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Editors

MODELS AND MODELING IN SCIENCE EDUCATION

Visualization: Theory and Practice in Science Education

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VISUALIZATION: THEORY AND PRACTICE IN SCIENCE EDUCATION

Models and Modeling in Science Education

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Introduction

John K. Gilbert, Miriam Reiner and Mary Nakhleh

Interest in the educational value of material objects, pictures, diagrams, tables, graphs and the like, in science education has increased greatly in recent years (Gilbert, 2005). This has been facilitated to a large extent by the exponential rise in the memory capacity of personal computers and to the associated investment made in software development, which have combined to enable major innovations in instructional techniques to take place. For any educational innovation to succeed – to be widely adopted and persistently practiced – three associated aspects of any pedagogic innovation have to be initially addressed. Practical, user-friendly, examples of the innovation must be developed, tried out in classrooms, and their use evaluated. The contribution of the innovation to the curriculum must be explored – an identification of where the innovation may be used either to improve existing educational practice or to provide new forms of instruction. Why an innovation is successful – why it makes a worthwhile contribution to learning – must be established. These three aspects are inter-related and should be mutually reinforcing. The biggest issue of all – the provision of widespread and effective opportunities for teacher 'continuing professional development' in respect of the innovation – must be addressed from the outset.

The problem in many such cases, and certainly the case here, is that each one of these aspects is taken as a focus for work by a different academic community. The development of practical examples of such innovations is undertaken by the science community, often primarily interested in their use within scientific research and perhaps secondarily in their use in the training of future scientists. The curricular contribution of these innovations and opportunities for continuing professional development receives the attention of the science education community. The nature of their contribution to learning is seen as the province of the cognitive science community. The success of this type of innovation is hindered because these communities are not in any systematic direct contact with each other. We believe that one of the strengths of this book is that it brings together a collection of papers that contain the theoretical perspectives, understandings, and frameworks of several of

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these communities. We hope that this book can serve as the beginnings of a bridge between these diverse communities.

However, a lack of communication means that the drawing together of the contributions to the field by authors from diverse academic backgrounds will be hindered by their use of different specialist terminologies. Key words may be used in different ways, yet a commonality of meaning must be established if insights are to synthesised and new perspectives opened up. There are two generic systems in use in this area of innovation. In Convention 1, a representation is the depiction of anything; an external representation is one that has been placed in the public realm, in either a material object, visual, verbal, or symbolic form; an internal representation is one that is constructed mentally by an individual; a visualization is the understanding of, the meaning attributed to, an internal representation. In Convention 2, a visualisation is a representation that has been placed in the public realm in either material object, visual, verbal, or symbolic form; the mental representation produced by an individual from a visualization is an image. The difference between the two Conventions lies in the meaning of the word visualization: in Convention 1 it is a verb (to visualize something is to mentally act on it); in Convention 2 it is a noun (a visualization is something that is in the public realm). There are, inevitably, phrases that cut across the two conventions: 'visual representation', 'visuo-spatial thinking', 'representational insights'.

We have brought together the chapters of this book to promote the formation of links between those concerned respectively with theory, curriculum place, and pedagogic practice. In writing for and editing for it, we have decided to adopt Convention 1, for we wish to place the emphasis on the nature of the mental actions undertaken by individuals in using representations. Some of the contributing authors have adopted Convention 2. In order to avoid confusing the reader, where the word visualization is used in the Convention 2 sense, we have entered it as 'visualization', leaving the use of the word without parenthesis to be the meaning in Convention 1.

The book is divided into three Sections, dealing respectively with the first three aspects of innovation in respect of external representation, internal representation, and visualization.

Reference

Gilbert, J. K. (Ed.). (2005). *Visualization in science education*. Dordrecht: Springer.

Chapter 1
Visualization: An Emergent Field of Practice and Enquiry in Science Education

John K. Gilbert

Abstract Modelling as an element in scientific methodology and models as the outcome of modelling are both important aspects of the conduct of science and hence of science education. The chapter is concerned with the challenges that students face in understanding the three 'levels' at which models can be represented – 'macro', 'sub-micro', 'symbolic' – and the relationships between them. A model can, at a given level, be expressed in 'external representations' – those versions physically available to others – and in 'internal representations' – those versions available mentally to an individual person. The making of meaning for any such representation is 'visualization'. It is of such importance in science and hence in science education that the acquisition of fluency in visualization is highly desirable and may be called 'metavisual capability' or 'metavisualization'. Criteria for the attainment of metavisualization are proposed. Two approaches to the ontological categorization of representations are put forward, one based on the purpose which the representation is intended to serve, the other based on the dimensionality – 1D, 2D, 3D – of the representation. For the latter scheme, the requirements for metavisualization are discussed in some detail in terms of its components. General approaches to the development of metavisualization are outlined. Multi-disciplinary teams are needed if the research and development needed to improve visualization in science education is to take place.

Representation and Visualization in Science

In a nightmare world, we would perceive the world around us as being continuous and without structure. However, our survival as a species has been possible because we have evolved the ability to 'cut up' that world mentally into chunks about which we can think and hence give meaning to. This process of chunking, a part of all cognition, is modelling and the products of the mental actions that have taken place are models. Science, being concerned with the provision of explanations about the natural world, places an especial reliance on the generation and testing of models.

