rather than of mathematicians that separates these two groups.

A main goal of reading is the interpretation of text, so visualization objects often are used with the aim of assisting the reader to make sense of written material. To be sure, there is much to be said about interpretation of images as adjuncts to text, by which here we mean the printed word, but often the point of reading is the interpretation of text, making the visualization object a means to that end. Not surprisingly, then, much of the research on visualization in reading follows the lines of dual coding theory, as suggested in Chapter 3. A main finding presented in Chapter 6 is that visualizations can assist with reading but only for students who have been provided explicit instruction in their use.

In science, as shown in Chapter 7, the situation differs again. Visualization objects in science are sometimes used to illuminate particular features of an object of scientific study. Anatomical diagrams are of this sort: the point of the diagram is to assist the student to identify some salient features of the object of the diagram. Many scientific visualization objects, however, are schematic rather than realistic. In these cases, the point of the diagram is to assist in calculations or descriptions of some phenomenon or process. Electrical circuit diagrams are a case in point. There is no information in a circuit diagram telling students what electrical circuits or components look like. The point of the circuit diagram is to show how the circuit is built. The benefit of the circuit diagram is that it allows one to give a description of a number of related properties and events in a working circuit. Visualization research in science education is informed by either dual coding theory or the visual imagery hypothesis. We did not find research that is informed by both.

The following three chapters on mathematics, reading, and science education are discussed separately for purposes of organization. However, they are not intended to be mutually exclusive.

Chapter 5
Visualizations and Mathematics

The question of whether visualizations help develop mathematical concepts has an ambiguous, and oftentimes contradicting, response. We reviewed over 40 articles focusing on visualizations in mathematics classrooms, with the majority focused on general mathematics, followed by geometry (see Fig. 5.1).

Two central issues arose: (1) a theoretical issue over the function of visualization objects as mathematical entities and (2) a practical issue over the effectiveness of visualization objects in learning and in doing mathematics. Intermingled with the two issues are the goals of mathematics instruction, which depending upon their formulation can emphasize or deemphasize the need for visualization. Hershkowitz (1989) studied the role of visualization in the process of geometrical concept attainment for middle school students, 142 pre-service elementary teachers, and 25 in-service senior elementary teachers. She claimed that "we cannot form an image of a concept and its examples without visualizing its elements" (p. 61) and stated further that visualization is complex and works in two opposing ways. First, we need to visualize elements in order to form an image of a concept. Second, a concept image may be narrowed by the visual elements. Hershkowitz presented participants with a verbal definition of two contrived geometrical concepts ("bitrian" and "biquad") and then asked half the students and teachers to identify those concepts from a set of shapes, while the other half were asked to draw the concepts. She found that the majority of participants identified the simplest examples of each concept or drew at least one example correctly. The results showed that despite the identical attributes

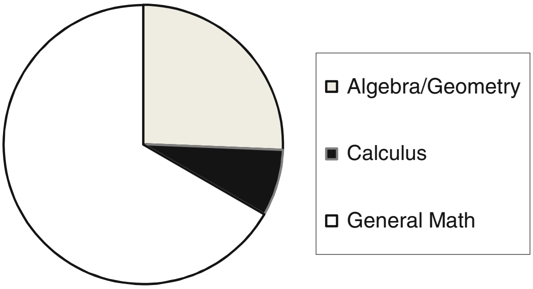


Fig. 5.1 Percentage of mathematics-related articles by specific subject

L.M. Phillips et al., *Visualization in Mathematics, Reading and Science Education*, Models and Modeling in Science Education 5, DOI 10.1007/978-90-481-8816-1_5,
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in the examples, certain examples were viewed differently by the participants, and these were prototypes. She explains: “if we examine the prototypical examples we will find in each of them some specific attribute(s), in addition to the critical attributes of the concepts. . .which are dominant and ‘draw our attention’. . .[because they] usually register in our mind spontaneously via visual codes” (pp. 73–74). Hershkowitz concludes that the prototypes create visual–perceptual limitations, and that in turn can affect identification abilities for people of all ages and stages of education. However, “individuals do not usually attain any example of the concept unless they have already attained the prototypical example” (p. 74).

Visual–Spatial Images

In a study by van Garderen (2006) 66 grade six students from four urban south Florida elementary and middle schools were asked to solve mathematical problems printed individually on a card presented to them by the author and a research assistant. The students “represented three levels of problem-solving ability: students with learning disabilities (LD), average-achieving (AA) students, and gifted (G) students” (p. 498). After solving each problem, they were interviewed to determine “how they solved it and whether a visual image had been used” (p. 498). Using three measures (the number of problems solved correctly, whether a visual image was used while solving the problem, and whether that visual image was pictorial or schematic in nature) the author found that “students with high spatial visualization ability (defined as ‘the ability to mentally manipulate, rotate, or twist, or invert a pictorially presented stimulus object’ (McGee, 1979, p. 893)) tended to produce images that were primarily schematic in nature, whereas students with low spatial visualization ability tended to produce images that were primarily pictorial in nature” (p. 504). This study suggests that “deficits in visual-spatial competencies may interfere with the ability to solve word problems” (p. 504). With increased aptitude for spatial visualization, students will have the ability to use the more sophisticated schematic imagery when solving math problems.

Presmeg (1986) claims that most gifted math students are non-visualizers. She states that “it emerged strongly in the task-based interviews that for success in school mathematics the one-case concreteness of an image or a diagram must be transcended, and that many if not most visualizers are not aware of how to accomplish this task. For non-visualizers this problem does not arise” (p. 301). She maintains that the practice of procedures and formulas in math leads to habituation, which takes a learner away from the visual method. Presmeg summarized reasons that gifted mathematicians are not visualizers. The internal reasons are that single-example concreteness may tie thoughts to irrelevant details and may induce inflexible thinking, and that an uncontrollable image may arise which prevents multiple avenues of thought. The external reasons are that mathematics simply might favour the non-visual thinker due to the verbal–logical component involved in mathematical abilities (Krutetskii, 1976), and that school curriculum is developed in such a way that the time constraints of examinations do not permit a full exploration of the visual side of the problems. Another external reason again points to the classroom, where the teaching emphasis is most always on non-visual methods, with a focus on orderly logical progression of information that does not include visual proofs or examples (pp. 306–307). Habre (1999) reemphasized the latter point in a discussion about a university calculus class in which 26 students were exposed to both analytical and visual methods of solving problems. Habre noted that even with instructor emphasis on visualization, most students tended to prefer the analytical approach, likely because “many students might be coming from traditional schools of mathematical instruction. Consequently, their view of mathematics is entirely algebraic” (p. 21). The author maintained that students did have an appreciation for the visualization skill, even if they had yet to acquire proper knowledge and experience in applying it to problem solving.

Several other studies emphasized the negative outcomes that could arise from the use of visuals in mathematics classrooms. Aspinwall, Shaw, and Presmeg (1997) examined the role of imagery in the conceptual understanding of one college-level calculus student. They state that the historical use of graphics in mathematics was to express a solution to the problem, rather than using graphics within the methods of solving the problem. The authors tested their participant with 20 different non-routine problems, observing when the student used graphics and how he was able to control the images that appeared in his mind while solving the problems. They concluded that “there is a tendency for thought to be riveted to an image which is inappropriate or which prevents mathematical generalization” (p. 304), and that “vivid and dynamic imagery invoked by calculus graphs can create an impediment to mathematical understanding” (p. 314).

Counter to the above-described articles, Palais (1999) discussed and encouraged mathematical visualization as well as the integrations of computer graphics into the math classroom. He stated that “applied mathematicians find that the highly interactive nature of the images produced by recent mathematical visualization software allows them to do mathematical experiments with an ease never before possible” (1999, p. 648). Palais examined three major software programs, the drawback of all being that they have unique programming languages that the user must learn. He argues that the main task of a mathematical visualization programme should be to display the mathematical process, rather than the product.

Tomas, Johnson, and Stevenson (1996) examined the prevalence of computer visualizations in middle and high school math classrooms. They define visualization as “a computer graphic technology developed to extend the use of our visual system to contexts and problem-solving situations where sight itself is not directly possible or in which normal vision fails to provide adequate opportunity for analysis” (p. 268). They claimed that “specialized educational products that include curricular materials with the scientific data and visualization tools have enormous potential to motivate and empower students to explore their world” (p. 290). The authors provided guidelines for the use of visualizations, suggesting factors that teachers need to take into account before automatically using this method of instruction in the classroom: versatility and power of the visualization (How accessible is it to all levels of learners?); the ease of operations (Is the computer program created in such a way that there are limited malfunctions that the student may experience?); and costs of the visualization.

Computer Visualizations and Visual Representations

Another interesting approach was taken by Rivera (2007) when he interviewed 22 ninth grade students in a beginning algebra course to assess how they established a generalization for a tiling squares problem. The study was motivated by the fact that the results of a 5-year district-wide study involving patterns and functions found that "[w]hile 70 percent of ninth graders tested could extend patterns one by one, less than 15 percent of them could develop an algebraic generalization in closed form" (p. 69). In order to find out which strategies might enable ninth graders to see beyond the particulars to develop an algebraically useful generalization, interviews were conducted. They were asked questions about specific patterns: for example, a tile H configuration that systematically increases in size through the addition of tiles. Three patterns emerged from students' responses: a figural additive strategy wherein some students saw an additive growth in the figural sequence but unfortunately some jumped to an invariant formula that in the end required them to count individually the number of tiles in each figure; two figural multiplicative strategies in which students resorted to counting by sides because they saw symmetry among the figural cues—these students thought in multiples of "side"; and finally a technique of concentric versus visual counting that resulted in students repeating the addition of one square on each side or arm of a figural cue. Rivera concluded that if algebraic generalizations are promoted through visualizations, then patterns must be seen as mathematical objects rather than everyday objects. He further reiterated Raymond Duval's (2006) claim that students' way of seeing, observing, and noticing patterns may be in an everyday way and not in a mathematical way. "When we focus on visualization, we are facing a strong discrepancy between the common way to see the figures, generally in an iconic way, and the mathematical way they are expected to be looked at. There are many ways of 'seeing'" (p. 115).

The spatial visualization ability of seven mathematically gifted students (six in grade six and one in grade seven) was studied by Ryu, Chong, and Song (2007). The task included a regular icosahedron pictured in two dimensions and four specific problems of comparing side lengths and angle sizes. Students had 60 min to solve the tasks followed by an interview. These gifted students shared the ability to imagine the rotation of a depicted object, to visualize its configuration, to transform it into a different form, and to manipulate it in their imagination. Only two of the seven students displayed spatial visualization ability of 3D objects in a 2D representation. The remaining five were challenged to manipulate mentally an object depicted in a plane as a spatial object. If students are presented visual facts in a planar picture, confusion is likely to occur if they are asked to distinguish the edges of a spatial object from the depicted illustration and to distinguish planes in a 3D object from its 2D representation.

Attempts to make mathematics easier and more interesting are commonplace. In a study by Figueira-Sampaio, Ferreira dos Santos, and Carrijo (2009), 46 students in their sixth year of primary school were divided into two groups. Group A used the computer laboratory to study and analyse five first-degree polynomial equations of increasing difficulty ($x + 4 = 10 + 4$) to ($5x + 50 = 3x + 290$) using a prepared visual panel. Group B went to the mathematics laboratory where the equations were written on the blackboard and students were to use a conventional beam balance as a metaphor for the equation. Both classes lasted 50 min and students were observed to determine whether the visual panel was an advantage. Regrettably, no measures of students' understanding of first-degree equations were taken. Using the computer tool in pairs seemed to help students but the authors made no claim about improved mathematical understanding of either group to solve first-degree equations.

Visual representations constructed by emergent mathematics learners (38 kindergarteners aged 5–6 years and 34 first graders aged 6–7 years) were investigated by Deliyianni et al. (2009). Their study was designed to investigate and compare the modes of representations used by the children and to examine the extent to which the children used the rules of the didactic (systematic use of rules and mathematical knowledge) contract. Over a 2-week period the children were given four problems one at a time (two standard and two problematic—could not be solved). For example, Problem 1 was a standard addition: "In a fruit dish there are four apples. Mother put two more apples. How many apples are there in the fruit dish?" (p. 102). Problem 3 had no solution: "Mrs. Maria gave George 2 candies and 3 chocolates. George put them in a box. How old is George?" (p. 102). Children were instructed to listen carefully to the problem being read and to use their paper, crayons, and pencils to solve the problems. The children's types of representations were analysed into five categories: pictorial, symbolic (equation), symbolic (numerical), pictorial and symbolic (equation), and pictorial and symbolic (numerical). The types of representations as well as children's responses to the didactic contract were also analysed. The results showed that all children used a picture to reach an answer. The kindergarteners drew pictures of varying details: some drew six apples while some drew circles; some drew a fruit dish with six apples in it; some drew two fruit dishes, one with four and the other with six apples; some drew the apples in two rows; and some drew the mother holding the two apples or standing near the fruit dish.

The grade one children tended to use a symbolic equation to solve the standard problems and the remainder gave the equation accompanied by a picture. The kindergarteners tried to solve the problematic problem by drawing a picture and attempting to give a numerical response, whereas the first graders tried to obey the didactic contract because they gave the sum of the candies and chocolates as an answer, even though they doubted the structure of the problem.

Overall, the kindergarten children tended to generate pictorial and descriptive representations of the context of the problem, whereas the first graders tended to use symbolic representations in an effort to solve each problem. The authors concluded that their study presented "a strong case for the role of spontaneous or functional visual representations not only in solving standard problems, but principally in solving problematic problems. Furthermore, the influence of the didactic contract rules on pupils’ responses appears to be a function of pupils’ age” (Deliyianni et al., 2009, p. 109). Whether the children would have performed similarly if they had been provided varied visual representations remains an interesting and unresolved question.

Concluding Comments

In conclusion, as we said at the onset, the research is mixed. Not only is there a theoretical controversy over whether visualizations have anything but a possible heuristic role in mathematics, it seems the usefulness of visualizations is tied to the goals themselves of mathematics instruction. If the goal is analytic proficiency then it seems visualization may interfere. As well, visualizations seem to work differently for more and less gifted students and for older and younger students, although the trends appear unclear. The research indeed is ambiguous and often contradictory.

Chapter 6
Visualizations and Reading

The research reviewed in this chapter supports the conclusion that there are few unqualified generalizations about the efficacy of visualization objects in reading. We begin with an examination of the important motivational role of visualization objects. Second, we examine the effect of visualizations on reading comprehension, taken to be the main aim of reading. Then, we turn to the properties of visualization objects and their effects on reading. Finally, we examine the research on the use of multimedia and visualizations.

Visualization Objects as Motivators

One possible reason to use visualization objects is as motivation to readers. Samuels, Biesbrock, and Terry (1974) examined whether illustrations influence beginning readers' attitudes towards stories. They noted that "the motivating effect of pictures for sustaining interest is often given as a rationale for including pictures in children's books" (p. 243) but correctly recognized that strong though the intuition might be, it requires empirical support. To that end, Samuels, Biesbrock, and Terry tested 54 second grade students by having them read three stories on three successive days, each under different conditions. One story was accompanied by a full colour picture, one had a modified outline picture without colour, and one had no picture. After reading each story presentation students were asked to respond to questions regarding their attitudes towards the story. Samuels, Biesbrock, and Terry found no significant difference between colours and outline picture treatments, but did find a large difference between colour and no picture and also outline and no picture—both types of pictures were strongly preferred to having no picture at all. Beyond this, Samuels, Biesbrock, and Terry noted that "the effect of pictures on one's attitude toward a story is related to one's skill as a reader. . .poorer readers were more negative toward non-illustrated stories than were better readers. This suggests a relationship between reading skill and the importance of pictures as vehicles for motivating reading preferences" (p. 246). The theme of illustrations being a motivating factor reoccurs in later research (see Brookshire, Scharff, & Moses, 2002; Jones & Smith, 1992; Kwinn, 1997; Levie & Lentz, 1982; Mohler, 2000;

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Peeck, 1993; Reid, Briggs, & Beveridge, 1983) which on the whole shows that illustrations may facilitate attention or cause distractions, may induce elaboration, and may establish a connection between verbal and nonverbal cues or may not. In others words, results are conditional and ambiguous and either way *how* reading is facilitated or impeded is unclear.

