BOOK REVIEW

Visualization in Science Education

John K. Gilbert (Ed.), 2007

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Visualization is an area that has fascinated scientists and science educators alike yet, it has proved problematic for research and study (Mathewson, 1999). It is only in the last ten years that science educators have had some success in understanding and tackling the questions related to visualization and its role in learning. Research in this area has been eclectic in nature, often spurred by the entry of new visualization technologies into the classroom, and drawing on theoretical frameworks and analytical tools developed by cognitive scientists as well as historians of science and science educators. The studies have so far remained scattered over a range of disciplines and several interdisciplinary journals and books. The present volume does an exemplary service in bringing together the research in this new and emerging field, placing it firmly on the radar of science educationists.

In science education the closely related area of models and modelling has been of interest for some time now. The book 'Visualization in Science Education' is in fact the first in a series of volumes on 'Models and Modelling in Science Education' edited by John Gilbert and published by Springer. Several articles in this volume examine in detail the relationship between "models" and "visualization" in science education.

The book is organised into four sections that recall a classic sequence in education: "The significance of visualization in science education", "Developing the skills of visualization", "Integrating visualization into curricula in the sciences", and "Assessing the development of visualization skills". John Gilbert's introductory chapter brings out the relationship between models, both "in the world" and "in the mind", and visualizations, which too could be both external and internal. Gilbert sees visualization as a metacognitive skill, involving the monitoring and control of an image being learnt, knowing how to rehearse and retain it in memory, retrieving the appropriate image when necessary and finally, amending and transforming the image according to the reasoning demanded by the task at hand. This chapter gives several examples to bring out the role of visualization in student learning and in classroom practice.

Chapter 2 by Barbara Tversky looks at the many ways in which external depictions convey information. Tversky is a psychologist who has researched visualization in relatively complex domains. She therefore easily moves beyond the common psychological paradigm of visuals as percepts, to consider visuals that could be related with mental models. Her examples are drawn from route maps, mechanical diagrams and animations used in education. Tversky suggests some cognitive design principles for effective visualizations, both static diagrams and animations.

In Chapter 3 David Rapp draws on work in cognitive and educational psychology to outline the characteristics of mental models. He looks at the evidence for mental models coming from the domains of text comprehension, logical reasoning, and understanding of mechanical systems. Rapp then goes on to examine some qualities of educational situations that influence learning with mental models. Identifying "cognitive engagement" and "interactivity" as two supporting factors, Rapp points out the mixed evidence for effectiveness of "multimedia learning". Thus visualizations, used here in the sense of "novel visual presentations of data", are shown to be not consistently helpful in learning, or in building mental models.

In Chapter 4 Michael Briggs and George Bodner use a phenomenographic approach to propose a theoretical model of molecular visualization. Drawing on data from an exploratory study with college undergraduates the authors describe the role of visualization in understanding molecular structures, arguing that this process leads to the construction of a mental model. Briggs and Bodner see visualization as an operation that brings about a one-to-one correspondence between a mental representation and its referent, serving therefore as the dynamic component of model-based reasoning.

Chapter 5 by Janice Gobert focuses on external visualizations and their role in supporting learning. Gobert reviews the literature on the processing of textual and graphic information in both static and dynamic form, finding that experts' use of visualizations is highly sensitive to domain and task contexts. Although Gobert holds that mental visualizations are not tractable to empirical research, she does use the framework of model-based teaching and learning to examine students' mental models as they work in a technology-supported environment. She describes two projects developed to enhance students' model-based reasoning: 'Making thinking visible' and 'Modeling across the curriculum'. 'Making Thinking Visible' used WISE, a web-based science learning environment which allowed students to access real-time data (related to plate tectonics) through the web and also interact with peers from geographically distinct locations. In 'Modeling across the curriculum', Pedagogica TM was used to track students' interactions with models (from genetics, classical mechanics and chemistry) and to get an index of their reasoning and modelling skills. Students' domain knowledge as well as their understanding of the nature of modelling was found to be enhanced.