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The models produced by science are expressed in three distinct *representational levels* (Johnstone, 1993) (Gabel, 1999). These are:

- The macroscopic level. This consists of what is seen in that which is studied. Simple examples in the formal science curriculum are: a solution of a pure chemical, a puck moving on an air-track, a cross-section of a leaf. These are all a representation in which some aspects of a natural phenomenon have been abstracted or detached from the whole for the purposes of study. Thus: a pure chemical was historically separated from the complex mixture in which it naturally occurs; a puck is an object that has been very largely liberated from the constraints of friction; a leaf is taken from a plant considered typical of a given family of plants. The macroscopic level is therefore a representation of a chunk of the world-as-experience that science is able to explore conveniently.
- The sub-microscopic level. This consists of representations of those entities that are inferred to underlie the macroscopic level, giving rise to the properties that it displays. Thus: molecules and ions are used to explain the properties of pure solutions; lubricants are used to explain the ready movement of an object; cells are used to explain the structure of a leaf.
- The symbolic level. This consists of any qualitative abstractions used to represent each item at the sub-microscopic level. These abstractions are used as 'shorthand' for the entities at the sub-microscopic level and are used to show quantitatively how many of each type of item are present at that level. Thus: chemical equations and the mathematical equations associated with the 'mole' concept are used jointly to represent a pure solution; mathematical equations are used alone to represent friction-free movement; while cells can be represented formally to indicate their type, position and number.

Being able to work within each of these levels and to mentally switch between them is a vital skill needed for the full appreciation of the explanations that science provides of natural phenomena. As we shall see, acquiring this skill presents challenges to many students. These types of work involve *visualization*, the making of meaning of representations. Visualization in 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 – see Chapter 4 on haptics) is the result of external representation. External and internal representations are linked in that their perception uses similar mental processes (Reisberg, 1997).

Visualisation is thus, in the first instance, concerned with the formation of an internal representation from an external representation such that the nature and temporal/spatial relationships between the entities of which it is composed are retained. The attainment of visualization in a particular case can be shown by the production, the expression, of a version of the original for a particular purpose. An internal representation must be capable of mental use in the making of predictions about the behaviour of a phenomenon under specific conditions. It is entirely possible that, once a series of internal representations have been visualized, that they are amalgamated / recombined to form a novel internal representation that is capable of external expression: this is creativity.

Visualization is of especial importance in three aspects of the learning of science. In:

- Learning specific consensus or historical models
  A model that is currently used by a community of scientists in cutting-edge enquiry can be called a *consensus* model. Contemporary examples are: the double-helix model of DNA, the P-N junction model of a transistor, the gene in biology. A model that once had consensus status but which, although superseded in cutting-edge research, still has explanatory value, is known as an *historical* model (Gilbert, Boulter, & Rutherford, 2000). Historical and consensus models, or those simplified versions that can be called *curriculum* models, are invaluable in science education. First, being the major products of science, 'learning science' must involve learning the nature and use of these. Second, because a particular model can be used to provide an acceptable explanation of a wide range of phenomena and specific facts, it is a useful way of reducing, by chunking, the ever-growing factual load of the science curriculum. Visualizing external representations of such models and being able to form internal representations of them are at the core of turning them into knowledge.
- Learning to develop new qualitative models
  A major task in the conduct of a scientific enquiry into a hitherto-unexplored phenomenon is the production of a model of it: the process of modelling. Given its importance, all students of science should learn the complex skills of modelling. It has been suggested that these skills can be developed by following the sequence of learning how: to use an established model; to revise an established model; to reconstruct an established model; to construct a model de novo (Justi & Gilbert, 2002). External and internal representation, together with the associated visualization, is needed at each of these stages.
- Learning to develop new quantitative models
  Once science has developed a useable qualitative model of a phenomenon, a quantitative version of it must be produced for a comprehensive representation to be available. Progress in the scientific enquiry into a field is indicated by the value of a particular combination of qualitative and quantitative models in making successful predictions about its properties. Again, visualization is central the production of representations of these models.

Metavisualization and Criteria for its Attainment

Representation – both external and internal – is ubiquitously employed across all aspects of life: the physical, social, and intellectual environment. The associated visualization can be called 'spatial thinking' (N.R.C., 2006) (p. 28). A fluent performance in visualization has been described as requiring *metavisualization* and involving the ability to acquire, monitor, integrate, and extend, learning from representations (Gilbert, 2005) (p. 15). Before criteria for the attainment of metavisualization can be put forward, the ontology of its subject matter, the representations, must be put discussed. Typologies can be based either on the purpose for which a representation is created or on the dimensionality of the product

The Purpose for which a Model is Produced

All models are produced by the use of analogy (Hesse, 1966): the *target* which is the subject of the model is depicted by a partial comparison with a *source*. The classification scheme of Harré (Harre, 1970) (pp. 34–61) is binary: either the target and the source are the same thing (they are *homomorphs)* or they are not (they are *paramorphs).* Homographs may be either *micro-* and *macro-morphs*, being respectively either smaller (e.g. of an aeroplane) or bigger (e.g. of a virus) than the target. They can also be *teleiomorphs*, being either idealisations of the target where, whilst all the characteristics of it are present, some of them are emphasised (e.g. a so-called 'fashion model') or an abstraction based on the target, where only some of the properties are represented (e.g. the use of coloured wire to represent the vascular system of animals). *Metromorphs* are based on a target which is a class of phenomena rather than an individual example of a phenomenon, average properties being represented (e.g. of a 'typical family'). The purpose in using a homomorph is to focus attention upon, to emphasise, only some aspects of the target. Paramorphs, on the other hand, are used to model processes rather than objects, the processes taking place being thought to be the *same* in the target and the source (e.g. modelling a human performance of an arithmetic calculation based on how a computer functions) or only *analogous* to it (e.g. the electronic simulation of hydraulic networks). Although this scheme will not be discussed further here, it does offer the possibility to relating the sources of models and/ or the ways of representing them to the purposes to which they are to be put.