In 2002, Brookshire, Scarff, and Moses looked at the influence of illustrations on 71 first and third grade students' book preferences and comprehension. They provided students with either a book with text only, a book with text and illustrations, or a book with illustrations only. The illustrations were also separated into four different versions: bright-abstract, bright-real, sombre-abstract, and sombre-real. Brookshire, Scarff, and Moses found that illustration style significantly affected book preference, with bright-real being enjoyed the most by students. As well, they found that text-plus-illustration books were the most beneficial for comprehending the material. The authors suggest that "the effect of the preferred illustration styles on comprehension of the text-plus illustrations questions. . .was to enhance comprehension. . .this finding further suggests that, if the pictures are thoroughly processed (because they are liked), the redundancy may increase comprehension and long-term memory for the items" (p. 336). However, the authors go on to examine the shortcomings of pictures:

> For the illustrations that were most liked, there was a significant trend for text-plus-illustrations group to answer the text-only questions less accurately than the groups that did not receive the illustrations. Because they may contain more attention-capturing information, pictures may act as a distraction. (p. 336)

Other research suggests that beyond motivation, introspective visualization can improve both short- and long-term ability to decode and to follow written directions. Gill, Klecan-Aker, Roberts, and Fredenburg (2002) studied 30 elementary-aged children with language impairment and concluded that introspective visualization where the students were prompted to imagine the tasks that they were to perform was useful because it helped to attract and maintain attention in the material to be learned. The experiment compared language-impaired students who received language therapy sessions by placing them in three groups: traditional therapy, rehearsal strategy training, and rehearsal/visualization strategy training. They found that including introspective visualization in the training helped students with their long-term ability to follow instructions. "The benefit of including visualization in the present study was in its long-term effect, that is, only when rehearsal was combined with visualization was it maintained the next school year" (p. 95).

Comprehension

The late 1970s saw ambiguous results with respect to whether pictures aid the interpretation of text. James Thomas (1978) examined the influence of illustrations with written text on reading comprehension for 108 science students in the fourth grade. Results were based on reading comprehension tests following exposure to either a colour photograph with text, a line drawing with text, or just text. Thomas found that the inclusion or exclusion of pictures in elementary school science textbooks did not have any influence on the comprehension of the material.

Ruch and Levin (1979) tested 48 first grade students' recall abilities and found results similar to Thomas'. They compared results for students presented with narrative passages and accompanying colour-line drawings viewed only during the narration of the story, students presented with narrative passages and colour-line drawings viewed during narration and during questioning, and students presented with narration only. They found that children did not gain any benefits from images unless the images were reinstated during testing as retrieval cues.

Dunham and Levin (1979) examined the influence of illustrations on understanding oral prose. They placed 160 kindergarten and grade one students in one of the following conditions: control, imagery, supported imagery, covert repetition, and supported covert repetition. Students listened to a story and were given the appropriate prop (depending on their assigned group) and then were asked content-specific questions. The authors found that children learning oral prose did not benefit from illustrations being included in the study material, even with very concrete support in the form of pictures being provided. Counter to these results, Haring and Fry (1979) found that pictures had immediate and enduring benefits on recall of information. To answer the question "when do pictures facilitate reading comprehension" (p. 186) the authors took key ideas from stories and added illustrations that were redundant to the text and concluded that "pictures facilitate recall of main ideas of written text" (p. 188).

It is difficult to discern what caused the opposing results presented here, as all the studies are with elementary school children. It is perhaps significant that Haring and Fry (1979) studied slightly older students (fourth and sixth grade) than did the others. It is conceivable that there are differences in how the older students approached the tasks, making the effectiveness of the visualization different than it is with the younger students. This hypothesis, of course, requires empirical investigation. There may be other causal factors of relevance to the difference, including testing effects or errors.

A further complication is that it is not clear that comprehension gains facilitated by visualization objects are always desirable outcomes. Suppose that a teacher wishes students to understand a story. The students read the story and then watch a film based on the main events of the story. Suppose further that the students understand the events of the story better from reading and watching the film than from only reading the story. Is this a desirable outcome? If what is wanted is for the students to have a grasp of the narrative, then the combination of text and film is attractive. If the point of the exercise is to increase the students' reading abilities, then it is not clear that the film is helpful. The same would be true of other visualization objects, such as illustrations and graphs. In many contexts, however, the point of text and visualization is the comprehension of the content of some subject matter, making the modality of acquisition less important than the acquisition itself. In the teaching of reading, however, the subject matter content is rarely as important as the reading itself.

In 1968, Dwyer examined the efficacy of illustrations depicting the human heart to assist university students to better understand textual material that described heart structure and physiology. He found that illustrations that were not directly tied to instructional objectives could be a distraction to students, interfering with learning. In his later research in the 1970s, Dwyer found that even when illustrations were related to the material at hand, they could not necessarily be assumed to be an efficient aid to interpreting text. Presumably, factors other than relationship to objectives were of significance. Peeck (1974) contradicted Dwyer's results with his study of 71 children aged 9 and 10 years and sought to determine whether illustrations improved retention of both material that was and that was not directly represented by those illustrations. Peeck found that the presence of illustrations helped readers to retain information that was presented pictorially and also information presented by both text and illustrations. However, he also stated that, although there was no significant difference in retention of information presented solely as text, there was "an indication of some facilitation in the illustrated text condition" (p. 886).

Guttmann, Levin, and Pressley concurred with Peeck's results in their 1977 study of 240 young children's recall of narrative passages. They provided children in kindergarten, second grade, and third grade with short stories that had two accompanying coloured pictures. They next provided kindergarten students either with a picture depicting the whole object or with instructions to pretend that they had seen a picture. Finally, they repeated both studies with first grade students. The authors found that students performed better at recall tasks when they were given complete pictures than when they had to perform introspective imaging; this held especially true for the younger children. However, being provided with even a partial picture helped students in their recall performance and helped them to respond to objects that had only been implied and never actually pictured.

During the early 1980s, most of the research supported the thesis that illustrations help children's learning and recall of information. Szabo, DeMelo, and Dwyer's (1981) study involved showing 96 high school biology students images and text about the human heart. They found that complementing verbal instruction with visualization objects improved information acquisition. Readance and Moore (1981) noted that "one can assume that these aids have been placed in text to enhance students' comprehension and retention of the printed information" (p. 218), and so they analysed 16 previous research studies to determine the effects of experimenter-provided adjunct pictures on the comprehension of subject material. Readance and Moore found that "overall results of the combined studies indicate a small measure of association between reading text with adjunct pictures and subsequent comprehension. . .however, wide variability among the results were found" (p. 219). They elaborate by explaining the variables on which they focused. The first was text setting, whether the passage was traditional ("the passage was presented as connected discourse with adjunct pictures either interspersed within the actual text or presented alongside the text" (p. 221)) or non-traditional ("programmed text formats, cartoons, and filmstrips" (p. 221)). The authors concluded that adjunct pictures improve reading comprehension in both traditional and non-traditional passages in equal and small amounts. They also examined grade level of subjects, in which they concluded that "it appears that university-level students benefit from adjunct pictures in text more than do public school students" (p. 221). The third variable was the type of picture (line drawings, shaded drawings, and photographs), in which they found that "adjunct line drawings appear to facilitate reading comprehension more than do photographs. On the other hand, shaded drawings do not seem to differentially affect comprehension when compared with either line drawing or photographs" (p. 221). Fourth was the use of colour. Readance and Moore compared results of studies using colour pictures versus those that had black and white pictures and concluded that the use of colour in adjunct pictures had a positive impact on reading comprehension. Lastly, the authors examined the time of the comprehension post-test and found that there was "little change in the effect of pictures in the immediate versus the delayed post-test condition" (p. 221). Readance and Moore's final conclusion was that "there is some practical educational significance for the use of adjunct pictures to aid reading comprehension", especially for university-level subjects as their results "can be interpreted to mean that older readers have learned to use pictures, while younger readers are still developing that ability" (p. 222). They went on to say that "teachers can improve students' visual literacy by becoming aware of when pictures can help comprehension and by pointing out pertinent features of those pictures that will accomplish that purpose for reading" (p. 222). There thus might be an age effect on the usefulness of illustrations to interpretations.

During the early 2000s, even though advances in instructional technology made dynamic animations of visualizations possible, most of the experimental research concluded that dynamic visualizations are no more effective than static visuals in facilitating reading comprehension of authentic material. Lin and Chen's (2007) study involved 115 sophomores from two English First Language (EFL) classes. They were tested on their reading proficiency and then randomly assigned to four computer-based modules with identical material that described the parts of the human heart, blood circulation, and pressure: static visuals alone (SV), animated visuals alone (AN), animated visuals and descriptive advance organizer (A + D), and animated visuals and question advance organizer (A + Q). They found "dynamic visualization used to complement verbal information contained in the authentic material was no more effective than static visuals" (p. 96). They did point to the possibility of merit in the inclusion of a question advance organizer to facilitate students' learning. They suggested that "more research is needed to explore the relationship between effectiveness and efficiency in a technology-enhanced learning environment" (p. 97).

Other research suggests that question generation combined with designed visual simulations increase comprehension monitoring and learning. Johnson-Glenberg (2007) designed a web-based programme (3D-Readers) and conducted three separate studies on the 3D applications: a first study with 20 poor comprehenders from an urban middle school, which lasted 2 weeks; a second study with third to eighth graders with learning disabilities (ADHD); and a third study with 37 fourth to seventh graders in summer school. The *3D-Readers* is a web-based application designed "to both instruct and assess young adolescent readers' use of verbal and visual metacognitive strategies and their comprehension of hybrid-style science texts" (p. 293). The hybrid-style science includes four 2,000-word texts in order of increasing difficulty on how to measure a wave, on bacteria and experiments, on colour as wavelengths, and on genetics and survival. On a computer screen, students were prompted to pretend they are a teacher and to suggest a question to check students' understanding of the story so far (e.g., Are all bacteria bad for you?). Students were prompted to research, to re-read, and to scroll back throughout their reading (only four lines of text at a time) before utilizing the visual or verbal strategies embedded in the text. Students could drag icons or words from a toolbox in order to build their mental model of what was being read (after three incorrect submissions of their configuration of how, for example, bacterial growth is affected in an experimental kitchen (oven, refrigerator), "the system will build the correct model for the student" (p. 303). Students were prompted as they read the entire text to create questions to be assessed. Vocabulary development was also embedded and cued by a blue font that provides a link to a contextualized definition (for example, "sterile"—"Mr. C. handed two sterile dishes to each group. He had made the dishes sterile by heating them until there were no living bacteria or other microbes left to ruin the yogurt" (p. 297)).

Results from Study 1 showed significantly better comprehension responses by the experimental group to use metacognition strategies. There were no vocabulary gain differences and the poorer comprehenders tended to use the scrollback option to re-read. Results from Study 2 showed marginal vocabulary gains for the ADHD students. Results from Study 3, which was meant to be an exploratory pilot where teachers signed up to use the 3D-Readers without the benefit of researcher oversight, showed a significant average gain in the quality of self-generated questions. Johnson-Glenberg's study (2007) highlights the possibilities of web-based learning but points out the necessity for research on "large between-subjects designs to pull apart the efficacy of the strategies and to ascertain which instructional components truly benefit which types of readers" (p. 321). There seems to be promise in the use of web-based applications especially for atypical populations but the nature of that promise remains to be determined.

The above summary of contradictory results is provocative. We hypothesize that the nature of the illustrations (static, video, web-based, animated, etc.) and the nature of the recall tasks are critical in understanding the results. Based on Chapter 4, it is reasonable to expect that some illustrations have computational features that could assist students to reason through the tasks that they are assigned. If the illustrations are constructed so that in answering questions about the text, students can relieve some of their working memory, then the illustrations could be used to decode or to interpret. On the other hand, if the illustrations are such that they provide information that is redundant to, or at least closely supportive of, the presented linguistic materials, then it is possible that the mechanism that supports the dual coding hypothesis is engaged. Unfortunately, this distinction is only a hypothesis until further research into the nature of the content of the illustrations and of the assessment tasks is undertaken.

Relevant Properties of Visualization Objects

Philippe Duchastel (1981) compared delayed retention of verbal material from illustrated and non-illustrated versions of an instructional passage with 77 students aged 14 and 15 years. He used a passage about British history and illustrated half of the paragraphs with black and white photographs or drawings. Duchastel tested students by asking them to recall major topics and then questioned them about details from the passages; some students were tested immediately following the presentation of information, whereas others were tested 2 weeks later. Duchastel found that illustrations enhanced delayed retention more than immediate recall and the retention was for both illustrated and non-illustrated paragraphs. He concluded that although his study did not offer "a solid confirmation of a retentional role for illustrations in text, [it] has shown that illustrations can influence retention even when they have no influence on immediate recall" (p. 14).

Levie and Lentz (1982) did an extensive review of 55 previous studies to determine whether illustrations aided the learning of text material. They examined several different aspects of the studies and made some clear conclusions. First, "illustrations facilitate learning the information in the written text that is depicted in the illustrations.... Illustrations have no effect on learning text information that is not illustrated...[and] when the test of learning includes both illustrated and nonillustrated text information, modest improvement may often result from the addition of pictures" (p. 213).

Second, they found that "the various kinds of pictorial/imaginal adjuncts are not equally helpful in learning from text" (p. 218). For example, diagrams that depict organization and structure of key concepts can be helpful, "but not unless they are processed and learners may require strong prompts to get them to do so" (p. 215). Learner-produced drawings are those that the students are asked to construct on their own, and "learning is facilitated when learners produce their own drawings—if the drawings they produce are relevant to the text content (p. 216)", which might not be possible with young children who might be unable to differentiate between relevant and non-relevant content. As well, mental imagery has not consistently been shown to aid learning from text.

A third conclusion by Levie and Lentz (1982) is that illustrations can help comprehension of the material when students are listening to read prose, but not when learning to read. The authors examined research about the effects of listening to prose while simultaneously being shown pictures and found that "pictures do help children learn oral prose, probably more so than written prose" (p. 217), because, unlike reading when students have control over their exposure to information, with oral prose they are being exposed to verbal and visual at the same time and thus more modalities are engaged. The assumption is that more modalities engaged in interpretation should lead to greater comprehension. This assumption may require further study as well, as is predicted by dual coding theory. The authors found that representational pictures—primary drawings and photographs that show what things look like—are most helpful in the context of listening to read prose. Levie and Lentz went on to suggest that the situation for reading is very different from listening: "the inclusion of pictures is likely to interfere with learning to read words" (p. 218). Levie and Lentz summarized by stating that "illustrations can facilitate learning from text. . . [but] how they do so is not clear. . .thus the effects of text illustrations depend on how they are used—both by learners and by those who design instructional texts" (pp. 224–227). It is likely these observations point to the importance of the structure of illustrations in relation to the students' background knowledge and to the assessment task.

In the mid-1980s, research into the use of visualization objects to aid in interpreting text continued to encourage the benefits of visuals, but added stipulations for their use. For example, Alesandrini (1984) examined research on representational, analogical, and arbitrary pictures and made several conclusions about the role a picture can play in the learning processes of adults. Representational pictures, "those that share a physical resemblance with the thing or concept that the picture stands for" (p. 63), "have aided recall, although not necessarily for material that is highly abstract or complex" (p. 68). An analogical picture, one that "conveys a concept or topic by showing something else and implying a similarity" (p. 68), can facilitate adult learning when a learner can recognize and comprehend the analogy. The effect of logical pictures, pictures that "do not look like the things they represent but are related logically or conceptually" (p. 70), varies depending on the learner's ability. The author concludes that all three types of pictures "deserve attention by practitioners as ways to communicate information and facilitate learning" (p. 74).

Waddill, McDaniel, and Einstein (1988) tested the idea that the effect of illustrations on memory was a function of the type of text (narrative versus expository) and the type of information in the illustrations (details in a certain proposition versus details conveyed by the interrelationship of several propositions). They included 72 undergraduate psychology students in their study and provided passages that allowed the effects of the individual variables to be noted. The authors concluded that "pictures serve a supplementary function. That is, adjunct pictures alone, without special processing instructions, do not help learners to encode information that is not ordinarily encoded in the first place" (p. 463).