Section B, consisting of four chapters, is concerned with ways of developing the skills of visualization. Chapter 6 by Mike Steiff, Robert Bateman and David Uttal critically examines the role of computer-based visualisation tools in the science classroom. The authors review both content-specific tools and general modelling environments. They note that research in the effectiveness of these tools has suffered from limitations of design and occasional mixed results, while both research and development of visualization strategies have lacked a clear theoretical perspective on why the particular tools are likely or unlikely to help learning. Steiff et al. offer some cognitively grounded principles for the design of effective visualization tools in chemistry, investigation of their role and efficacy, and development of suitable pedagogies for their use. Visualization tools should support spatial cognition by helping students comprehend spatial relationships as well as manipulate molecules to solve a given problem.

In Chapter 7 Robert Kozma and Joel Russell review the research related to developing representational competence in students of chemistry. They consider the chemical curriculum in terms of two important goals: students' acquisition of chemical concepts and principles, and their participation in the investigative practices of chemistry -- "students becoming chemists". These goals pertain to cognitive or learning theory and to situative theory respectively. Beginning with the latter, the authors look at the everyday practices of chemists during scientific investigations and compare them with those of students, showing that competence in using visual representations is a feature distinguishing the two practices. They then review the literature on learning theories applied to multimedia learning and consider their implications for investigative work, particularly in defining representational practices in chemistry. The chapter concludes with an extensive review of research pertaining to chemical visualization technologies of two major kinds: molecular modelling, and computer simulations and animations of dynamic chemical processes.

Chapter 8, by Galit Botzer and Miriam Reiner, recalls the practice of physics in history, focusing on the specific case of electromagnetic theory. Mental models and visual imagery are believed to have played a major role in the work of Galileo, Newton, Faraday, Maxwell and Einstein. Botzer and Reiner begin with a scheme of classification derived by Arthur Miller from the history of physics, in which modes of representation are seen as sensory-based, pure imaginary or formalism-based. They look at case studies of ninth grade students collaboratively exploring magnetic phenomena and find that the historically derived classification works well with students -- when nuanced with cognitive considerations like projections of former experiences to explain a new situation, and transformations of mental images. Implications for physics learning are suggested in terms of conceptual understanding, communication and tools for research and evaluation.

In Chapter 9 John Clement, Aletta Zietsman and James Monaghan take on the challenge of studying mental imagery in science learning. They review three prior studies in elementary mechanics with the aim to develop observable indicators for the presence of imagery, using these to support their ideas of how imagery is used in understanding and problem-solving by students and experts. Their first study uses extreme cases as facilitators for construction of visualizable models of the action of levers, the second looks at imagery and simulations used by expert scientists (though only a single episode is discussed here) while the third study uses a computer simulation to develop mental simulations of relative motion. The authors note video sequences involving accounts or projections of human actions (consistent with kinesthetic imagery), depictive hand or pencil motions and static or dynamic imagery reports occurring during problem solving. They interpret their results in terms of flexible perceptual motor schemas that generate and run imagistic simulations of moving objects.

Section C is concerned with the problem of integrating visualization into science curricula. The three chapters in the section are in the area of electromagnetism, genomics and geology, all at the undergraduate level. Chapter 10, by Judy Dori and John Belcher, describes an undergraduate teaching program in electromagnetism. Dori and Belcher review some literature on visualization in science learning, focusing then on studies of simulations, Microcomputer-Based Laboratory (MBL) and real-time graphing in physics. They describe the Technology-Enabled Active Learning (TEAL) Project at MIT, which uses both passive and interactive visualizations of physical phenomena that are normally invisible, along with textual explanations and real desk-top experiments, within an active learning environment. They present the quantitative learning outcomes of the project and give examples of classroom discourse using the various types of visualizations.