The Dimensionality of the Representation

Because visualization depends on the perception and mental manipulation of objects in space, a system is suggested which depends on the number of physical dimensions of the representation. The idea that modelling involves the progressive reduction of the experienced world to a set of abstract signs (Bowen & Roth, 2005) (p. 1064) can be set out in terms of dimensions are follows:

(Three dimensions) *are simplified to* (Two dimensions) *are simplified to* (One dimension)

This enables us to position the levels of external representation roughly in terms of dimensions, as in Table 1.1:

Table 1.1 Types of representation for the triplets of dimensions and levels

	Three dimensional (3D)	Two dimensional (2D)	One dimensional (1D)
Macro level	Perception of the world-as-experienced	Perception of the world-as- experienced	
Sub-micro level	Gestures, concrete representations	Photographs, virtual representations, diagrams, graphs, data arrays	
Symbolic level			Symbols and equations

The first systematic encounter that students have with representations in 3D is through the laboratory practical work that is included in the science curricula of many countries. In the process of learning the scientific explanations at the sub-micro level for the phenomena encountered in that practical work, they often make gestures in 3D and use concrete (or material) representations e.g. the 'skeletal' 'ball-and-stick' and 'space filling' representations used in chemistry.

Students can initially encounter representations in 2D during their laboratory practical work e.g. a cross-section of a leaf or of a wave. However, the major sources of experience with 2D representations are through the use of photographs (whether directly of 3D phenomena or the products of scientific instrumentation e.g. spectrographs), virtual representations (those pseudo-3D representations produced on computer screens by the use of modeling software packages), diagrams of all types, graphs. Whilst photographs are often not considered as representations, this will be done here because they both frame the perception of the viewer and provide strong interpretational cues for their visualization. The genre of diagrams covers a wide range: data maps, time-series, space-time narratives, relational graphs (Tufte, 1983).Graphs include scatterplots , pie-charts, and Cartesian line graphs. The word 'array' is used to cover the range of forms of number display: tables and histograms.

1D representation is inherently an abstraction and consists of symbols. Some commonly encountered examples in science education are chemical symbols, chemical equations, and mathematical equations.

Criteria for Metavisualization

Three criteria are suggestion for the attainment of metavisual status. The person concerned must be able to:

1. demonstrate an understanding of the 'convention of representation' for all the modes and sub-modes of 3D, 2D, 1D representations. That is, what they can and cannot represent.
2. demonstrate a capacity to translate a given model between the modes and sub-modes in which it can be depicted.

3. demonstrate the capacity to be able to construct a representation within any mode and sub-mode of dimensionality for a given purpose.
4. demonstrate the ability to solve novel problems using a model-based approach. This can be done by the drawing of a suitable analogy to an already-solved problem (Polya, 1957) (p. 27), or either by providing a visual-recall cue and by removing irrelevant material from perception of the problem (Beveridge & Parkins, 1987) (p. 235).

Acquiring Meta Status for the Visualization of External Representations at the Macro-level

Many, if not most, science educators would *not* see the macro-level as being an 'external representation' that requires 'visualization'. Rather, they would see it as being the world-as-experienced *itself* i.e. as 'reality'. I would argue that this commonplace agreement is misguided. Whilst science certainly does seek to provide explanations of natural phenomena, the complexity of these requires that exemplars, whether relatively simple or artificially simplified versions of the world-as-experienced, are actually investigated. In short, science investigates idealised external representations of the everyday world.

In both science and science education, those external representations of the macro-level are the phenomena that are actually investigated in the laboratory, in field studies, or in simulations of both. As scientific enquiry into a particular field advances, the versions of the phenomena investigated become either ever closer to or ever more distant from the naturally occurring phenomena. However, science education rarely follows far down this path or, if does so, it does so slowly. It is vital that practical experience is included in science education, for there is ample evidence e.g. (Driver, Guesne, & Tiberghien, 1985) that students needs guidance as to what aspects of a phenomenon are to be the focus of a particular scientific study. Moreover, if transfer of learning from 'scientific' to 'everyday' contexts is sought, students must have structured experience of how to model macro-phenomena.

Such investigations are, in the formal science curriculum, collectively called 'practical work'. A summary of research findings about practical work, heavily based on that produced by Judith Bennett (Bennett, 2003) (p. 76), is as follows:

- practical work by students forms a significant part of the science curriculum in many countries;
- students generally report practical work to be enjoyable;
- practical work serves a wide variety of purposes;
- there is a lack of clarity over the purposes of much practical work;
- different types of practical work are needed to achieve different purposes;
- practical work makes phenomena real for students;
- practical work can help students gain some understanding of how science progresses;

- because of the ambiguity over purposes, practical work can sometimes hinder the development of an understanding of scientific ideas;
- the development of transferable skills through practical work is doubtful;
- students' performance in practical work depends on their understanding of the scientific ideas underlying it;
- some aspects of practical work are problematic for students, particularly the control of variables and judgment about data reliability;
- teachers' assessment has an important role in the valid assessment of achievement in practical work.

The main purposes of practical work have been summarised by (Hodson, 1990) as:

- to teach laboratory skills;
- to enhance the learning of scientific knowledge;
- to provide insight into the nature of scientific methodology;
- to develop 'scientific attitudes' e.g. objectivity;
- to motivate students to learn by providing them with enjoyment and stimulating their interest.