In 1989 Rina Hershkowitz examined the use of visualization for identification, drawing, and reasoning concepts in middle school geometry classes for both students and teachers. Hershkowitz argued that the learning of new concepts comes about from the abstraction of key features from prototypes. A student learns about triangles, for example, by looking at prototypical triangles and abstracting the features that separate triangles from other kinds of objects. As quoted previously Hershkowitz said, "we cannot form an image of a concept and its examples without visualizing its elements" (p. 61). These prototypes come from experience, and it is possible to be mistaken about them: "the prototype is a result of visual-perceptual limitations which affect the identification ability of individuals—students as well as teachers" (p. 68). Clearly, the selection of prototypes is crucial on this view. If students are presented with unhelpful prototypes, then their concept formation is less likely to capture the truly relevant features that the teacher intends. Hershkowitz concludes that "individuals do not usually attain any example of the concept unless they have already attained the prototypical example" (p. 74) and claims that visualization is not merely important, it is necessary for geometrical concept formation.

Presmeg (1989) dealt with visualization in mathematics classrooms as well, but her subjects were in an Indian high school. Presmeg noted that visual properties are often best understood if they are situated within a pre-existing context in the student's life. She argued that in a multicultural classroom, visual elements can be incorporated to make the lessons relevant to all the students, giving the example of Rangoli patterns that would be familiar to many Indian students. According to Presmeg, the students' familiarity with these patterns makes it easier for a teacher to approach their geometric properties than to introduce some other shapes. She says "visual imagery which is meaningful in the pupil's frame of reference may lead to enhanced understanding of mathematical concepts at primary and secondary levels" (p. 21).

During the 1990s results continued to be varied in the many studies examining the effectiveness of visual aids in classrooms. Chan, Cole, and Morris (1990) designed a study examining the use of visual images with 39 children with reading disabilities, aged between 7 and 11 years. They audiotaped short stories and asked the students multiple-choice questions aimed to assess their comprehension of the material. The authors also created magnetic cardboard figures of the main characters and objects of the stories, and these visuals were displayed. Students were separated into visualization instruction only (students had to generate their own visual images while reading the story), visualization instruction and pictorial display (students were given the same verbal instruction but also shown a pictorial display of cardboard figures), and read–re-read control (students were instructed to read and then re-read the story, without any instructions to visualize). The authors concluded that

> . . .providing support in generating visual images in visualization instruction was found to enhance comprehension of prose materials. Yet at the same time, it seemed to be detrimental to generalization of learning. . . . One explanation for the decline in mean performance in the generalization session is that the pictorial display may have unintentionally encouraged dependence on external aids in the generalization of visual images, thereby preventing internalization of the visual-imagery strategy and unprompted spontaneous generation of visual images. (pp. 9–10)

Winn, Li, and Schill (1991) sought to explain the effectiveness of diagrams as adjuncts to or replacements for text. They asked 40 graduate-level education students to solve problems using information presented on a family tree, either with visual trees or with written text statements on a computer. The authors concluded that "diagrams in which conceptual relationships are expressed through spatial arrangement permit more rapid problem solving than equivalent texts" (p. 27). Joan Peeck (1993) discussed the impact of pictures in text. She summarized previous research and claimed that pictures improve retention because they have the ability to

> . . .motivate the learner to study the accompanying text; they might focus the attention or induce more elaborate processing of text information covered in illustrations, they might help to clarify and interpret text content that is hard to comprehend, or they might help to establish nonverbal codes alongside verbal ones and as a result increase retrieval potential for the illustrated text content. (pp. 227–228)

Counter to these studies, Aspinwall et al. (1997) proposed that imagery can be disadvantageous in mathematics because students sometimes retain unnecessary details. Their subject, a 28-year-old college calculus student, was tested on 20 non-routine problems in order to assess the student's thinking through the tasks. They found that the student was unable to apply rules for determining derivatives in various situations and stated that "vivid and dynamic imagery invoked by calculus graphs can create an impediment to mathematical understanding" (p. 314). Dechsri, Jones, and Heikkinen (1997) also contradicted the commonly held belief that visual aids help students, stating that visual aids can overload students' memory. They tested 83 university-level chemistry students on achievement tests, laboratory tests, and an achievement post-test. One group did the lab tests using a manual with pictures and diagrams, while the other used a manual that had text only. Their results showed that the students using the pictorial manual scored higher on the achievement tests and had a more positive attitude about the lab work, so they concluded that "visual information aids consisting of pictures and diagrams integrated with text in the design of chemistry laboratory manuals can help students perform better in the cognitive, affective and psychomotor domains" (p. 901). However, they continue by stating that illustrated textbooks with explanatory text can still "overload student memory and may not help students learn more than text-based materials without pictures or diagrams" (p. 901). These results are encouraging for the use of illustrations in laboratory manuals, but also signal the need for further research. In particular, it would be helpful to have guidelines regarding the boundary between helpful illustrations and illustrations that lead to memory overload. One possible approach is in the calculation of visual complexity. Lee, Plass, and Homer (2006) used this calculation in their study of visual overload in multimedia presentations. (See Chapter 7 for more details.) In particular, they were interested in the specific conditions under which visualizations are effective.

Multimedia

Sewell and Moore (1980) tested differences in information retention by examining responses to text, audio, and visual channels. Their subjects were 150 university students in a communication class. Subjects were assigned to one of the following groups: text only, cartoon text (handout with text plus cartoons), audiovisual (audio of the text cued to slides of the cartoon embellishment); audio only, or visual only (slide presentation of the cartoon embellishment); students were then measured on a multiple-choice test about the basic content. The authors found "there was no significant difference between the printed text, cartoon-embellished text and audiovisual presentation in terms of comprehension of the content. This result would seem to lend additional strong support to earlier studies. . .that found that information can be just as easily processed in one of several sensory modalities or combination of modalities" (p. 45).

The idea of exploring the dynamic usage of multimedia was furthered during the 1990s and into the new millennium, as is evident in the number of studies focusing on computers and animation (see Chapter 7 for further details). In 2001, a study by Sanger, Brecheisen, and Hynek examined whether viewing computer animations helped university-level biology students with their conceptions of molecular processes. They tested 149 students about molecular behaviour associated with the processes of diffusion, through either computer animations or textual material. Sanger, Brecheisen, and Hynek concluded that "students who viewed computer animations depicting the molecular processes. . .developed more accurate conceptions of these processes based on the particulate nature and random motion of matter. They also had a better conceptual understanding of the dynamic processes. . .these results suggest that instruction including computer animations at the particulate level can help students understand chemistry and biology concepts involving molecular processes" (p. 108).

Schnotz (2002) concluded that having simultaneous presentation of text and visual information helps children process and retain information better than does having text alone. He summarized research that was focused on the benefits and detriments of using visuals in teaching and stated that "visual displays are considered tools for communication, thinking, and learning that require specific individual prerequisites (especially prior knowledge and cognitive skills) in order to be used effectively" (p. 102). He found the main results of previous studies showed that text information is best remembered when presented simultaneously with illustrations, but maintained that students need to know how to extract appropriate information from those visuals in order for them to be effective. For example, abstract visual displays such as graphs "require knowledge about specific forms of representations. The individual has to acquire specific cognitive schemata (graph-schemata) in order to understand these so-called logical pictures" (p. 114). The author maintained that learners need support to negotiate between one form of representation and another.

Counter to these studies, Linn's (2003) discussion about the use of technology in science education found that visualizations can confuse learners because they do not have the same background knowledge as the designers of the visuals. She says that "visualizations often require that students interpret complex visual representations rather than immediately recognizing their implications" (p. 745). Students and teachers need extensive background knowledge in order to interpret visualizations, and often when students have to make their own illustrations they present superficial ideas. Linn concludes that "the appeal of visualizations overshadows the challenges of designing effective materials" (p. 746).

Concluding Comments

Most recent research shows results similar to Baker and Dwyer's (2005) meta-analysis of 11 studies in which they summarize the instructional effects of different types of visualization strategies. They concluded that "analysis of the results within the different studies were consistent with current research indicating that carefully designed and positioned visualization, rehearsal and feedback strategies can significantly improve learner achievement" (p. 78). To design visualization objects that are effective aids to the comprehension of text, attention must be given to their structure, their relationship to the text, and the readiness and background experiences of the students. Students may need to learn how to take advantage of an object before it can be a successful adjunct to text.

In addition, there seems to be few generalizations about the use of visualizations that apply across all or most students. Rather, most of the research points to interactive effects: pictures can be motivating, especially in increasing comprehension, and for older readers; illustrations can help learners grasp what is depicted, but have no effect on their grasp of related material that is not depicted; illustrations can help with understanding text, but more so when the child is being read to than when the child is learning to read; and visualizations can help students comprehend science concepts, but the same visualization can confuse other students. Perhaps if there is any generalization, it is the one mentioned in the previous paragraph: visualizations work best for the student who has been taught how to use them. They are not devices that somehow work on their own.

Chapter 7
Visualizations and Science

By way of contrast to the situation in mathematics education, there has been a general consensus among researchers during the past 20 years that visualization objects assist in explaining, developing, and learning concepts in the field of science. DeFanti et al. (1989) went so far as to claim that "much of modern science can no longer be communicated in print. DNA sequences, molecular models, medical imaging scans, brain maps, simulated flights through a terrain, simulations of fluid flow, and so on, all need to be expressed and taught visually" (pp. 12–13). We found approximately 65 studies that focused entirely on visualization in science and categorized them by subject. The largest number of articles was related to chemistry, followed by general science. Most of these general science studies were done with students in lower grade levels. By the time students reach university, the science subjects are more specific. The breakdown of science studies by subject can be seen in Fig. 7.1.

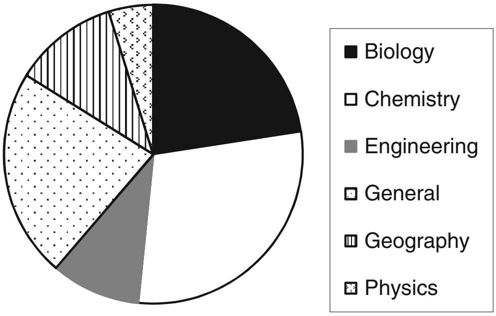

Fig. 7.1 Percentage of science-related articles by specific subject

Visual Representations, Diagrams, and Animation

Winn and Holliday (1981) noted that diagrams can help in a science classroom by "replacing critical verbal information with graphic devices such as lines and arrows" (p. 22), an observation quoted approvingly by Levie and Lentz (1982, p. 22). Mayer

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and Anderson (1991) slightly modified that sentiment in their article about combining animations and narration. In an experiment involving the viewing of an animation depicting the operation of a bicycle tire pump, Mayer and Anderson found that 30 undergraduate students who were presented with words and pictures performed better on problem-solving activities than those who received only words or only pictures to explain the concepts. They concluded that "effective understanding of scientific explanations requires a mapping between words and pictures" (p. 484). Mayer and Anderson intended their research to be an experimental validation of the dual coding hypothesis. Their results suggest, as we outlined in Chapter 4, that the coding of concepts in both the visual and the verbal modes provides for better understanding than can be achieved through coding in just one of them.

Gilmartin (1982) studied the effect on student learning of map presence in a college geography text. She claimed that maps "are most valuable in their explicative function—for their ability to communicate spatial relationships that are inexpressible verbally" (p. 145). One hundred and thirty-three students were assigned to read either a text-only passage, a passage accompanied by a map, or a passage accompanied by a map that included some text from the original passage. The students were asked to answer questions about the information they had read. Gilmartin concluded, "maps provided with a passage of regional geography text helped students learn the content of the text, both for immediate testing and for delayed testing" (p. 149). She interpreted this finding appealing to the visual imagery hypothesis (see Chapter 4), hypothesizing that the maps conveyed spatial information more efficiently than the verbal descriptions or that the maps served as an aid to memory, allowing students to store results on the page rather than in memory. Finally, she noted that there may have been a testing effect, because the items mapped in the text also showed up on the test. Perhaps Gilmartin's most intriguing result was in the gender differences she observed. Males outperformed females in the text-only group, but males and females scored equally in the text-plus-maps groups. This effect warrants further investigation.

In their discussion of the role of visualization in chemistry learning, Wu and Shah (2004) wrote that "chemistry is a visual science" (p. 465). "To visualize the synthesis process, chemists always sketch structures of reactants and products, and draw symbols, arrows, and equations to describe chemical processes (Kozma et al., 2000)" (p. 466). Wu and Shaw maintained that a high level of visuospatial ability is relevant to chemistry comprehension, and they suggested that "one major characteristic of chemistry visualization tools should be providing multiple representations and descriptions of the same information. . .because multiple representations enable students to visualize the connections between representations and relevant concepts" (p. 483). They also suggested that visual representations in chemistry should make linked referential connections visible, present the dynamic and interactive nature of chemistry, promote the transformation between 2D and 3D thinking, and reduce cognitive loads by making information explicit (p. 485).

Winn (1988) examined the use of instructional diagrams in high school science instruction in his study, specifically looking to "establish relationships between the explicitness with which the elements in a diagram are represented and students' success at performing tasks" (p. 377). Winn claimed that "the effectiveness of diagrams in science instruction is not universal. It is dependent on a number of mediating factors. Most important among these are the task that the student is able to perform as a result of studying the diagram, and the student's ability to learn information in the diagram that is relevant to that task" (p. 375). His study found that instructional diagrams (in this case, about circuits) informed students about concepts under discussion and about how the elements interact. They conveyed information in a holistic (big picture) manner when the diagrams contained fewer explicit details and in an analytic (small picture) manner when there were explicit details in the diagram.

In a study of 69 ninth grade students, Wilder and Brinkerhoff (2007) found that "participants generally performed better on questions including visualizations" (p. 15). The authors' results suggest that "computer-based biomolecular visualization instruction was an effective curriculum component supporting the development of representational competence" (p. 5). Wilder and Brinkerhoff's use of the program Chemscape Chime appears to have been met with positive responses from the majority of the participants. In a telling reason cited for selecting computer-based activities, a common participant response was, "I learn best by seeing" (p. 17).

An important educational conclusion from Lee et al.'s (2006) study of 257 seventh grade Korean students was that when designing instructional materials, learner differences need to be considered (p. 912). This study was more about determining the best conditions under which a simulation is effective than simply attempting to determine if simulations are effective in general (p. 902). After being given a demographic information questionnaire on the first day, the seventh grade Korean students were given 15 min to use a computer simulation of the ideal gas law "which describes the interrelationship among temperature, pressure, and volume of an ideal gas" (p. 906). Students were given either a visual display that crowded all the relevant information onto one screen or a display that separated the information into two screens. The division was based on a calculation of the visual complexity of the display. After completing their work in the computer simulation, the students were asked to complete a comprehension test and then a transfer test on the second day. The hypothesis was that separating the visual and cognitive load into smaller pieces would allow for more efficient processing and retention. The main result of this study was that all students benefited from having the visualization object split into two smaller pieces. Notably, student prior knowledge made a large difference in the effect of lessening the load. The greater the students' prior knowledge, the greater the benefit to visual load reduction.

Huk (2006) aimed to "investigate the educational value of 3D visualization in the domain of cell biology education" (p. 393). Huk hoped to determine, through the use of the CD-ROM The Cell II—The Power Plant—Mitochondrion and Energy Metabolism, whether the use of 3D models is useful for low spatial ability learners as opposed to high spatial ability learners by having 106 German biology students at high school and college level work with the CD-ROM for 20 min. Huk measured auditory recall and visual recall by administering a pencil-and-paper test after the students had used the software. The results of the study showed that "the addition of sophisticated 3D models depicting a plant/animal cell fostered remembering of auditory as well as visually presented information only in students with high spatial visualization ability" (p. 401). In conclusion, Huk posits that the "presence of 3D models resulted in a cognitive overload for students with low spatial ability, while high spatial ability students benefited from 3D models, as their total cognitive load remained within working memory limits" (p. 401).