Chapter 11 by Kathy Takayama is about visualization in genomics. Takayama describes the novel challenges and opportunities involved in the field of genomics and shows how visualization is inherent in every step in the process of scientific inquiry. She considers examples from the teaching of genomics, within comparative genomics involving the analysis of sequences and 3-d protein structures, and functional genomics, calling for analysis of gene expression using microarrays. Genomics research is dependent upon visual comparative analysis of voluminous complex information, a kind of processing typically carried out by machines, but requiring visual literacy on the part of researchers. Takayama describes an international online research project: "Visualizing the Science of Genomics" in which teams of students from diverse backgrounds, ranging from microbiology and medical chemistry to mathematics and computer science, worked collaboratively to formulate models based on genomic sequence data from HIV-1, in a context of case studies based on actual data. Modeling and manipulation of 3-d protein structures was done using the open source web-based "Protein Explorer". Takayama describes the modes of interaction within and between teams and with their instructor using a variety of tools and taxonomies.

Chapter 12 by Stephen Reynolds, Julia Johnson, Michael Piburn, Debra Leedy, Joshua Coyan and Melanie Busch is concerned with visualization in undergraduate geology. The unique problems in visualizing geological structure and events lend themselves to the development of computer-based representations. Geological events occur over a large range of space and time scales. Challenges include learning to visualize 3-d topography from 2-d maps, inferring 3-d geometries from limited exposed structures and imagining a history of events recorded in spatial layers of rock. The authors describe the different types of visualization abilities required in undergraduate geology courses and the interactive animations (Quick Time Virtual Reality movies) which they created and embedded into web-based modules or used individually. Animations were either of "panorama" type which could be scanned to obtain a 360 degree view, or "object" type where the object of interest could be rotated or cut to change perspective or displaced or eroded to simulate a geologic event. Students followed the virtual exercises with field-based studies. The results of classroom studies are described in brief and the chapter concludes with a description of a newer and more sophisticated visualization software called GeoWall.

Having acknowledged the importance of visualization for concept learning and given the introduction of ever more sophisticated visualization tools into the science classroom it follows that one needs to develop new tools for the assessment of visualization skills. Section D consists of two chapters concerned with assessing the effectiveness of molecular structural representations in chemistry. Chapter 13, by Vesna Ferk Savec, Margareta Vrtacnik and John Gilbert, investigates the use of different types of representations of molecular structure: concrete 3-d models, static computer models and standard stereo-chemical formulae. The study pays careful attention to design, considering tasks that involve simple perception or rotation and reflection of the molecules as well as combinations of these, to assess mental visualization using different molecular representations. The authors go on to examine the effectiveness during problem-solving of "help tools" in the form of concrete or virtual 3-d representations. Overall the results show that static computer images helped visualization more than did standard stereochemical formulae while concrete 3-d models had an edge over virtual models in terms of students' preferences (not performance), but successive use of the two actually hindered problem-solving.

In Chapter 14 Joel Russell and Robert Kozma take off from Chapter 7, in which they reviewed literature on developing representational competence in chemistry particularly through multimedia tools. In this chapter Russell and Kozma assess the design and effectiveness of five multimedia chemical visualization softwares -- SMV:Chem, Connected Chemistry, Molecular Workbench, ChemSense and Chem Discovery. All five projects have been found to enhance the learning of chemistry concepts and development of scientific investigative process skills, by developing the social processes of investigations in either a laboratory or a virtual setting; or by improving visualization process skills. Multimedia testing items were used for the evaluation which addressed conceptual and process skills. The authors apply the levels of representational competence discussed in Chapter 7 to show changes in the visualization abilities of students. They end with suggestions for future development of visualization software and instructional material.

In an end piece to the volume, John Gilbert makes several recommendations for research and development on visualization in science education. He points out that much of the recent work on visualizations has consisted of the development and implementation of external visualizations particularly those based on computers, especially at the University level. He calls for a tighter coupling between research and development in this field, as well as the use of qualitative and interpretative methods of research. He closes appropriately with a list of open questions for further research.

In sum this is a remarkable collection of papers on visualization in science education, a "first" in the field. Many of the chapters are strong on reviews and so useful for a beginning researcher. The chapters illustrate a range of methodologies and theoretical positions, though there might be some unevenness in terms of thoroughness and insights offered. Some papers have minor formatting problems like uneven size of bullets and other oversights in proofreading which should be corrected in further reprints and hopefully in a paperback edition. For this book deserves to be read. We venture to predict that "Visualization in Science Education" signals the birth of a new area of research in science education.

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