The review of research suggests that the educational impact of particular examples of practical work is diminished because of an ambiguity of address to these purposes (Nakhleh, Polles, & Malina, 2002). Developing the capacity to 'visualize an external representation at the macro level' need not be hindered by this ambiguity, but would certainly be enhanced if explicit attention was paid to this requirement within the above purposes as follows:

- showing how the version of a phenomenon was related to, produced or derived from, a naturally occurring phenomenon;
- focusing on those aspects of a phenomenon under study that require explanation to be provided through sub-microscopic and symbolic levels of representation;
- showing how science provides explanations of progressively increasing insight that apply to ever-more complex examples of a phenomenon;
- appreciating that external representations at the macro level have a distinct relationship to the world-as-experienced;
- showing students that macro-level representations provide them with an entry point to the exploration of the world-as-experienced.
- helping students to generate questions, based on external representations at the macro-level, such that their perceptions of the world-as-experienced are enhanced.

Acquiring Meta Status for the Visualization of External 3D Representations at the Sub-micro Level

Gestures

Arguably a very prevalent, yet almost completely un-researched, form of 3D representation used in science and science education is the 'gesture': moving the hands and arms during a discussion. (Roth & Welzel, 2001), on the basis of science classroom-based studies, concluded that:

> 1. gestures arise from the experiences in the phenomenal world, most frequently express scientific content before students master discourse, and allow students to construct complex explanations by lowering the cognitive load; 2. gestures provide a medium on which the development of scientific discourse can piggyback, and 3. gestures provide the material that 'glues' layers of perceptually accessible entities and abstract concepts (p. 103)

Whilst the acquisition of a formal technical vocabulary did lead to a decline in dependence on gesture, Roth and Welzel found that its use was retained. They confirmed the view that gestures can take one of three forms, as being: iconic, where their surface structure is isomorphic with their content; deistic, where they emphasis salient aspects of the phenomenon under discussion; metaphoric, for example where a sweeping gesture indicates the notion of 'limit'. We suggest that the teaching of, or at least the encouraging of, the use of gesture in science classes – particularly when explanations are being constructed – could support the development of 3D metavisual capability. It may well be that students from different cultures bring varying usages of gesture to the study of science.

Structural Representations

However, when 3D external representation is discussed, it is usually the range of structural representations that is being referred to. In the case of chemistry, they can be divided into three types: 'open' (ball-and-stick, skeletal), 'space filling' (molecular, ionic) and 'orbital' (Ingham & Gilbert, 1991) (p. 194). These are, in Harré's terms, paramorphs, that are used to represent severally the dimensions of nature, size, and arrangement. (Hesse, 1966) divided the aspects of any source into two major parts: the 'positive' analogy, those aspects that have some similarity to aspects of the target; the 'negative' analogy, those aspects that definitely do not have any similarity to aspects of the target. The positive analogies to different aspects of a target that are represented in the various types of 3D external visualizations are given in Table 1.2.

There is long-standing evidence that students get confused between the several representational systems usually available for a phenomenon, leading to inadequate

Table 1.2 Similarities represented in different 3D representational systems (+ indicates 'present' and – indicates absence)

Aspect	Open				Space Filling				Orbital	
	B & S		Skeletal		Molecular		Ionic			
	+	–	+	–	+	–	+	–	+	–
Entity natures	*		*		*		*		*	
Entity sizes	*			*	*		*		*	
Entity shape		*		*	*		*		*	
Bond angle	*		*			*		*	*	
Entity surface		*		*	*		*		*	
Entity texture		*		*	*		*			*

or incorrect visualization. For example, (Carr & Oxenham, 1985) found that high school students often confused the precepts of the Lowry-Bronsted and Arrhenius models of acids and bases. Even when they had been taught more advanced models, (Coll & Treagust, 2001) found that university chemistry students tended to prefer to use the simpler (often more historically distant) models that they had learnt at school. One problem seems to be that students are not systematically taught the conventions circumscribing particular types of representation. For example, (Ingham & Gilbert, 1991) found that, in respect of the use of ball-and-stick representations, of a sample of 39 undergraduate and graduate chemists, 6 did not recall ever being taught the conventions, 24 claimed to be unfamiliar with the conventions involved (yet were able to deduce them in an interview situation), and 9 were both unfamiliar with them and were unable to deduce them.

Notwithstanding these problems, the use of 3D external representations in teaching has been found beneficial. For example, (Huddle, White, & Rogers, 2000) found that 'teaching models' (Gilbert & Boulter, 2000) were effective in correcting the misconceptions of high school and university students in the subject of electrochemistry. There is no doubt that students are increasingly willing to use multiple types of 3D representation to explain a phenomenon as they gain experience of them, as (Harrison & Treagust, 2001) found in a longitudinal study of high school chemistry them, as (Harrison & Treagust, 2001) found in a longitudinal particular models, providing them with opportunities to explore the scope and limitations of those models, and encouraging them to use several models in a given field, both improves the understanding of the field generally and enables the students to appreciate the value of the particular models used more clearly (Harrison & Treagust, 2000).

Acquiring Meta Status for the Visualization of External 2D Representations at the Sub-micro Level

The complex material here can best be presented with the use of a 'spectrum' of types of representations which ranges from the near – 3D to the near –1D.