Dynamic Media and Learning Performance

In a case study of 212 eighth grade students in Greece, Korakakis et al. (2009) set out to determine whether the use of specific types of visualization (3D illustration, 3D animation, and interactive 3D animation), combined with verbal narration and text, enhances students' learning of "methods of separation of mixtures" (p. 394). The separation themes include distillation, fractional distillation, pouring, centrifugation, filtering, evaporation, paper chromatography, sieving, and magnetic separation (see p. 394).

Students were randomly assigned to each of the three groups. Students worked individually on their assigned multimedia application for 1 h and then were asked nine questions—multiple-choice, fill in the blank, and visualized questions. The results were not straightforward because students seemed to need time to become familiar with the task that lay before them—those with 3D animations and interactive 3D animations took more time than those assigned 3D illustrations. Students seemed to experience difficulty in constructing relevant information from the dynamic visuals because the information was unfolding too quickly. Thus, the degree of familiarity students had with the interactive controls seemed to introduce an extra cognitive load and they seemed to lack the spatial ability to conceive the visualizations completely, a result pointed out by Gilbert (2005) and Gilbert et al. (2008). Improved student interest and attraction to the interactive 3D and 3D animation was noted. Understanding was not improved. Korakakis, Pavlatou, and Spyrellis concluded that, "the contribution of all three types of visualization is differentiated in a multimedia application. In particular, both interactive 3D animations and 3D animations dominate the 3D illustrations regarding the increase in interest for the thematic unit while the last units were the least attractive to the students. On the other hand, the third type dominates the first two regarding the reduction of cognitive load" (p. 400).

In 1997 Johnstone queried whether chemical education is science or alchemy. Accordingly, he posited that chemistry can be thought of as three forms likened to the three corners of a triangle—neither superior to the other but complementary: macro (tangible, what can be seen, touched, or smelt); the submicro (atoms, molecules, ions, and structure); and the representational (symbols, formula, equations, molarity, mathematical manipulations, and graphs). In order for chemistry to be understood, the behaviour of substances must be interpreted at the unseen and molecular level and be recorded in a representational language and notation (Johnstone, 1997).

Limniou, Roberts, and Papadopoulos (2008) compared 2D chemical animations with 3D chemical animations designed for a full immersive virtual reality environment (CAVE^{TM}) in order to study how virtual reality animations could raise students' interest and motivation for learning. Fourteen college students were presented the two different kinds of animation (2D and 3D) to learn about (1) the reaction of methyl orange with acid and its behaviour in water and (2) the air and the formation of acid rain. After the two presentations, students were asked the same multiple-choice questions. Students comprehended the molecular structure and the change during a chemical reaction after participation in 3D animations at the CAVE better than during the 2D animations on the computer's desktop, and students were more enthusiastic about the former presentation. The questions remain whether students were enamoured with the virtual reality experience, explaining their enthusiasm, and whether they truly understood given "they had the feeling that they were inside the chemical reactions. . ..they face[d] the 3D molecules as if a real object was in front of them trying to grab them" (p. 592).

In 2009, Annetta, Minogue, Holmes, and Cheng (2009) investigated the impact of teacher-created video games, Multiplayer Educational Gaming Application (MEGA), for instructional programmes on 129 high school students' engagement in and learning about genetics in general biology classes. The MEGA "was designed and built to probe students' understandings of pedigrees, Mendelian inheritance, blood types, and DNA fingerprinting through a problem-based crime scene investigation" (p. 77). The MEGA was used as a review tool after the unit on genetics had been taught. Sixty-six students in the experimental group played the MEGA in pairs on a desktop computer for approximately 90 min and the control students reviewed the genetics unit using whole group discussion and paper-and-pencil practice.

All students completed a post-test after their respective type of review. Students in the experimental MEGA group were more engaged than the control standard-discussion-and-paper-and-pencil group, but no differences were found in students' performance on the cognitive assessment. Annetta et al. (2009) queried whether 2D paper and pencil assessments can get at the "sensorily rich institutional environment" (p. 79). The need for research designed to tease out the impact of the technology on student learning from the cognitive impact of a skilled teacher was identified. Finally, the authors caution that games are not a panacea and stressed the need for specific design and evolution criteria with more emphasis on the instructional content and less on animation, text, and audio that do not aid in the learning process (p. 80).

Animations, Visualizations, and Conceptual Change

The effects of animations on overcoming 11th graders' alternative conceptions of chemical bonding was studied by Özmen, Demircioğlu, and Demircioğlu (2009). The authors claimed that "chemical bonding is one of the most important topics in undergraduate chemistry and also a topic that students commonly find problematic and develop a wide range of alternative conceptions" (p. 683). Twenty-eight students were in the experimental group and 30 in the comparison group. "Shape of molecules, bond polarity, intermolecular forces, polarity of molecules, and general bonding were evaluated in the study" (p. 684). The chemical bonding achievement test (CBAT) was administered to all students as a pre-test. The comparison group received regular instruction with the teacher who used lots of examples and illustrations in a "chalk and talk" approach. The experimental group received conceptual change texts based on results of the pre-test coupled with computer animation instruction (CCT-CA). The CBAT was administered to all students as a post-test 1 month after the intervention and then again 2 months after the post-test. The results showed that students' alternative conceptions persisted even after the CCT-CA instructions and implementation of the National Science Foundation (2007) advice to make animations interactive and to increase student involvement in learning (p. 685). Thus other considerations must be regarded as a way to enhance students' learning of chemistry concepts.

Silén, Wirell, Kvist, Nylander, and Smedby (2008) worked with 62 medical students in order to understand the possible educational value of introducing 3D visualizations related to anatomy and physiology. They used high-resolution CT and MR images. Questions were administered to the students to learn about their experiences with and attitudes towards such visualizations and about their learning processes. The authors concluded that "visualizations with varying degrees of interactivity….are a promising resource in student-centered medical education" (p. 124).

Using a semi-structured interview, Garmendia et al. (2007) interviewed 12 first-year engineering students to learn about the difficulties they experience in visualization and drawing tasks. "The engineer must have the skills to read and write the language of the drawing. The need to learn how to read a drawing is absolute…" (p. 315). The aim of the study was to learn the steps, procedures, and forms of reasoning engineering students use to solve three-part visualization problems. Students were asked to solve the problems upon completion of their engineering graphics course in first year undergraduate engineering. The results were not good according to the researchers because all had just passed the course, and problems posed were representative of the fundamental level. Students analysed statements in a superficial manner, displayed a tendency to use the same solution method without considering its suitability, and "resort[ed] to trial and error and to intuition" (p. 321). The results confirm that students did not know the different methods and solution strategies for visualization problems. The results confirmed Mathewson's (1999) conclusion that visual–spatial thinking is overlooked by educators.

Biotechnology is now an integral part of science curricula but according to Yarden and Yarden (2009) "the most problematic issue in learning biotechnology has been found to be the biotechnological methods involved" (p. 1). Specifically, they were interested in whether 12th grade biology majors showed a difference in their comprehension of the polymerase chain reaction (PCR) when using animation or still images as an aid. The relationships of students' prior content knowledge and their comprehension with animation or still images, and the difference in conceptual states of the PCR methods between those students who learned using animation and still images, were examined.

Students were asked to complete a questionnaire on their prior content knowledge about DNA replication and to learn PCR for the first time. The experimental group (90 students) received the PCR animation and the comparison group received the still image cards (83 students) taken directly from the animation. Students in both groups worked in pairs for the class periods and their discussions were audiotaped. Upon completion, all students individually completed a questionnaire on their understanding of PCR. Results showed an advantage for the PCR animation over still images for student learning. Mixed results were found in the relationship between prior content knowledge and students' comprehension of PCR: in the still images group, those with low prior content knowledge achieved low post-intervention scores, those with high prior knowledge achieved high on the post-test; for the animation group, students' level of prior content knowledge had no effect on their post-intervention scores. These results are at variance with other studies where high prior content knowledge generally provided the greatest advantages.

Eight transcripts of students' conversations were chosen randomly, four from the animation group and four from the still images group in order to gain a deeper understanding of students' understanding of the PCR method. Differences were found in specific areas: the function of the DNA polymerase enzyme, the function of the primers, and the specific temperatures at which different stages in the PCR method occur. Animation helped students learn the mechanistic aspects of biotechnological methods. Yarden and Yarden caution that their research showed a distinctive advantage of animation for demonstrations of molecular phenomena. The results may not be similar for motion or other physical phenomena. The mechanistic aspects of the PCR method were at the core of the advantages the students gained from animations over still images.

"When young children are able to create visual representations of their ideas they are then able to work at a metacognitive level" (Brooks, 2009), p. 327). This claim is consistent with the work of Gilbert (2005) who has identified metavisual capabilities as essential to scientific understanding. Brooks (2009) demonstrates how some 6-year-olds explained their ideas on light. They had noticed a change in the amount of light in the classroom. Children brought flashlights from home because they wanted "to test a variety of light sources that might be possible to read by" (p. 328). The children then used pencils and coloured crayons to draw the flashlight of interest to them. They used black plastic to create a dark space in their classroom. They then noted that differences in the amount of light in the dark space depended on the flashlight used—some gave a good range of light and others did not, some had three levels of light and some just one level. One of the children drew what he saw with the flashlight with three levels of light. The children drew pictures to explain how light worked, and in so doing their spatial visualizations and orientations improved. Moreover, they extended their work on flashlights to explore how they might trap light. The children noticed the mirror behind the bulb in each flashlight and asserted that the mirror was necessary because that made the light "bounce off" and "keep moving". Brooks maintained that the visualization examples developed by the children showed they are able even at a very young age to represent complex ideas which "assist young children's interactions and competencies with spatial visualizations, interpretations, orientations and relations" (p. 340).

The earth–sun–moon (ESM) system has been the topic of many studies on the varying misconceptions held by a significant portion of the population. Subramaniam and Padalkar (2009) seem to be among the first to try to understand what explanations are offered by participants and how participants change these explanations when inconsistencies are pointed out (p. 397). Eight master's students (four studying architecture and four studying physics) were interviewed and asked to explain the lunar phases. They were then given two short questionnaires: "Hint Sheet 1; (i) Some people think that the phases of the moon occur because the earth's shadow falls on the moon. Do you think this is correct? Give arguments to support your answer. (ii) Do we ever see a half moon in the sky? Could this shape be caused by the earth's shadow? Give reasons. Hint Sheet 2 included questions such as (i) How much of a spherical ball in a uniformly lit room is visible when we look at it? (ii) What is the shape of the boundary of the visible part?" (p. 399).

The results revealed that only one physics student presented a visually acceptable model with the correct explanation. Four architects and one physics student were then given Hint Sheet 1. Four of the five participants changed their explanations of the lunar phases and reaffirmed the eclipse mechanism as causing the phases. The second hint sheet was designed to trigger a rethinking about the phases of the moon. The students were interviewed about changes in their explanations. A major source of difficulty "was to understand that the earth's rotation or the observer's position on the earth has no causal role in the occurrence of the lunar phases, but only determines when and whether the moon is visible at all" (p. 409). The master's students successfully recalled factual and verbal knowledge associated with the ESM but experienced difficulty integrating it with visuospatial reasoning. Diagram-based reasoning showed promise for the enhancement of visuospatial reasoning through representations, transformations, and projections of 3D objects onto 2D.

Mathai and Ramadas (2009) explored the role of diagrams and text on the digestive and respiratory systems using a three-part methodology. Eighty-seven mixed-ability eighth graders completed written questionnaires on both human body systems. Their responses included a combination of text and diagrams. Results showed that students had a preference for and more competence with text than with diagrams. Many students did not draw diagrams, but those that had high test scores tended to have high visualization scores. The authors conjectured that good visualizers were also good verbalizers (p. 449). Mathai and Ramadas prepared a series of structure and function diagrams for the students in an attempt to encourage visualization. Students experienced "difficulties in comprehending diagrams related to understanding of cross-sections, microscopic or chemical processes, and structure-function relationships" (p. 454).

Wang, Chang, and Li (2007) aimed "to investigate the comparative effects of using web-based tutorials differentiated in including either 2D representation or interactive 3D representation, on the influence of undergraduate students' spatial visualization ability" (p. 1945). Using CooTutor the authors presented the same information using different representations (2D and 3D) to 23 undergraduate earth sciences students. The students completed a pre-test, self-paced learning session, and a post-test. Although it was harder for the small size of samples used in this study to achieve the statistical significance a larger sample size might have garnered, results indicated that "students in different groups (2D and 3D) revealed very different behaviors regarding time duration they spent in using the program" (p. 1953). Noting that the small sample size limited their ability to generalize, the authors admitted that "it may be beyond the scope of this study whether staying long is good or bad" (p. 1953).

Holzinger, Kickmeier-Rust, and Albert (2008) expressed the need for researchers "to discern which factors contribute to the success or failure of static or dynamic media" (p. 279). Their experimental study of 129 computer science undergraduates (control and experimental groups) set out to learn whether there is "a discernable difference in learning performance between electronic learning material. . .(containing dynamic media), and printed matter (static media, including diagrams, and pictures). . .if there is a difference, what are these differences and how far do they extend?" (p. 280). Students were asked to complete a pre-test on previous knowledge and to read a one-page textbook lesson that included organized paragraphs and three static images. Those in the static image condition were provided copies of the textbook page and those in the dynamic animation condition were presented the information on a computer screen with flash animations. The control group received one page of text on the screen. All three groups of students were asked to complete a post-test. Results showed that the more complex the learning material the greater the advantages of the dynamic media in comparison to the static. Holzinger et al. (2008) were careful to state "dynamic media are only appropriate and facilitate learning *when they represent a meaningful mental model* of a process or a system. This representation must also be within the limits of the cognitive system, and it must build upon learners' previous knowledge and expertise" (p. 287).

Schönborn and Anderson (2006) claimed in their discussion of the importance of visual literacy in the education of biochemists that "all biochemists would readily agree that visualization tools are essential for understanding and researching the molecular and cellular biosciences" (p. 94). They formulated "three major claims for recommending that visual literacy should be explicitly taught as an essential component of all modern biochemistry curricula" (p. 97). First, Schönborn and Anderson pointed out that students are exposed to more and more exceptionally diverse and possibly confusing external representations. To understand and use these representations effectively will require a better understanding of visual literacy. Second, they stated that students must be taught further visualization skills than those they would normally attain unofficially on their own. Third, students with reduced visual literacy show proof of troubles that can affect their aptitude for interpreting and learning from external representations (p. 97).

As we noted in Chapter 6, Linn (2003) found that scientific visualizations can confuse learners because they do not have the same background knowledge as the people who created the visualization. Linn discussed the role of technology in science education and stated that visualizations created by experts "may not help students consider an alternative or stimulate learners to sort out their ideas" (p. 744). This is because "visualizations can fall into the trap of transmitting complex information that students find impenetrable" (p. 744). Although she maintained that visualization can support the process of interpreting ideas, she says that "without instruction in visualization techniques, students often have difficulty interpreting three-dimensional information" (p. 747) and concluded that "the appeal of visualizations overshadows the challenges of designing effective materials" (p. 746). Dechsri et al. (1997) found opposing results with their study in which they sought to determine whether illustrations and diagrams in undergraduate chemistry laboratory texts can improve recall and comprehension for students. Eighty-three students were split into control (lab manual had no pictures or diagrams) and experimental (lab manual had accompanying pictures and diagrams) groups and were given pre-tests and also post-tests examining their chemistry lab skills. Students also were asked to complete attitude surveys which questioned their consideration of lab work as part of chemistry learning, the quality of the lab experiences, and their enthusiasm for lab work. Their results showed that students who used the manual with accompanying visuals achieved better results in interpreting data and comprehending reaction rates and equilibrium, as well as demonstrating a more positive attitude towards laboratory work. Dechsri, Jones, and Heikkinen concluded that when visual aids are integrated with text in chemistry manuals, "students perform better in the cognitive, affective and psychomotor domains" (p. 901). Although they concluded that chemistry learning is better with visual accompaniment, they also noted that visual aids can still "overload student memory and may not help students learn more than text-based materials without pictures or diagrams" (p. 901).

Improvements in computer technology have greatly increased the possibilities of using graphics, animation, and 3D visuals in the science classroom. Several computer programs have come onto the market in the past few years that are a supplement to chemistry textbooks. The visualization tool eChem is designed to help students visualize, understand, and mentally manipulate interactions between chemical molecules. In a study by Wu, Krajcik, and Soloway (2001), eChem was integrated into an 11th grade work unit, and the researchers found that teaching with a combination of computational and concrete models helped improve students' ability to acquire conceptual knowledge at the micro and macroscopic levels as well as have a more accurate understanding of properties, structures, and underlying concepts (p. 833). They stated that "a positive learning effect, shown by the significant difference between the scores of pre- and post-tests, may be partially attributed to using a visualization tool in science classrooms" (p. 838), yet they maintained that both computational and concrete models should be provided in the classroom in order to accommodate different learning styles and preferences. Furthermore, they suggest that an important factor in chemistry computer programs is to link several chemistry representations and ensure that these representations have a comprehension stage which resolves any co-references between them (p. 838).

Connected Chemistry is another program designed to provide opportunities to interact with and manipulate a simulated molecule and is based on similar programs previously used in biology and physics classes. Stieff and Wilensky (2003) did a study with six undergraduate science students to see whether computer models aided in answering and applying concepts to traditional textbook questions about chemical equilibrium. They found that the model helped improve students' abilities to "(1) define chemical equilibrium; (2) characterize factors that affect equilibrium; and (3) transition between submicro-, macro- and symbolic levels during problem solving" (p. 299). However, the authors noted that "much of the software is 'first generation' and does not yet fully employ an inquiry approach to teaching chemistry" (p. 287).

Yang, Andre, and Greenbowe's (2003) study of 415 chemistry undergraduates aimed to investigate the impact of a computerized animation on their learning of concepts and their level of spatial ability. The authors found that "instructor-guided computer animations facilitated students' learning of chemistry, most probably by allowing students to visualize chemical reactions at the microscopic level and to create imaginal representations of those reactions" (p. 347). They stated that their results "indicate that there are varied benefits to using animation depending on students' spatial abilities. . .using an instructor-guided animation in isolation is not effective, the animations need to be incorporated as part of a robust learning module designed to promote conceptual change" (p. 347). Rieber's (1990b) study focused on the effects of using animated computer visualizations during elementary school physics lessons. He compared the effect of static graphics, animated graphics, and no graphics when presented in conjunction with textual information about Newton's laws of motion. Rieber found that "animated presentations of the lesson content influenced student performance when practice was provided. However, this effect was eliminated without practice. . . [although] cognitive practice was less prone [than behavioural practice] to variation or dependence on visual elaboration" (pp. 138–139). Rieber did not find a significant difference in general attitude about the lesson content between the three groups, but attributed that to "the opportunity and the attention they received as a result of their participation" (p. 139). He concluded that animations can be beneficial when

1. teaching lessons which require visualizing motion;
2. teaching material which is adequately but not unreasonably challenging;
3. an animation can cue a student's attention to the detail in the graphic; and
4. using animation in collaboration with other instructional activities (p. 139).

Many studies conclude that visualization has a quantified usefulness in science, but that visual aids need to be supplemented during the lesson with explicit verbal explanations, concrete models, and processes to invoke past knowledge in order to be most effective (Booth & Thomas, 1999; Presmeg & Balderas-Canas, 2001; Wu et al., 2001). Cifuentes and Hsieh (2003) suggested, upon completion of their study of 75 undergraduate oceanography students, that student-generated visuals are more meaningful than instructor-generated ones because they allow students to create and manipulate their own knowledge construction. They stated that "student-generated visuals surpass illustrations in their effectiveness for instruction because they are more personally meaningful and relevant to students' understandings and prior knowledge and because they contribute to construction of meaning" (p. 264). They hypothesized that teacher feedback is also extremely important in order for students to reflect and revise their level of understanding and tested this by separating students into groups that were completely unguided, encouraged-to-visualize, or oriented in how and when to visualize. The authors found that "neither encouragement to visualize nor a visualization orientation positively affected test performances" (p. 270), which they explained as follows: "participants in the oriented group may not actually have mastered the identified skills, or perhaps they did not have time to effectively use their newly acquired skills. . .applying a new strategy requires concentration on that strategy and may interfere with an individual's study routine, thus inhibiting rather than facilitating learning" (p. 271). They suggested providing flexible study time and a powerful orientation to visualization prior to implementing it as a study strategy.

Hall and Obregon (2002) argued that visualization can provide tools for scientific and industrial communities to transform data into 3D formats which assist in understanding information in all disciplines, in a much deeper manner than ever before possible. They claimed that "images and graphics can be easily used to relay information over any distance and in almost any discipline" (p. 2). Following their 2005 discussion article about visualization in science and engineering at a Chinese university, McGrath and Brown stated that "visual approaches let scientists and engineers communicate more complex and subtle concepts to each other and to students, and visual approaches to learning engage the student more fully in the ideas presented" (p. 56). They claimed that there is lack of empirical evidence that visualization helps learning, but they focused on a study that assessed the thinking styles of engineering students and that showed that most students and professors were visual thinkers. They conclude by stating that as a collaborative learning methodology, visual thinking "is crucial to the future of learning" (p. 63).

Concluding Comments

The usefulness of visualization in science seems to have much to do with a match between the activity and the desired outcome. Visualization often involves using schematic or symbolic diagrams as computational aids. In these cases, the visual objects tend to be simple and direct. For conceptual understanding, richer objects in combination with verbal or textual instruction offer the possibility of rich experiences for students. The verbal component seems essential, because visualizations rarely can stand alone. This seems to be especially true in science education, where difficult-to-imagine objects can be depicted dynamically for students to appreciate how these objects change over time. Finally, there appear to be important concepts that cannot be visually clarified and great disputes over whether visualizations have any place at all.

Part III
Cautions and Recommendations

Chapter 8 opens a new topic of computer-generated visualizations. Although some research dealing with visualizations developed, displayed, and used in computers has been described under the content areas of mathematics, reading, and science, computer-generated visualizations are sufficiently pervasive as to justify a separate chapter devoted to them. More to the point, there are many unwarranted assumptions made about the beneficial effects of computer-generated visualizations that we would be remiss if we did not deal with them. Thus, we turn to the research and provide a balanced account, prompting cautions on what is reasonable and not reasonable to expect and recommendations for the use of computer-generated visualizations in instruction.

Chapter 9 is both retrospective and prospective. We reflect on the preceding chapters and draw several recommendations for the use of visualizations in mathematics, reading, and science education. Then we look to the future and point to several areas of needed research.

Chapter 8
Research and Guidelines on Computer-Generated Visualizations

Throughout the literature, the themes of technology and computer development recur. We found 40 articles dealing with computer software and animations in general, as well as many other articles that emphasized computer-based visualization in the context of the specific subjects of mathematics, reading, and science. The impact that technology is having on educational visualization is already significant and is showing signs of growth. We further note that a peer-reviewed journal dedicated to computer issues in visualization has emerged, the *IEEE Transactions on Visualization and Computer Graphics*. This journal deals mainly with technical issues in the construction of computer-based visualization objects, such as algorithms, software, and hardware, but it does welcome and publish articles dealing with the implementation and use of these objects. Computer-based visualization has become a mainstream field both in science and in education. The purpose of this chapter is to review some of the research that has been conducted on computer-based visualizations and to repeat several cautions and recommendations that stem from that research.

Since the mid-1970s, computer technology and software have enhanced the resourcefulness and creativity of visualization designers. There has been a remarkable increase in the number of studies about visualization since computers were developed, and the number of studies which focused strictly on the impact of computer programs on visualizations took a drastic increase since the early 1980s (see Fig. 8.1). Accordingly, the number of studies about animation, "the process of generating a series of frames containing an object or objects so that each frame appears as an alteration of the previous frame to show motion" (Ju & Cifuentes, 2002, p. 47) followed a similar path to the proliferation of computer-based visualization software. Although it is true that computer-based visualizations in all areas are increasing in number, it is particularly notable in the field of chemistry. Along with animation, the idea of student interaction with a visualization object has also been furthered since computers entered the classrooms in the 1980s (see Fig. 8.1).

Computer-based visualization objects are able to construct physical representations that would be cumbersome to build or to use with other media. Ainsworth and Van Labeke (2004) discussed the many uses of such representations, claiming that

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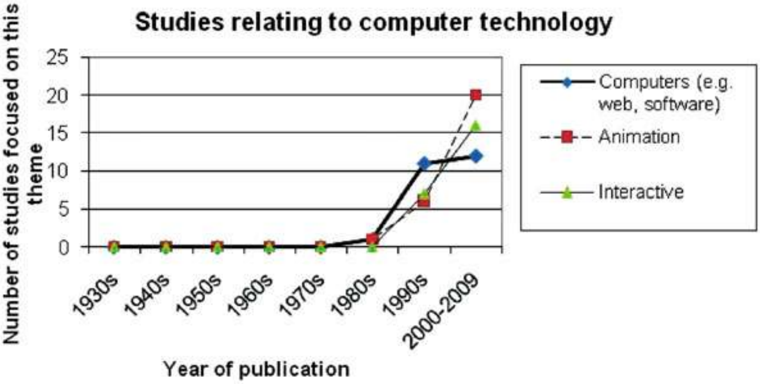

Fig. 8.1 Number of published studies related to computer technology, animation, and interactive computer visuals

"they may show blood pumping around the body, the flux of high and low pressure areas in a weather map, the developing results of a computer program running (algorithm animation) or the movements in physical systems such as series of pulleys" (p. 241). Hall and Obregon (2002) also discussed applications for visualizations and claimed that for secondary and post-secondary classrooms, virtual visualizations are easier to generate than physical models and can represent more detailed features. They go on to say that "unlike virtual models, physical prototypes have size limitations, require highly skilled technicians for creation, and are localized to a specific location. Because virtual models are digital information, ideas can be shared over any distance" (p. 2). In a review of computers' impact on teaching, Kraidy (2002) contends that "through images and graphical simulations, computers represent an entirely virtual environment with almost no limitations of time and space" (p. 103). Kraidy further notes that "the paradox is that visual representations simultaneously have the potential to aid the understanding of abstract concepts while also furthering conceptual abstraction by promoting virtual representations instead of reality" (p. 103).

Although enthusiasm for computer-based visualization remains strong, many researchers have been careful to attend to the drawbacks of computers and animation. Mayer and Anderson, in their 1991 study with 30 university-aged students, examined the level of learning achieved when animations were presented with and without accompanying narration. The authors found that "animation without narration can have essentially the same effect on students' scientific understanding as no instruction" (p. 490). Mayer and Moreno (2002) observed that "animation (and other visual forms of presentation) is not a magical panacea that automatically creates understanding" (p. 97). Park and Hopkins (1993) discussed conditions for using dynamic visual displays (DVDs), and although they concluded that DVDs were a beneficial adjunct in the classroom, they also provided three considerations for the presentation of displays:

1. There must be a verbal explanation accompanying the dynamic features. Students' attention to the task at hand should be guided through appropriate narration.
2. There must be an appropriate level of fidelity of content of the displays and animations to the objects or phenomena they depict. Fidelity is an amorphous concept; the required level of fidelity varies from one depiction to another and from one instructional context to another.
3. The display should be designed in such a way that students are able to perceive and understand the information. Materials must always be appropriate for the students' prior knowledge and current interpretive abilities (pp. 444–445).

Milheim (1993) reviewed previous research about the effectiveness of animation as an instructional tool. He noted that the positive attributes of computer-based instruction include the use of colour, learning interaction, student control of pacing, and animation which can be controlled by the learner (p. 171). In addition to his positive findings, Milheim noted that computer-based visualizations often do not achieve the goals for which they are intended. He concluded that despite the significant potential for the use of animation, it "will not necessarily be effective whenever it is used simply because it provides information in a somewhat motivating format" (p. 173). He provides guidelines which would facilitate individuals' ability to use animations to their advantage:

1. Develop simple animations—complex enough to convey the message, simple enough to understand.
2. Focus on important objectives, particularly with novice learners.
3. Include options for varying the speed to provide emphasis where needed.
4. Use animation that is directly related to the important objectives of the instructional lesson.
5. Use animation when instructional content includes motion or trajectory.
6. Use animation when the instruction requires visualization (especially spatially oriented information).
7. Use animation to emphasize invisible events (for example, sub-atomic collisions of microscopic particles).
8. Include a coaching component to assist the learner in interpreting and extracting the relevant information from the animation.
9. Use interactive, dynamic graphics in which the learner can manipulate the graphic.
10. Use animation to gain attention and increase motivation.
11. Avoid overuse of animation sequences that could be distracting.
12. Avoid using animation with novices who are unable to differentiate between relevant details and cues of the animation (p. 177).

Many of Milheim's points have been seen elsewhere in the visualization literature. Even recommendation number 7, "use animation to emphasize invisible events", has been seen before. Recall the Feynman diagram (Fig. 2.3) that shows graphically events in space and time without depicting any physical appearances. Milheim's comments on relevance, coaching, and motivation echo our findings in Chapters 3 and 4.

Borwein and Jorgenson (2001) discussed the significance of visualization in mathematics and the use of computer technology in that field. They stated that "computer graphics offers magnitudes of improvement in resolution and speed over hand-drawn images and provides increased utility through colour, animation, image processing, and user interactivity" (p. 897). Their statement implies the traits that they commend as useful to an effective visual. The authors provided some general guidelines for the characteristics of an effective visualization: dynamic (representation changes over time), guidance (leads the viewer through steps in the correct order), flexibility (support the viewer's own exploration of the ideas presented), and openness (underlying algorithms and details of the programme are available for inspection) (p. 900). Bennett and Dwyer (1994) also had similar suggestions in their work with 178 undergraduate students examining "the instructional effect of varied visual interactive strategies in facilitating student achievement" (p. 23). They examined results of students receiving word instructional script complemented with drawings that varied in their degree of required interactivity. They stated that "interactive visuals which allow the learner to take an active role in the learning process can influence the learner's ability to select, acquire, construct, and integrate concepts" (p. 23). The study concluded that "for optimum learning to occur, it may be necessary to explain to students how precisely the rehearsal (interactive) strategy is going to help them achieve their specific objective—that of helping them to organize and structure the information for acquisition and retrieval" (p. 31).

In their longitudinal study of the data analysis processes of two bioinformaticians, Saraiya, North, Lam, and Duca (2006) recognized that "it is important to create visualization tools that maximize human capabilities to perceive and understand complex and dynamic data" (p. 1512). The authors observed these bioinformaticians as they analysed data from a microarray experiment in an attempt to "gain basic understanding into the visual analytic process" (p. 1511). The findings gave some insight into the importance of visualization tools matching the analytical process within which they are used.

In an attempt to use computers simultaneously to present visual material and to interpret user interactions to modify the presentation, Jankun-Kelly, Ma, and Gertz (2007) began with the claim that, "A visualization technique with no means of storing results is wasted. A visualization system which does not communicate to its user where they have been, where they are, and where they could go is inefficient" (p. 357). In an attempt to fill this gap, the authors developed the P-Set Model of Visualization Exploration that "encapsulates the interactions a user can have with a visualization system and how these interactions are part of the greater exploration session" (p. 359). Their model addresses the theoretical concern that some of the benefit derived from a computer-based visualization object is lost if the user does not have access to a robust system that allows for the review and retrieval of previous results. The P-Set Model combines information about results that the user has noted or achieved with parameters derived from details of the user's activity. "Systems utilizing the process model assist in reuse since they clearly track where a user has been, where they are, and possibly suggest where to go" (p. 365). This development offers the promise of using computers not only to present visualization objects but also to shape the way that users interact with the objects.

It appears, then, that computers have greatly added to the possible uses of visualization in school, but that they have not changed the basic uses and abuses of visualization. In particular, computer-based visualization appears to be particularly well suited to visualization for understanding. This is so because the computer lends itself so naturally to representations with text, sound, and visual displays. The possibility of combining language and a dynamic visual display while allowing for the user to control speed and other presentational factors underwrites much of the current enthusiasm for computer-based visualization.