Virtual Representation

Virtual, or pseudo-3D, representations are produced using software packages on a computer. Although in fact 2D, they are encoded by the user as 3D by virtue of the inclusion of a full range of 'visual cues' (e.g. shading, distancing). Their value is enhanced by the ability of the computer system to 'rotate' and 'invert' them i.e. they are dynamic in nature. This book is a testimony to the growing influence of virtual approaches to representation in science education, with efforts at research gradually rising to meet the extent of work on system development. In a careful study of representations in general, Verk Savec found that students' ability to perceive a 3D molecular structure as such decreased when this was done with the aide of 3D representations, through the use of static virtual representations, to the use of static 2D representations (Ferk Savec, Vrtacnik, & Gilbert, 2005) (p. 269). The value of dynamic representations, which make full use of the medium, has been summarised by (Lowe, 2004):

> (As) a good match between the representational medium and the characteristics of the phenomenon being represented is considered instructionally desirable—animations have the advantage of being able to present situational dynamics explicitly and appropriately so that the majority of learners' processing capability could be devoted to comprehending the content directly—Interactive animations that can be freely interrogated by learners may help to reduce the likelihood of information processing problems (p. 258/9)

The attainment of metavisual capability must, in today's world, involve students being able to fluently scan the internal structure of a dynamic representation. Lowe (2004) (p. 262) has set out the strategies involved in the successful scanning of such visualizations: there is some evidence that they can be developed in students (Ploetzner & Lowe, 2004). Mentoring by an expert during problem solving would seem an obvious strategy, albeit a very expensive one.

Photographs

Photographs are often not discussed alongside other forms of representation, being perhaps sub-consciously considered more 'real' than other forms. Yet, the similarity to the-world-as-experienced is delusory, for photographs frame the field of perception of the viewer and, by virtue of the notion of 'composition', provide strong interpretative cues to the viewer as to its visualization.

In one of the very few studies of the use of photographs in science education, (Pozzer & Roth, 2003) examined their use in high school biology textbooks. Their work suggests some items of 'good practice' which would enable students to understanding fully (i.e. to visualize) the message of a photograph when inserted in a text i.e.

- the background to the phenomenon which is the focus of the photograph should be both distinct and relevant;
- multiple photographs, taking different perspectives on, or at different magnification of, the focal phenomenon, should be used;
- the photograph should have a caption which links it appropriately to the main text;
- the text should make distinctive use of a photograph that is explicitly referred to;
- learning from the photograph should be encouraged by the insertion of suitable questions into the text.

The extent to which these precepts were followed in the four Brazilian high school biology textbooks analysed (Pozzer & Roth, p. 1094) is given in summary form in Table 1.3:

Different educational systems do, of course, rely on the use of textbooks to varying degrees. Biology as a subject lends itself to the use of decorative and illustrative photographs. However, the Pozzer and Roth study does show that promoting

Table 1.3 The different approaches to the use of photographs in Brazilian biology textbooks

Category of photograph	Description	Frequency (%)
Decorative	Photographs without captions or references in the text	5.4
Illustrative	Photograph with the name of the phenomenon only in the caption	35.1
Explanatory	Photograph with the name and some explanation of the phenomenon in the caption	28.4
Complementary	Photograph with the name of the phenomenon and some additional information not given in the text	31.1

metavisualization calls for a systematic development of the genre of photographs, with much more emphasis being placed on the 'explanatory' and 'complementary' forms of use.

Diagrams

Although diagrams are widely used in textbooks, there seem to be no agreed conventions on their design and the implications of these for learning. In an interesting small-scale study, (Newberry, 2002) got a class of high-achieving 14–15 year olds (U.K., Year 10) to comment on the value for learning of the diagrams that they had encountered in their recently- completed study of the 'Rock Cycle'. The pupils collectively produced the following hierarchy:

- Cartoons were viewed as fun and memorable but more suitable for younger pupils. Even then the pupils expressed reservations, feeling that cartoons may lead to misconceptions and / are limited tools for explaining complicated phenomena;
- Pictorial diagrams were believed to be the best kind for pupils like themselves to grasp ideas in the first place;
- Thereafter, diagrams with increasing amounts of labelling and process arrows would be of steadily increasing value;
- Abstract line drawing diagrams were perceived to be the most suitable for higher achieving pupils and for others as a revision aid {for public examinations} once the basic ideas had been understood (p. 7)

Whilst the 'pictorial diagrams' and the 'abstract line drawing diagrams' may be seen as canonical forms, each with a finite set of 'codes of interpretation' relating the diagram to the phenomenon shown, there are myriad intermediate forms. The codes of interpretation for even the canonical forms, such as those found by Newberry's pupils for the 'Rock Cycle', have not yet been elucidated, although extensive discursive work on 'the grammar of visual design' has taken place (Kress & Van Leeuwen, 1996).

In an attempt to promote 'visual literacy', what is called 'metavisual capability', attention has been paid to the inter-relation between the interpretation of diagrams and of the text in which they are placed. This inter-relation between the material reality of the diagram and social reality in which it is embedded and interpreted is seen to produce a semiotic reality (Unsworth, 2001) (p. 72). Put succinctly:

- representational/ideational structures verbally and visually {jointly} construct the nature of events, the objects and participants involved, and the circumstances in which they occur;
- interactive/interpersonal verbal and visual resources {jointly} construct the nature of relationships amongst speakers/listeners, writers/readers, and viewers and what is viewed;
- compositional/textual meanings are concerned with the distribution of the information value or relative emphasis amongst elements of the text and image

(Unsworth, 2001) (p. 72)

If a student is to achieve metavisual capability in respect of diagrams, two primary conditions have to be met. First, the codes of interpretation of the material content of diagrams and for the social contexts embedded within them must be known. Second, the way that diagrams relate to the structure of the text must be known. Given the current lack of attention to these issues at a pragmatic level directly accessible to students, the attainment of metavisual capability is perhaps more a matter of luck than instructional judgment.

Graphs

The importance of representation in the form of graphs is emphasized by its centrality in any list of ways of handling data, for example that expressed by the National Research Council. Thus, students should be able to:

- describe and represent relationships with tables, graphs, and rules;
- analyse functional relationships to explain how a change in one quantity results in a change in another;
- systematically collect, organize, and describe data;
- estimate, make and use measurements to describe and compare phenomena;
- construct, read, and interpret, tables, charts, and graphs,
- make inferences and convincing arguments that are based on data analysis;
- evaluate arguments that are based on data analysis;
- represent situations and number patterns with tables, graphs, verbal rules, and equations and explore the inter-relationships of these representations;
- analyse tables and graphs to identify properties and relationships

(NRC, 1996) (pp. 105–121)

This emphasis is because:

> Graphing methods tend to show data sets as a whole, allowing us to summarize the general behavior and to study detail. This leads to much more thorough data analysis (Cleveland, 1985) (p. 10).

Again, the sub-forms of ‘graph’ are multiple. However, (Tufte, 1983) has identified four canonical forms:

- data maps. Here the positions of objects or events are represented in an identifiable geographical space. For example, the distribution of a wild flower in a meadow
- Time series. Here the positions of objects or events are represented as a function of time. For example, the migration of a species of bird over the years;
- Space-time narratives. Here the positions of objects or events are represented as function of both time and identifiable geographical space. For example, the migration of a species of bird over the years as a function of points on the migration route;
- Relational graphics. Here the variation of one abstract concept with another is represented.

Whilst science and science education make use of all four forms, arguably the greatest use is made of the fourth – 'relational graphics'.

The problems that students have with attributing meaning to – visualizing – the various sub-forms of relational (or Cartesian) graphs must start within their degree of experience of them. (Roth, Bowen, & McGinn, 1999) identified four sub-forms that were used in ecology journals: scatter plots including data points only; scatter plots with a line connecting points; scatter plots with best-fit curves; graphs of a mathematical model. When they looked at high school ecology textbooks, they found that these four were hardly ever present, the dominant sub-form being a quasi-qualitative graphical model without scales or units. It is hardly surprising then that there is a difference between the quality of 'expert' and 'novice' interpretation of the 'scientific' sub-forms. (Bowen, Roth, & McGinn, 1999) found that: 'experts' established meaning for a graph by drawing on a range of interpretative frameworks, whilst 'novices' had a limited range of such resources; that 'experts' had a broader range of linguistic resources to draw on that did the 'novices'. The situation was made more complex by the fact that scientists from different specialisms tend to use different interpretational frameworks for the same task. An inferred absence of 'graphical education' inevitably leads to general problems in graph use, for example an inability to transfer learning about graphs from the school subject of 'mathematics' to that of 'science'. Thus (Aberg-Bengtsson, 1999) noted that upper secondary students were unable to locate specific information in a graph and lacked a perception of the overall trends contained within a graph. These types of problem, that have been widely observed, perhaps partially stem from their science teachers: (Bowen & Roth, 2005) found that pre-service science teachers preferred to use only scatter plots and 'best fit lines' to represent data.

If we wish all students to achieve metavisual capability in respect of graphs, then they must experience all the sub-forms, also being provided with a commentary on the scope and limitations of each. Most importantly, the graphs that they encounter must be of excellent quality, in that they:

- show the data;
- induce the viewer to think about the substance (or what is being represented);
- avoid distorting what the data have to say;
- present many numbers in a small space;
- make large data sets coherent;

- encourage the eye to compare different pieces of data;
- reveal the data at several layers of detail—;
- serve a reasonably clear purpose—;
- be closely integrated with the statistical and verbal descriptions of a data set

(Tufte, 1983)(p. 14),

Acquiring Meta Status for the Visualization of External Representations at the Symbolic Level

A major group of external symbolic representations that is unique to science is composed of 'chemical equations'. It is common, at least in the UK, to introduce students to the idea of chemical equations by means of 'word equations', in which only the names of the species are given. For example:

$$\text{Zinc} + \text{hydrochloric acid} \rightarrow \text{zinc chloride} + \text{water}$$

This strategy has several attractions to teachers. First, it links representation at the symbolic level directly to that at the macro level, without the complexity of the sub-micro level being interposed. Second, it enables teachers to group reactions e.g. metal + acid, acid + salt, metal oxide + acid etc. At a more sophisticated level, reactions can be grouped into types along somewhat more theoretical lines e.g. displacement, neutralization, redox, thermal decomposition. However, as (Taber, 2002) (pp.141–4) points out, such an approach has a number of drawbacks. First, word equations are not based on the law of conservation of matter i.e. that the same amounts of all elements (in whatever form) must appear on both sides of the equation. Second, students are often unfamiliar with the large number of technical terms used e.g. 'tetraoxosulphate (VI)' (for the more commonly used 'sulphate'). These problems lead to students being unable to perceive the changes occurring as a whole. For these reasons, word equations are often seen as an inadequate bridge to formulae equations.