Chapter 9
Concluding Comments, Recommendations, and Further Considerations

We opened this book with the question: Is there a single defensible theoretical model of visualization? The short answer is that there is not, at least not at this time. The current state of research does not point to a single model of visualization but, rather, to partial models. We expect that in the short run educators and researchers should use the available results in contexts similar to those in which they were found, because we do not have theories adequate to the task of determining their generalizability to other situations. First, in this chapter, we review three important distinctions that we have made. Second, we focus on the first of these, visualization objects, and recall several recommendations concerning their use. Third, we turn specifically to animation, a specific type of visualization object, and provide several recommendations on their creation and use. Fourth, we draw several very general recommendations for teachers and close with some suggested areas for future research.

We have noted that there are significant disagreements among researchers regarding an appropriate definition of the key terms relevant to visualization. To shape our analysis, we have divided the umbrella term "visualization" into three concepts:

1. *Visualization Objects.* These are physical objects that are viewed and interpreted by a person for the purpose of understanding something other than the object itself. These objects can be pictures, 3D representations, schematic representations, animations, etc. Other sensory data such as sound can be integral parts of these objects and the objects may appear on many media such as paper, computer screens, and slides.
2. *Introspective Visualization.* These are mental objects that are believed to be similar to visualization objects. Introspective visualization is an imaginative construction of some possible visual experience.
3. *Interpretive Visualization*. This is an act of making meaning from a visualization object or an introspective visualization by interpreting information from the objects or introspections and by cognitively placing the interpretation within the person's existing network of beliefs, experiences, and understanding.

This division separates the physical artefact—the visualization object—from cognitive action—interpretive or introspective visualization. Interpretive

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visualization is a cognitive act initiated by interaction with a visualization object or introspective visualization. Introspective visualization is an imaginative exercise performed in the absence of a visualization object. Phenomenologically, introspective visualizations can be very similar to viewing a visualization object. For some vivid imagers, the experience of imaginatively constructing or remembering a physical object can be quite like the experience of seeing it. For other individuals, as researchers from Galton in the 1880s to the present have noted, very little introspective imagery is available. Galton (1880b) may have believed that non-imagers were cognitively deficient, but Presmeg (1986) assures us that the better mathematics students image less well than the weaker ones. The reason for this apparent anomaly might be that mathematics does not require visualization. The ability to create introspective imagery remains largely unexplored; it may be more useful in some areas than others. It remains an open question whether interpretive and introspective visualization are ever or always cognitively equivalent or if they are even cognitively similar activities.

Visualization Objects

Dual coding theorists have explored the use of static and dynamic visualization objects as adjuncts to other forms of instruction. The main idea of dual coding theory is that visual information is coded differently in the brain than is linguistic information. In the studies we examined, no distinction was made between printed text and oral language. It was presumed by the researchers that both of these forms of communication were processed as verbal information. This is far from an obviously correct move. Regardless, dual coding theorists are clear that visualization offers an opportunity to reinforce linguistically based instruction. On their view, whatever is learned linguistically can be supplemented in a nuanced way through the introduction of appropriately selected visualization. The point is that if a student learns the material through two different modalities, then the information will be more robust and more readily accessible than if it were learned through only one (Clark & Paivio, 1991; Paivio, 1986).

In Chapter 4, we acknowledged Vekiri's (2002) summary of recommendations from the dual coding perspective. Regardless of whether dual coding proves to be a fruitful model in the future, Vekiri's list has the support of empirical research.

1. "Displays need to address the goal of the task" (p. 275). It is crucial that the visualization object match the most important features of the linguistic instruction. A mismatch is likely to lead to confusion.
2. "Displays should be provided along with explanations and guidance" (p. 275). Visualization objects are not self-explanatory. The instruction must point to the relevance of the visualization.
3. "Displays need to be spatially and timely coordinated with text" (p. 275). To avoid inefficient or contradictory coding across modalities, the student needs to

be able to put the pieces together. Words and pictures should be close together and should be presented at roughly the same time.
4. Students' prior knowledge affects their style and ability in interacting with displays. It is crucial that the student have an appropriate repertoire of previous knowledge and skills in order to maximally match the coding.
5. Students' visuospatial ability affects their ability to use the display. It is not just concepts that matter, but students must also have the basic skills required to understand how the object represents space and time.

Advocates of the visual imagery hypothesis emphasize the use of visualization objects as computational aids. On this view, interactions between visual images and language are not seen as particularly important. Visual images are tools to be used while thinking not a means of encoding non-visual information. Pylyshyn (2003) outlined five instances where visualization is computationally efficacious.

1. When visualization objects are logical systems that exploit visual operations they can encode logical relationships efficiently.
2. Visualization objects can be guides for derivational milestones.
3. Diagrams and charts often provide a way to exploit visual generalizations.
4. With visualization, a student can track instances and alternatives.
5. Visualization can provide external memory of spatial patterns (pp. 439–455).

Both lists are potentially of tremendous importance for educators. The first list outlines the key features of visualization for understanding. The second list outlines possibilities for visualization for analysis. When the point of the visualization is to acquire understanding of material that is available in verbal form, then the dual coding list offers concrete suggestions for constructing and using visualization objects and exercises. On the other hand, if the point of the visualization is to apply some knowledge or skills to a problem, then the visual imagery list offers solid examples of the circumstances in which certain types of objects will be helpful. It seems to us that however the visual imagery, dual coding theory, and conjoint retention hypothesis debate is resolved, these lists will continue to provide strong guidance to educators.

In addition to images presented to students, there are also the possibilities of students, producing their own visualization objects and of introspectively visualizing. Dwyer (1968) noted that realistic detail can be distracting for students trying to construct their own drawings of the human heart. He concluded that when the visualization object that is intended to reinforce information contains too much detail, students will have difficulty differentiating the relevant from the irrelevant. This differently signals the need for teachers and the producers of educational materials to be aware of the importance of simplicity. In producing animated displays, Lee et al. (2006) appealed to a calculation of visual complexity to assist their decision to divide a display into two simpler displays. This approach may have other applications in education, but further research is in order. We suspect that other measures of complexity will be necessary for some other types of display, for example, schematic diagrams. Little is known at this time about the relative merits of teacher-produced and student-produced visualization objects.

Surprisingly little empirical work on introspective visualization was found during our review. Certainly it is a major topic in the popular literature, but we found so little empirical data that we are inclined not to generalize. We do note with interest Gill et al.'s (2003) observation that language-impaired students who received training in introspective visualization of tasks they were about to perform showed long-term improvement in their ability to follow instructions.

Animations and Computer-Based Visualization

Most of the considerations in the above section apply as much to animations and computer-based visualization as they do to static drawings, graphs, and diagrams. Animations, admittedly, are attractive and entertaining, but in an educational context they are to serve the functions of aiding understanding or of providing computational aids. We found considerably more concrete advice with regard to animations than we found for static visualizations. Below is a compilation of the main recommendations from Chapters 6 and 7. Like static visualization objects, animations can be divided according to their function. When the function of the visualization activity is understanding, then the animation is typically supporting other means of representation, such as text or narration. The research-based recommendations for visualization for understanding are the following:

1. Use animations when they are more appropriate for the learning task than are other media. No animation would better teach a small child the concepts of "rough" and "smooth" than a touch-based activity. Animations are especially effective in showing changes across time.
2. Make animations simple enough so that the relevant cues provided by the animation are understood. As with all other visualizations, visual overload militates against understanding. Avoid distractions.
3. Feedback from the animation is often very helpful. Computers make it possible for a system of continuous reinforcement for the student. The computer can keep track of what has been accomplished and can adjust the speed and depth of the presentation to match the student's work.
4. Animations can very effectively draw attention to relevant details. Animations can speed up or slow down processes. They can zoom in or out to reveal new relationships or processes that otherwise might have been missed.
5. Animations are more effective for developing understanding when they are used in conjunction with other instruction, not as a replacement. Text and narration support the instructional effects of the animation.
6. Animations must be consistent with student abilities and prior beliefs. It is often necessary to do stage-setting activities with students before they can make use of these objects. Not all students are equally ready to make full use of a visualization activity. Background knowledge and skills in understanding the visualization need to be in place before the student can gain full benefit.

7. Include options for varying the speed to provide emphasis where needed. When the student can control the speed, the student can examine unclear material to suit her/his current level of understanding.
8. Animation can be used effectively to emphasize invisible events. Atoms don't *look* like anything because they are too small to reflect light. Yet visualizations provide students with the possibility of understanding how atoms would behave *if* they could be seen.

Recommendations for Teachers

The first question facing the teacher is whether visualization activities are worth doing. Of course, there is no general answer to this question, because considerations of which activities with which students for which purposes have to be addressed first. As we have seen, we can divide visualization activities into two categories: visualization for understanding and visualization for analysis. Visualization for understanding requires that the visualization be done conjointly with language-rich instruction. The point of these activities is to allow students the opportunity to encode the important information in more ways than one. When the visualization is intended to assist student analysis by relieving the load on working memory, it is incumbent on the teacher to make sure that the chosen objects and activities make that possible. A sketch of the relevant information to solve a mathematics problem, for example, should be comprehensible to the student and should show only the important features of the problem. It is essential that students understand which features of the visualization object are fixed, which features are variable, and which are irrelevant to the problem.

An important recurring theme in the literature is that interpretive visualization relies both on the nature of the visualization object and on the nature of the student. We have mentioned in several places that student prior knowledge and visuospatial ability are crucial prerequisites for success in educational visualization. As Linn (2003) stated, it is not sufficient for the visualization object to make sense to its creators. The expert who creates the object has a much larger repertoire of skill and knowledge than the students who will use it. Inferences about the users' background knowledge must inform the basic structure and operation of the visualization. Further, the student's ability to make inferences based on the visualization will be different from the teacher's and the creator's. It is not reasonable to expect students to have powers similar to their teacher's. These observations point to three key recommendations:

1. Use visualization objects that have been carefully selected to be level-appropriate for the students.
2. Do preparatory work with students before they begin the visualization activities.
3. Monitor and assess student visualization activities to ensure that (1) and (2) are satisfied.

There is reason for teachers also to encourage students to construct their own visual objects. Levie and Lentz (1982) found that "learning is facilitated when learners produce their own drawings—if the drawings they produce are relevant to the text content" (p. 216). This is supported by Cifuentes and Hsieh (2003) who found that "student-generated visuals surpass illustrations in their effectiveness for instruction because they are more personally meaningful and relevant to students' understandings and prior knowledge and because they contribute to construction of meaning" (p. 264). It appears that the same cautions that we made about teacher-supplied visual objects also apply to student-generated drawings. Keep the drawings relevant to the task at hand, be clear about expectations, and make sure that the task is appropriate to the students' background knowledge and skills.

Areas for Future Research

Our survey has allowed us to generalize about some aspects of visualization, but it also points to some areas that are provocative and that appear to be ill understood. We close with a short list of questions that we believe should be addressed empirically.

1. *Can visualization help students learn to read?* Perhaps the greatest disagreements in the research were in the area of visualization and reading. This is very likely due to the wide range of activities that are considered to be relevant to reading. We would like to see more refined research questions, especially with regard to beginning readers' learning to decode text. The apparently simple question, "What sort of visualizations can help students learn to read?", has not to our knowledge been addressed.
2. *Is there a relationship between gender and visualization?* Gilmartin (1982) found a pronounced difference in the benefits received by female students when they combined visualization and text. What makes this result so provocative is that for the activities she was testing (learning regional geography with text only versus text plus maps) female students gained much more from visualization than males. In the text-only control group, the male students outperformed the females. The visualization proved to be an equalizer, bringing the female scores equal to the male scores. If this is a genuine effect, then there are a number of important questions to be pursued.
3. *Can measures of visual complexity assist the development of visualization objects?* Lee et al. (2006) successfully used visual complexity calculations to divide an animation of the ideal gas law into manageable pieces for students. If this result is generally applicable, it will provide a concrete and repeatable measure of how much information can be safely included in individual chunks of student visualization.
4. *What benefit can be derived from introspective visualization?* Introspective visualization is ubiquitous in popular literature, but we found very little attention

to it in the empirical research. The single main result we found indicated that instruction in mental rehearsal assisted language-impaired students to better follow directions than the control group (Gill et al., 2003). We wonder if mental rehearsal can be shown to be efficacious in other educational areas.

5. *When does visualization not help?* Aspinwall et al. (1997) noted that visualization has the possibility of confusing mathematics students by leading them to focus on unnecessary detail. Are there topics that are best left abstract? What makes these topics different from the others?

Final Word

Years of research on visualization show remarkable progress both technologically and conceptually. Nonetheless, there is a need to advance knowledge on the conceptual processes of visualization in the disciplines of mathematics, reading, and science education. Existing research points to the need for commonality across the many usages of the term visualization and in the research bases across disciplines.

The link between research and practice is sketchy and research findings loosely prescribe practice. Moreover, there is a unifying role for research to bring researchers together from across disciplines to enable a scientific and scholarly discourse on the need for scientific evidence on visualizations. Unsubstantiated claims about the benefits of visualizations through technology impede the cumulative growth of knowledge that could otherwise inform teaching and learning. Being responsive to empirical evidence is a critically important next step for those who advocate the use of technological visualizations. We hope that our book plays a significant role in informing research and practice on visualizations.

References

Ainsworth, S. (1999). The functions of multiple representations. *Computers and Education, 33*, 131–152.

Ainsworth, S., & Van Labeke, N. (2004). Multiple forms of dynamic representation. *Learning and Instruction, 14*(3), 241–255.

Alesandrini, K. L. (1984). Pictures and adult learning. *Instructional Science, 13*(1), 63–77.

Amsden, R. H. (1960). Children's preferences in picture story book variables. *Journal of Educational Research, 53*(8), 309–312.

Annetta, L. A., Minogue, J., Holmes, S. Y., & Cheng, M. (2009). Investigating the impact of video games on high school students' engagement and learning about genetics. *Computers and Education, 53*, 74–85.

Antonietti, A. (1991). Why does mental visualization facilitate problem-solving? In R. H. Logie & M. Denis (Eds.), *Mental images in human cognition* (pp. 211–227). New York: Elsevier.

Antonietti, A. (1999). Can students predict when imagery will allow them to discover the problem solution? *European Journal of Cognitive Psychology, 11*(3), 407–428.

Arcavi, A. (1999). *The role of visual representations in the learning of mathematics*. Proceedings of the Annual Meeting of the North American Chapter of the International Group for the Psychology of Mathematics Education, Morelos, Mexico (ERIC Document Reproduction Service No. ED 466382).

Arnheim, R. (1966). *Toward a psychology of art*. Berkley, CA: University of California Press.

Arnheim, R. (1991). Perception, cognition and visualization. *Journal of Biocommunication, 18*(2), 2–5.

Aspinwall, L., Shaw, K. L., & Presmeg, N. C. (1997). Uncontrollable mental imagery: Graphical connections between a function and its derivative. *Educational Study in Mathematics, 133*(3), 301–318.

Baigrie, B. (1996). Descartes scientific illustrations and 'la grande mécanique de la nature'. In B. S. Baigrie (Ed.), *Picturing knowledge: Historical and philosophical problems concerning the use of art in science* (pp. 86–134). Toronto, ON: University of Toronto Press.

Baker, R. M., & Dwyer, F. M. (2005). Effect of instructional strategies and individual differences: A meta-analytic assessment.*International Journal of Instructional Media, 32*(1), 69–84.

Barry, A. M. S. (1997). *Visual intelligence: Perception, image, and manipulation in visual communication.* Albany, NY: State University of New York Press.

Barwise, J., & Etchemendy, J. (1996). Visual information and valid reasoning. In G. Allwein & J. Barwise (Eds.), *Logical reasoning with diagrams* (pp. 3–26). New York: Oxford University Press.

Ben-Chaim, D., Lappan, G., & Houang, R. T. (1989). The role of visualization in the middle school mathematics curriculum. *Focus on Learning Problems in Mathematics, 11*(1–2), 49–60.

Bennett, L. T., & Dwyer, F. M. (1994). The effect of varied visual interactive strategies in facilitating student achievement of different educational objectives. *International Journal of Instructional Media, 21*(1), 23–32.

L.M. Phillips et al., *Visualization in Mathematics, Reading and Science Education*, Models and Modeling in Science Education 5, DOI 10.1007/978-90-481-8816-1,

© Springer Science+Business Media B.V. 2010

Bishop, A. J. (1989). Review of research on visualization in mathematics education. *Focus on Learning Problems in Mathematics, 11*(1), 7–16.

Bohr, N. (1928). The quantum postulate and the recent development of atomic theory. *Nature, 121*, 580–590.

Booth, R. D. L., & Thomas, M. O. J. (1999). Visualization in mathematics learning: Arithmetic problem-solving and student difficulties. *The Journal of Mathematical Behavior*, *18*(2), 169–190.

Borwein, P., & Jorgenson, L. (2001). Visual structures in number theory. *The American Mathematical Monthly, 108*(10), 897–910.

Brooks, M. (2009). Drawing, visualization and young children's exploration of "big ideas". *International Journal of Science Education, 31*(3), 319–341.

Brookshire, J., Scharff, L. F. V., & Moses, L. E. (2002). The influence of illustrations on children's book preferences and comprehension. *Reading Psychology, 23*(4), 323–339.

Brown, J. R. (1996). Illustration and inference. In B. S. Baigrie (Ed.), *Picturing knowledge: Historical and philosophical problems concerning the use of art in science* (pp. 250–268). Toronto, ON: University of Toronto Press.

Buckley, A. R., Gahegan, M., & Clarke, K. (2000, December 1). Geographic visualization. University Consortium for Geographic Information Science 2000 Research White Papers. Retrieved October 21, 2008, from http://www.ucgis.org/priorities/research/research_white/2000%20Papers/emerging/Geographicvisualization-edit.pdf

Carlbom, I., Terzopoulos, D., & Harris, K. M. (1991). Reconstructing and visualizing models of neuronal dendrites. In N. M. Patrikalikis (Ed.), *Scientific visualization of physical phenomena* (pp. 623–638). New York: Springer.

Chan, L. K. S., Cole, P. G., & Morris, J. N. (1990). Effects of instruction in the use of a visual-imagery strategy on the reading -comprehension competence of disabled and average readers. *Learning Disability Quarterly, 13*(1), 2–11.

Chen, C. (2003). *Mapping scientific frontiers: The quest for knowledge visualization*. London: Springer.

Cifuentes, L., & Hsieh, Y. J. (2003). Visualization for construction of meaning during study time: A quantitative analysis. *International Journal of Instructional Media, 30*(3), 263–273.

Clark, J. M., & Paivio, A. (1991). Dual coding theory and education. *Educational Psychology Review, 3*(3), 149–210.

Dechsri, P., Jones, L. L., & Heikkinen, H. W. (1997). Effect of a laboratory manual design incorporating visual information-processing aids on student learning and attitudes. *Journal of Research in Science Teaching, 34*(9), 891–904.

DeFanti, T. A., Brown, M. D., & McCormick, B. H. (1989). Visualization—Expanding scientific and engineering research opportunities. *Computer, 22*(8), 12–25.

Definitions and Rationale for Visualization. (1999). Retrieved March 20, 2007, from http://www.siggraph.org/education/materials/HyperVis/visgoals/visgoal2.htm

Deliyianni, E., Monoyiou, A., Elia, I., Georgiou, C., & Zannettou, E. (2009). Pupils' visual representations in standard and problematic problem solving in mathematics: Their role in the breach of the didactical contract. *European Early Childhood Education Research Journal, 17*(1), 95–110.

Descartes optics.jpg. Retrieved July 29, 2009 from http://en.wikipedia.org/wiki/File:Descartes_optics.jpg

Duchastel, P. C. (1981). Illustrations in text: A retentional role. *Programmed Learning and Educational Technology, 18*(1), 11–15.

Dunham, T. C., & Levin, J. R. (1979). Imagery instructions and young children's prose learning: No evidence of "support". *Contemporary Educational Psychology, 4*, 107–113.

Duval, R. (1999). *Representation, vision and visualization: Cognitive functions in mathematical thinking. Basic issues for Learning*. In F. Hitt & M. Santos (Eds.), Proceedings of the Annual Meeting of the North American Chapter of the International Group for the Psychology of Mathematics Education, Cuernavaca, Morelos, Mexico.

Duval, R. (2006). A cognitive analysis of problems of comprehension in a learning of mathematics. *Educational Studies in Mathematics, 61*, 103–131.

Dwyer, F. M. (1967). Adapting visual illustrations for effective learning. *Harvard Educational Review, 37*, 250–263.

Dwyer, F. M. (1968). When visuals are not the message. *Educational Broadcasting Review, 2*(5), 38–43.

Dwyer, F. M. (1970). Exploratory studies in the effectiveness of visual illustrations. *AV Communications Review, 18*(3), 235–249.

Dwyer, F. M. (1971). Color as an instructional variable. *AV Communication Review, 19*(4), 399–416.

Enns, J. T. (2004). *The thinking eye, the seeing brain: Explorations in visual cognition*. New York: W. W. Norton.

Figueira-Sampaio, A., Ferreira dos Santos, E. E., & Carrijo, G. A. (2009). A constructivist computational tool to assist in learning primary school mathematical equations. *Computers and Education, 53*, 484–492.

Foley, J., & Ribarsky, B. (1994). Next-generation visualization tools. In L. Rosenblum, R. A. Earnshaw, J. Encarnacao, H. Hagen, A. Kaufman, S. Klimenko, et al. (Eds.), *Scientifi visualization: Advances and challenges* (pp. 103–128). London: Academic Press.

Fujishiro, I., & Takeshima, Y. (2000). Solid fitting: Field interval analysis for effective volume exploration. In H. Hagen, G. M. Nielson, & F. Post (Eds.), *Scientifi visualization* (pp. 65–78). Los Alamitos, CA: IEEE Computer Society.

Galileo , G. (1953). *Dialogue on the great world systems.* (T. Salusbury, Trans.). Chicago: Chicago University Press. (Original work published in 1632).

Galton, F. (1880a). Mental imagery. *Fortnightly Review, 28*, 312–324.

Galton, F. (1880b). Statistics of mental imagery. *Mind, 5*(19), 301–318.

Garmendia, M., Guisasola, J., & Sierra, E. (2007). First-year engineering students' difficulties in visualization and drawing tasks. *European Journal of Engineering Education, 32*(3), 315–323.

Gershon, N. (1994). From perception to visualization. In L. Rosenblum, R. A. Earnshaw, J. Encarnacao, H. Hagen, A. Kaufman, S. Klimenko, et al. (Eds.), *Scientifi visualization: Advances and challenges* (pp. 129–142). London: Academic Press.

Giere, R. N. (1996). Visual models and scientific judgment. In B. S. Baigrie (Ed.), *Picturing knowledge: Historical and philosophical problems concerning the use of art in science* (pp. 269–302). Toronto, ON: University of Toronto Press.

Gilbert, W. (1600). *De magnete*. London: Chiswick Press.

Gilbert, J. K. (2005). Visualization: A metacognitive skill in science and science education. In J. K. Gilbert (Ed.), *Visualization in science education*. Netherlands: Springer.

Gilbert, J. K., Reiner, M., & Nakhleh, M. (Eds.). (2008). *Visualization: Theory and practice in science education*. Netherlands: Springer.

Gill, C. D., Klecan-Aker, J., Roberts, T., & Fredenburg, K. A. (2003). Following directions: Rehearsal and visualization strategies for children with specific language impairment. *Child Language Teaching & Therapy, 19*(1), 85–101.

Gillham, N. W. (2001). *A life of Sir Francis Galton*. New York: Oxford University Press.

Gilmartin, P. P. (1982). The instructional efficacy of maps in geographic text. *Journal of Geography, 81*(4), 145–150.

Gooding, D. C. (2004). Cognition, construction and culture: Visual theories in the sciences. *Journal of Cognition and Culture, 4*(3–4), 552–593.

Gregory, R. L. (1970). *The intelligent eye*. New York: McGraw-Hill.

Griffin, M., & Schwartz, D. (2005). Visual communication skills and media literacy. In J. Flood, S. B. Heath, & D. Lapp (Eds.), *Handbook of research on teaching literacy through the communicative and visual arts* (pp. 40–47). Mahwah, NJ: Lawrence Erlbaum.

Guttmann, J., Levin, J. R., & Pressley, M. (1977). Pictures, partial pictures, and young children's oral prose learning. *Journal of Educational Psychology, 69*(5), 473–480.

Habre, S. (1999). Visualization enhanced by technology in the learning of multivariable calculus.*International Journal of Computer Algebra in Mathematics Education, 8*(2), 115–130.

Hagen, H., Nielson, G. M., & Post, F. (2000). Preface. In H. Hagen, G. M. Nielson, & F. Post (Eds.), *Scientific visualization.* Los Alamitos, CA: IEEE Computer Society.

Hall, K. W., & Obregon, R. (2002). Applications and tools for design and visualization. *Technology Teacher, 61*(7), 7–11.

Haring, M. J., & Fry, M. A. (1979). Effect of pictures on children's comprehension of written text. *Educational Communication and Technology Journal, 27*(3), 185–190.

Healy, L., & Hoyles, C. (1999). Visual and symbolic reasoning in mathematics: Making connections with computers? *Mathematical Thinking and Learning, 1*(1), 59–84.

Hershkowitz, R. (1989). Visualization in geometry—two sides of the coin. *Focus on Learning Problems in Mathematics, 11*(1), 61–76.

Hertzog, C., & Dunlosky, J. (2006). Using visual imagery as a mnemonic for verbal associative learning: Developmental and individual differences. In T. Vecchi & G. Bottini (Eds.), *Imagery and spatialcognition: Methods, models and cognitive* assessment (pp. 259–280). Philadelphia: John Benjamins.

Holzinger, A., Kickmeier-Rust, M., & Albert, D. (2008). Dynamic media in computer science education; content complexity and learning performance: Is less more? *Educational Technology and Society, 11*(1), 279–290.

Hortin, J. A. (1982). A need for a theory of visual literacy. *Reading Improvement, 19*(4), 257–267.

Huk, T. (2006). Who benefits from learning with 3D models? The case of spatial ability. *Journal of Computer Assisted Learning, 22*, 392–404.

Jacob, P., & Jeannerod, M. (2003). *Ways of seeing: The scope and limits of visual cognition.* Oxford: Oxford University Press.

Jankun-Kelly, T. J., Ma, K. L., & Gertz, M. (2007). A model and framework for visualization exploration. *IEEE Transactions on Visualization and Computer Graphics, 13*(2), 357–369.

Johnson-Glenberg, M. C. (2007). Web-based reading comprehension instruction: Three studies of 3D-Readers. In D. S. McNamara (Ed.), *Reading comprehension strategies: Theories, interventions, and technologies*. New York: Lawrence Erlbaum.

Johnson-Laird, P. N. (1998). Imagery, visualization, and thinking. In J. Hochberg (Ed.), *Perception and cognition at century's end* (pp. 441–467). New York: Academic Press.

Johnstone, A. H. (1997). Chemistry teaching: Science or alchemy? *Journal of Chemical Education, 74*(3), 262–268.

Jones, L. L., & Smith, S. G. (1992). Can multimedia instruction meet our expectations? *EDUCOM Review, 27*(1), 39–43.

Ju, Y. C., & Cifuentes, L. (2002). Children learning from artfully designed, three dimensional computer animation. *Information Technology in Childhood Education Annual, 14*, 45–60.

Kaput, J. (1999). Representations, inscriptions, descriptions and learning: A kaleidoscope of windows. *Journal of Mathematical Behavior, 17*(2), 265–281.

Kemp, M. (1996). Temples of the body and temples of the cosmos: Vision and visualization in the Vesalian and Copernical revolutions. In B. S. Baigrie (Ed.), *Picturing knowledge: Historical and philosophical problems concerning the use of art in science* (pp. 40–85). Toronto, ON: University of Toronto Press.

Klimenko, S. V., Nititin, I. N., & Burkin, V. V. (2000). Visualization of complex physical phenomena and mathematical objects in virtual environment. In H. Hagen, G. M. Nielson, & F. Post (Eds.), *Scientific visualization* (pp. 159–168). Los Alamitos, CA: IEEE Computer Society.

Korakakis, G., Pavlatou, E. A., Palyvos, J. A., & Spyrellis, N. (2009). 3D visualization types in multimedia applications for science learning: A case study for 8th grade students in Greece. *Computers and Education, 52*, 390–401.

Kozma, R. B., Chin, E., Russell, J., & Marx, N. (2000). The roles of representations and tools in the chemistry laboratory and their implications for chemistry instruction. *Journal of the learning sciences, 9*(2), 105–143.

Kraidy, U. (2002). Digital media and education: Cognitive impact of information visualization. *Journal of Educational Media, 2*(3), 95–106.

Krutetskii, V. A. (1976). *The psychology of mathematical abilities in schoolchildren.* Chicago, IL: University of Chicago Press.

Kulhavy, R. W., Stock, W. A., Peterson, S. E., Pridemore, D. R., & Klein, J. D. (1992). Using maps to retrieve text: A test of conjoint retention. *Contemporary Educational Psychology, 17*(1), 56–70.

Kwinn, A. (1997). High fidelity images—how they affect learning. *Journal of interactive instruction development, 10*(2), 12–16.

Lanzing, J. W. A., & Stanchev, I. (1994). Visual aspects of courseware engineering. *Journal of Computer Assisted Learning, 10*, 69–80.

Larkin, J. H., & Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science, 11*, 65–99.

Latour, B. (1990). Drawing things together. In M. Lynch & S. Woolgar (Eds.), *Representation in scientific practice* (pp. 19–68). Cambridge, MA:MIT Press.

LaViola, J. J., Jr. (2007). Advances in mathematical sketching: Moving toward the paradigm's full potential. *IEEE Computer Graphics and Applications, 27*(1), 38–48.

Lee, H., Plass, J. L., & Homer, B. D. (2006). Optimizing cognitive load for learning from computer-based science simulations. *Journal of Educational Psychology, 98*(4), 902–913.

Levie, W. L., & Lentz, R. (1982). Effects of text illustrations: A review of research. *Educational Communication and Technology, 30*(4), 195–232.

Levin, J. R., Anglin, G. J., & Carney, R. N. (1987). On empirically validating functions of pictures in prose. *Psychology of Illustration, 1*, 51–85.

Limniou, M., Roberts, D., & Papadopoulos, N. (2008). Full immersive virtual CAVE$^{\text{TM}}$ in chemistry education. *Computers and Education, 51*, 584–593.

Lin, H., & Chen, T. (2007). Reading authentic EFL text using visualization and advance organizers in a multimedia learning environment. *Language Learning and Technology, 11*(3), 83–106.

Linn, M. C. (2003). Technology and science education: Starting points, research programs, and trends. *International Journal of Science Education, 25*(6), 727–758.

Liu, B., Salvendy, G., & Kuczek, T. (1999). The role of visualization in understanding abstract concepts. *International Journal of Cognitive Ergonomics, 3*(4), 289–305.

Lodha, S. K., & Franke, R. (2000). Scattered techniques for surfaces. In H. Hagen, G. M. Nielson, & F. Post (Eds.), *Scientific visualization* (pp. 189–230). Los Alamitos, CA: IEEE Computer Society.

Lurie, N. H., & Mason, C. H. (2007). Visual representation: Implications for decision making. *Journal of Marketing, 71*, 160–177.

Massironi, M. (2002). *The psychology of graphic images: Seeing, drawing, communicating.* Mahwah, NJ: Lawrence Erlbaum.

Mathai, S., & Ramadas, J. (2009). Visuals and visualization of human body systems. *International Journal of Science Education, 31*(3), 439–458.

Mathewson, J. H. (1999). Visual-spatial thinking: An aspect of science overlooked by educators. *Science Education, 83*(1), 33–54.

Max, N. L., & Wyvill, G. (1991). Shapes and textures for rendering coral. In N. M. Patrikalikis (Ed.), *Scientific visualization of physical phenomena* (pp. 333–344). New York: Springer.

Maxwell, J. C. (1873). *A treatise on electricity and magnetism*. London: MacMillan.

Mayer, R. E. (1997). Multimedia learning: Are we asking the right questions? *Educational Psychologist, 32*(1), 1–19.

Mayer, R. E., & Anderson, R. B. (1991). Animations need narrations: An experimental test of a dual-coding hypothesis. *Journal of Educational Psychology, 83*(4), 484–490.