There are many sub-forms of formulae equations (Peters, 2006). The simplest sub-form merely states the names of species in terms the elements involved e.g.

$$\mathrm{HCl} + \mathrm{NaOH} \rightarrow \mathrm{NaCl} + \mathrm{H_2O}$$

The problem with this example of the first sub-type is that the reaction will not proceed under the anhydrous conditions implied. A more informative version includes the state symbols e.g.

$$\mathrm{HCl_{(aq)}} + \mathrm{NaOH_{(aq)}} \rightarrow \mathrm{NaCl_{(aq)}} + \mathrm{H_2O_{(l)}}$$

Several sub-forms introduce simplicity into the equation by removing unnecessary data, thus concentrating attention of the essence of the changes taking place and hence enhancing visualization. In one sub-form, 'spectator' sub-species are removed e.g.

$$H^+{}_{(aq)} + OH^-{}_{(aq)} \rightarrow H_2O_{(l)}$$

Where a reaction is complex, it is usual to provide a ‘shorthand’ version of the formulae equation by placing statements about such matters as the energy change occurring, the presence of a catalyst, the nature of any extraordinary physical conditions, above the arrow linking the reactants and products. For example, for the oxidation of ethanol to ethanoic acid

$$C_2H_5OH_{(l)} \xrightarrow{Cr_2O_7{}^{2-}/H^+{}_{(aq)}} CH_3COOH_{(aq)}$$

In theory at least, all chemical reactions are reversible. However, where the equilibrium constant is very high, or where the physical conditions drive the equilibrium towards the products side of the equation, it is usual to use a unidirectional rather than a reversible arrow between the reactants and products.

Achieving metavisualization in respect of chemical equations must involve the student in becoming aware of the scope and limitations of each sub-form in use. This level of detail will be needed for not only do textbooks use a range of these sub-forms but, even more disturbing, their own conventions that are a mixture of the generic forms e.g

$$Zn + 2H^+{}_{(aq)} \rightarrow Zn^{2+} + H_2$$

Visualization and the Translation Between Representations at the 3D, 2D, 1D, Levels

The ability to ascribe meaning to (i.e. to visualize) a representation that is 3D, 2D, or 1D, is the key aspect of metavisualization. A more advanced skill is that of using a visualization at one level of representation as the basis of a visualization of the same model at a different level of representation. The use of the metaphor ‘the translation of representations’ gives a flavour of the value and hazards of this enterprise.

Inevitably, given the lack of a general ‘visual education’, it is not surprising that students find the multiple possibilities (as many as: 1D to 2D, 1D to 3D, 2D to 1D, 3D to 1D, 2D to 3D, 3D to 2D) that link the macro to the sub-micro to the symbolic levels difficult to master. For example, (Hinton & Nakhleh, 1999) found that undergraduate chemistry students were able to form representations of a chemical phenomenon at the macro and symbolic levels, yet found it difficult to link these to the equivalent representations at the sub-micro level.

Expert chemists must be able to do this (Kosma, 2003; Kosma, Chin, Russell, & Marx, 2000; Kosma & Russell, 1997), a requirement that must have its equivalence in the other sciences, because there is evidence that doing so enhances capability to solve problems, whether explicitly requiring visualization or not (Bodner & McMillen, 1986).

Acquiring Meta Status for the Visualization of Internal Representations

Internal representation, being most commonly the outcome of the perception of an external representation, inevitably involves memory. (Nelson & Narens, 1994) have produced a three stage model of memory, to which a fourth stage has been suggested (Gilbert, 2005), that can be applied to the acquisition and visualization of internal representations. As a learner becomes increasingly metavisually capable, that person:

- becomes increasingly able to control the *acquisition* of internal representations. Confidence in the ability to visualize existing internal representation increases as does the judgment of how difficult it will be to acquire and make meaning of new internal representations;
- becomes increasingly able to *retain* an internal representation and its associated visualization;
- becomes increasingly confident that an internal representation will be *retrieved* in an accurate form such that its visualization can be relied on;
- becomes increasingly able to consciously *amend* a retrieved internal representation for particular purposes. This capability leads to amended external representations being consciously produced.

Supporting the acquisition of metavisual capability in respect of internal representations is something of a mystery. It would seem to depend on providing students with amble opportunities to both develop internal representations and to express them as external representations.

Sex Differences in Visualization

Whether males and females have the capabilities in respect of visualization continues to be the source of much, sometimes frivolous, discussion. That the same abilities are present is not in doubt:

> Infants begin with certain spatial skills—and these skills change with development (some of which include): the reweigh ting of initial spatial coding systems as the infant learns more about the world, the advent of place learning, and the acquisition of perspective taking and mental rotation. Children also begin to use symbolic representations of space, including maps, models and linguistic descriptions, and they learn to think about space and to use spatial representations for thinking (Newcombe & Learmonth, 2005) (p. 213)

But how far and how fast do these developments naturally take place? In a meta-analysis of the field, conducted 20 years ago, Linn and Petersen concluded that:

> (a) sex differences arise in some types of spatial ability but not others (b) large sex differences are found on measures of spatial perception, and (c) when sex differences are found, they can be detected across the life span. (Linn & Petersen, 1985) (p. 1479)

In general terms, these differences favour males. It does seem that both sexes improve their spatial abilities when provided with specific training, but that the differences never entirely disappear (Halpern & Collaer, 2005) (p. 200).