Mayer, R. E., & Simms, V. K. (1994). For whom is a picture worth a thousand words? Extensions of a dual-coding theory of multimedia learning. *Journal of Educational Psychology, 86*(3), 389–401.

Mayer, R. E., & Moreno, R. (2002). Animation as an aid to multimedia learning. *Educational Psychology Review, 14*(1), 87–99.

McCormick, B. H., DeFanti, T. A., & Brown, M. D. (1987). Visualization in scientific computing: A synopsis. *IEEE Computer Graphics and Application, 7*(7), 61–70.

McGee, M. (1979). Human spatial abilities: Psychometric studies and environmental, genetic, hormonial and neurological influences. *Psychological Bulletin, 86*, 889–918.

McGrath, M. B., & Brown, J. R. (2005). Visual learning for science and engineering. *IEEE Computer Society, 25*(5), 56–63.

Milheim, W. D. (1993). How to use animation in computer assisted learning. *British Journal of Educational Technology, 24*(3), 171–178.

Miller, A. I. (1986). *Imagery in scientific thought.* Cambridge, MA: MIT Press.

Miller, W. (1936). The picture choices of primary-grade children. *The Elementary School Journal, 37*, 273–282.

Mohler, J. L. (2000). Desktop virtual reality for the enhancement of visualization skills. *Journal of Educational Multimedia and Hypermedia, 9*(2), 151–165.

Nadel, L. (Ed.). (2003). *Encyclopedia of cognitive science.* New York: Nature Publishing Group.

Naka, T., Nishimura, F., Taguchi, F., & Nakase, Y. (1991). A new color conversion method for realistic light stimulation. In N. M. Patrikalikis (Ed.), *Scientific visualization of physical phenomena* (pp. 345–362). New York: Springer.

National Council of Teachers of Mathematics (NCTM). (2000). *Principles and standards for school mathematics*. Reston, VA: NCTM.

National Science Foundation (NSF). (2007). Special report—Visualization in scientific computing—A synopsis, 1987. *IEEE Computer Graphics and Applications, 7*(7), 61–70. Retrieved April 15, 2007, from http://ieeexplore.ieee.org.login.ezproxy.library.ualberta.ca/iel5/38/4057219/04057233.pdf

Nelson, D. W. (1983). Math is not a problem. . . when you know how to visualize it. *Instructor, 93*(4), 54–55.

Netz, R. (1998). Greek mathematical diagrams: Their use and their meaning. *For the Learning of Mathematics, 18*(3), 33–39.

Newton, I. (1687). *Philosphiæ naturalis principia mathematica.* London:Royal Society.

Newton, I. (1730). *Opticks* (4th ed.). London: William Innys.

Nielson, G. (1994). Research issues in modeling for the analysis and visualization of large sets. In L. Rosenblum, R. A. Earnshaw, J. Encarnacao, H. Hagen, A. Kaufman, S. Klimenko, et al. (Eds.), *Scientific visualization: Advances and challenges* (pp. 143–156). London: Academic Press.

Novak, M. (1994). Fractal geometry and its applications in visualization. In L. Rosenblum, R. A. Earnshaw, J. Encarnacao, H. Hagen, A. Kaufman, S. Klimenko, et al. (Eds.), *Scientific visualization: Advances and challenges* (pp. 323–348). London: Academic Press.

Özmen, H., Demircioğlu, H., & Demircioğlu, G. (2009). The effects of conceptual change texts accompanied with animations on overcoming 11th grade students' alternative conceptions of chemical bonding. *Computers and Education, 52*, 681–695.

Paivio, A. (1974). Language and knowledge of the world. *Educational Researcher, 3*(9), 5–12.

Paivio, A. (1986). *Mental representations: A dual codingapproach*. Oxford: Oxford University Press.

Palais, R. S. (1999). The visualization of mathematics: Towards a mathematical exploratorium. *Notices of the American Mathematical Society, 46*(6), 647–658.

Park, O. C., & Hopkins, R. (1993). Instructional conditions for using dynamic visual displays: A review. *Instructional Science, 21*(6), 427–449.

Peeck, J. (1974). Retention of pictorial and verbal content of a text with illustrations. *Journal of Educational Psychology, 66*(6), 880–888.

Peeck, J. (1993). Increasing picture effects in learning from illustrated text. *Learning and Instruction, 3*, 227–238.

Piburn, M. D., Reynolds, S. J., McAuliffe, C., Leedy, D. E., Birk, J. P., & Johnson, J. K. (2005). The role of visualization in learning from computer-based images. *International Journal of Science Education, 27*(5), 513–527.

Pinker, S. (1997). *How the mind works*. New York: W. W. Norton.

Presmeg, N. C. (1986). Visualisation and mathematical giftedness. *Educational Studies in Mathematics, 17*(3), 297–311.

Presmeg, N. C. (1989). Visualization in multicultural classroom. *Focus on Learning Problems in Mathematics, 11*(1), 17–24.

Presmeg, N. C. (1999). On visualization and generalization in mathematics. In F. Hitt & M. Santos (Eds.), Proceedings of the Annual Meeting of the North American Chapter of the International Group for the Psychology of Mathematics Education (21st, Cuernavaca, Morelos, Mexico, October 23–26, 1999, Vol. 1, pp. 23–27).

Presmeg, N., & Balderas-Canas, P. E. (2001). Visualization and affect in nonroutine problem solving. *Mathematical Thinking and Learning, 3*(4), 289–313.

Pylyshyn, Z. W. (2003). *Seeing and visualizing: It's not what you think.* Cambridge, MA: MIT Press.

Readence, J. E., & Moore, D. W. (1981). A meta-analytic review of the effect of adjunct pictures on comprehension. *Psychology in the Schools, 18*, 218–224.

Reid, D. J., Briggs, N., & Beveridge, M. (1983). The effect of picture upon the readability of a school science topic. *British Journal of Educational Psychology, 53*, 327–335.

Reis, A., Faísca, L., Ingvar, M., & Petersson, K. M. (2006). Color makes a difference: Two-dimensional object naming in literate and subjects. *Brain and Cognition, 60*, 49–54.

Reisberg, D. (2006). *Cognition: Exploring the science of the mind* (3rd ed.). New York: W.W. Norton.

Reisberg, D., & Heuer, F. (2005). Visuospatial images. In P. Shah & A. Miyake (Eds.), *The Cambridge handbook of visuospatial thinking* (pp. 35–80). New York: Cambridge University Press.

Reisberg, D., & Leak, S. (1987). Visual imagery and memory for appearance: Does Clarke Gable or George C. Scott have bushier eyebrows? *Canadian Journal of Psychology, 41*(4), 521–526.

Richardson, A. (1994). *Individual differences in imaging: Their measurement, origins, and consequences.* Amityville, NY: Baywood.

Rieber, L. P. (1990a). Animation in computer-based instruction. *Educational Technology Research and Development, 38*(1), 77–86.

Rieber, L. P. (1990b). Using computer animated graphics in science instruction with children. *Journal of Educational Psychology, 82*(1), 135–140.

Rieber, L. P. (1991). Animation, incidental learning, and continuing motivation. *Journal of Educational Psychology, 82*, 135–140.

Rieber, L. P. (1995). A historical review of visualization in human cognition. *Educational technology research and development, 43*(1), 45–56.

Rivera, F. (2007). Visualizing as a mathematical way of knowing: Understanding figural generalization. *Mathematics Teacher, 101*(1), 69–75.

Rosenbaum, L., Earnshaw, R. A., Encarnacao, J., Hagen, H., Kaufman, A., Klimenko, S., et al. (1994). *Scientific visualization: Advances and challenges*. London: Academic Press.

Ruch, M. D., & Levin, J. R. (1979). Partial picture as imagery-retrieval cues in young children's prose recall. *Journal of Experimental Child Psychology, 28*, 268–279.

Rudisill, M. (1952). Children's preferences for color versus other qualities in illustrations. *The Elementary School Journal, 52*(8), 444–451.

Rutherford, E. (1911). The scattering of α and β particles by matter and the structure of the atom. *Philosophy Magazine, 21*, 669–688.

Ryu, H., Chong, Y., & Song, S. (2007). Mathematically gifted students' spatial visualization ability of solid figures. In J. H. Woo, H. C. Lew, K. S. Park, & D. Y. Seo (Eds.), *Proceedings of the 31st Conference of the International Group for the Psychology of Mathematics Education, 4*, 137–144.

Ruse, M. (1996). Are pictures really necessary? The case of Sewell Wright's 'Adaptive Landscapes'. In B. S. Baigrie (Ed.), *Picturing knowledge: Historical and philosophical problems concerning the use of art in science* (pp. 303–337). Toronto, ON: University of Toronto Press.

Sadoski, M., & Paivio, A. (2001). *Imagery and text: A dual coding theory of reading and writing.*Mahwah, NJ: Lawrence Erlbaum.

Samuels, S. J., Biesbrock, E., & Terry, P. R. (1974). The effect of pictures on children's attitudes toward presented stories. *The Journal of Educational Research, 67*(6), 243–246.

Sanger, M. J., Brecheisen, D. M., & Hynek, B. M. (2001). Can computer animations affect college biology students' conceptions about diffusion & osmosis? *American Biology Teacher, 63*(2), 104–109.

Saraiya, P. North, C., Lam, V., & Duca, K. A. (2006). An insight-based longitudinal study of visual analytics. *IEEE Transactions on Visualization and Computer Graphics, 12*(6), 1511–1522.

Scaife, M., & Rogers, Y. (1996). External cognition: How do graphical representations work? *International Journal Human-Computer Studies, 45*(2), 185–213.

Schnotz, W. (2002). Towards an integrated view of learning from text and visual displays. *Educational Psychology Review, 14*(1), 101–120.

Schönborn, K. J., & Anderson, T. R. (2006). The importance of visual literacy in the education of biochemists. *Biochemistry and Molecular Biology Education, 34*(2), 94–102.

Sewell, E. H., Jr., & Moore, R. L. (1980). Cartoon embellishments in informative presentations. *Educational Communication and Technology Journal, 28*(1), 39–46.

Sharma, M. C. (1985). Visualization. *Math Notebook, 4*(5–6), 1–2.

Silén, C., Wirell, S., Kvist, J., Nylander, E., & Smedby, Ö. (2008). Advanced 3D visualization in student-centered medical education. *Medical Teacher, 30*(5), 115–124.

Simpson, J. A., & Weiner, E. S. C. (Eds.). (1991). *Oxford English dictionary* (2nd ed.). Oxford: Clarendon Press.

Stieff, M., & Wilensky, U. (2003). Connected chemistry —Incorporating interactive simulations into chemistry the classroom. *Journal of Science Education and Technology, 12*(3), 285–302.

Stokes, S. (2002). Visual literacy in teaching and learning: A literature perspective. *Electronic Journal for the Integration of Technology in Education, 1*(1), 10–19.

Strong, S., & Smith, R. (2001). Spatial visualization: Fundamentals and trends in graphics. *Journal of Industrial Technology, 18*(1), 2–6.

Subramaniam, K., & Padalkar, S. (2009). Visualisation and reasoning in explaining the phases of the moon. *International Journal of Science Education, 31*(3), 395–417.

Swetz, F. (1995). To know and to teach: Mathematical pedagogy from a historical context. *Educational Studies in Mathematics, 29*(1), 73–88.

Swetz, F., & Kao, T. I. (1977). *Was Pythagoras Chinese? An examination of right triangle theory in ancient China*. University Park, PA: Pennsylvania State University Press.

Szabo, M., DeMelo, H. T., & Dwyer, F. M. (1981). Visual testing—Visual literacy's second dimension. *Educational Communication and Technology Journal, 29*(3), 177–187.

Thomas, J. L. (1978). The influence of pictorial illustrations with written text and previous achievement on the reading comprehension of fourth grade science students. *Journal of Research in Science Teaching, 15*(5), 401–405.

Thompson, W. R., & Sagan, C. (1991). Computer visualization in spacecraft exploration. In N. M. Patrikalikis (Ed.), *Scientific visualization of physical phenomena* (pp. 37–44). New York: Springer.

Tomas, D. A., Johnson, K., & Stevenson, S. (1996). Integrated mathematics, science, and technology: An introduction to abstract. *Journal of Computers in Mathematics and Science Teaching, 15*(3), 267–294.

Tufte, E. R. (1983). *Visual display of quantitative information* Cheshire, CT: Graphics Press.

Tufte, E. R. (1990). *Envisioning information*. Cheshire, CT: Graphics Press.

Tversky, B. (2001). Spatial schemas in depictions. In M. Gattis (Ed.), *Spatial schemas and thought* (pp. 79–111). Cambridge, MA: MIT Press.

Tversky, B. (2005). Functional significance of visuospatial representations. In P. Shah & A. Miyake (Eds.), *The Cambridge handbook of visuospatial thinking* (pp. 1–34). New York: Cambridge University Press.

van der Waerden, B. L. (1983). *Geometry and algebra in ancient civilizations*. New York: Springer.

van Garderen, D. (2006). Spatial visualization, visual imagery, and mathematical problem solving of students with varying abilities. *Journal of Learning Disabilities, 39*(6), 496–506.

Vekiri, I. (2002). What is the value of graphical displays in learning? *Educational Psychology Review, 14*(3), 261–312.

Visualization (2007). In Merriam-webster Online Dictionary. Retrieved March 7, 2007, from http://www.merriam-webster.com/dictionary/visualization

Waddill, P. J., McDaniel, M. A., & Einstein, G. O. (1988). Illustrations as adjuncts to prose: A text-appropriate processing approach. *Journal of Educational Psychology, 80*(4), 457–464.

Wang, H., Chang, C., & Li, T. (2007). The comparative efficacy of 2D- versus 3D-based media design for influencing spatial visualization skills. *Computers in Human Behavior, 23*, 1943–1957.

What is Visualization? (n.d.). *Information Visualization Resources*. Retrieved July 14, 2008, from http://www.infovis.org/

Wilder, A., & Brinkerhoff, J. (2007). Supporting representational competence in high school biology with computer-based biomolecular visualizations. *The Journal of Computers in Mathematics and Science Teaching, 26*(1), 5–26.

Willingham, D. T. (2006/2007, Winter). How we learn. Ask the cognitive scientist: The usefulness of brief instruction in reading comprehension strategies. *American Educator,* 39–50.

Willingham, D. T. (2007). *Cognition: The thinking animal* (3rd, ed.). Upper Saddle River, NJ: Pearson Education.

Winn, W. (1988). Recall of the patterns, sequence, and names of concepts represented in instructional diagrams. *Journal of Research in Science Teaching, 25*(5), 375–386.

Winn, W. D., & Holliday, W. G. (1981, April 6–10). *Learning from diagrams: Theoretical and instructional considerations*. Paper presented at the Annual Convention of the Association for Educational Communications and Technology, Philadelphia.

Winn, W., Li, T., & Schill, D. (1991). Diagrams as aids to problem solving: Their role in facilitating search and computation. *Educational Technology Research & Development, 39*(1), 17–29.

Wu, H., & Shah, P. (2004). Exploring visuospatial thinking in learning. *Science Education, 88*(3), 465–492.

Wu, H. K., Krajcik, J. S., & Soloway, E. (2001). Promoting understanding of chemical representations: Students' use of a visualization tool in the classroom. *Journal of Research in Teaching, 38*(7), 821–842.

Yang, E., Andre, T., & Greenbowe, T. J. (2003). Spatial ability and the impact of visualization/animation on learning electrochemistry. *International Journal of Science Education, 25*(3), 329–349.

Yarden, H., & Yarden, A. (2009). Learning using dynamic and static visualizations: Students' comprehension, prior knowledge and conceptual status of a biotechnological method. *Research in Science Education*. Retrieved July 27, 2009, from http://www.springerlink.com/content/55682t6748672316/?p=6e318e9176d64731a0f3d456eb4eb5e0&pi=6

Zaraycki, P. (2004). From visualizing to proving. *Teaching mathematics and its applications, 23*(3), 108–118.

Zazkis, R., Dubinsky, E., & Dautermann, J. (1996). Coordinating visual and analytic strategies: A study of students' of the group D4. *Journal for Research in Mathematics Education, 27*(4), 435–457.

Zettl, H. (1990). *Sight sound motion: Applied media aesthetics*. Belmont, CA: Wadsworth.

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