Developing the Skills of Metavisualization

Acquiring metavisual status implies being able to progressively acquire understanding of (i.e. being able to visualize) representations at the 3D, 2D, 1D, level and being able to move between them. Whilst only concerned with representations in chemistry and not using the terminology adopted in this chapter, the scheme of 'progression in representational competence' by Kozma and Russell (see Table 1.4) (Kozma & Russell, 2005) is helpful as it suggests what educational opportunities should be provided. However, this progression does need to be recast in terms of the 'levels of representation' that are the focus of this chapter.

I would argue that two strategies have to underlie this development. First, a strategy is needed is to develop the epistemological beliefs about the nature of knowledge used by students. Perry identified four major positions in the epistemological development of undergraduate students (Perry, 1970). When displaying *dualism*, students see knowledge as either right or wrong. This gives way to *multiplism* in which all knowledge has an equal claim to acceptance. Later comes *relativism*, in which the value of knowledge is relative and context bound. Finally, in *commitment to relativism*, knowledge is seen to be enmeshed in a framework of ethical and social responsibility whilst also being contextually appropriate. In the absence of much, if any, specific teaching about the nature of knowledge, one would imagine that school and university science students are still, 30+ years after Perry's fascinating study, located at the bottom end of this typology. Second, the students must come to have an acceptable understanding of the concept of 'model' itself. (Grosslight, Unger, Jay, & Smith, 1991) developed a scheme to represent the development of this understanding. At Level 1, students believed that a model is a direct representation of reality. At Level 2, a model remains a direct representation of reality, but it is incomplete in that some aspects are neglected. Such a model is used for communication rather than the exploration of ideas. At Level 3, a model is a tool for thinking, being altered by the modeler to emphasise particular issues. Grosslight et al. found that, at the time of their study and in the absence of any specific education about the nature of models, most lower secondary school students displayed an understanding at Level 1, with only a few upper secondary students displaying a Level 2 understanding, the attainment of Level 3 being restricted to professional scientists. However, in the years following the Grosslight et al. study and with a gradually improving awareness of the importance of models and of epistemological commitments in science and science education, the situation has improved considerably, as a recent study shows (Chittleborough, Treagust, Mamiala, & Mocerino, 2005).

Four sets of tactics can be adopted to facilitate the developments of a more useful epistemological commitment and understanding of the 'nature of model':

Table 1.4 Summary of representational competence levels

LEVEL 1: REPRESENTATION AS DEPICTION

When asked to represent a physical phenomenon, the person generates representations of the phenomenon based only on its physical features. That is, the representation is an isomorphic, iconic depiction of the phenomenon at a point in time.

LEVEL 2: EARLY SYMBOLIC SKILLS

When asked to represent a physical phenomenon, the person generates representations of the phenomenon based on its physical features but also includes some symbolic elements to accommodate the limitations of the medium (e.g., use of symbolic elements such as arrows to represent dynamic notions, such as time or motion or an observable cause, in a static medium, such as paper). The person may be familiar with a formal representation system but its use is merely a literal reading of a representation's surface features without regard to syntax and semantics.

LEVEL 3: SYNTACTIC USE OF FORMAL REPRESENTATIONS

When asked to represent a physical phenomenon, the person generates representations of the phenomenon based on both observed physical features and unobserved, underlying entities or processes (such as an unobserved cause), even though the representational system may be invented and idiosyncratic and the represented entities or processes may not be scientifically accurate. The person is able to correctly use formal representations but focuses on the syntax of use, rather than the meaning of the representation. Similarly, the person makes connections across two different representations of the same phenomenon based only on syntactic rules or shared surface features, rather than the shared, underlying meaning of the different representations and their features.

LEVEL 4: SEMANTIC USE OF FORMAL REPRESENTATIONS

When asked to represent a physical phenomenon, the person correctly uses a formal symbol system to represent underlying, non-observable entities and processes. The person is able to use a formal representation system based on both syntactic rules and meaning relative to some physical phenomenon that it represents. The person is able to make connections across two different representations or transform one representation to another based on the shared meaning of the different representations and their features. The person can provide a common underlying meaning for several kinds of superficially different representations and transform any given representation into an equivalent representation in another form. The person spontaneously uses representations to explain a phenomenon, solve a problem, or make a prediction.

LEVEL 5: REFLECTIVE, RHETORICAL USE OF REPRESENTATIONS

When asked to explain a physical phenomenon, the person uses one or more representations to explain the relationship between physical properties and underlying entities and processes. The person can use specific features of the representation to warrant claims within a social, rhetorical context. He or she can select or construct the representation most appropriate for a particular situation and explain why that representation is more appropriate than another. The person is able to take the epistemological position that we are not able to directly experience certain phenomena and these can be understood only through their representations. Consequently, this understanding is open to interpretation and confidence in an interpretation is increased to the extent that representations can be made to correspond to each other in important ways and these arguments are compelling to others within the community.

(From: Kosma, R., Russell, J.{2005}. Students becoming chemists: Developing representational competence. In: J.K. Gilbert (ed.), Visualization in Science Education. Dordrecht: Springer. pp. 121–145)

- The explicit use of several models and levels of representation when teaching a given topic. Both (Harrison & Treagust, 1998) and (Chittleborough et al., 2005) provide evidence, both direct and indirect, that doing so is helpful.
- The explicit teaching of 'the principles of analogy'. This will help students to understand not only how particular models are developed but also how the 'translation between levels of representation' can take place. The 'Focus, Action, Reflection' (FAR) approach seems to be particularly effective (Treagust, Harrsion, & Venville, 1998)
- The adoption of 'good practice' in the use of representations by teachers and in textbooks. According to (Hearnshaw, 1994) this involves:

  - starting any sequence of representations with the most regular, geometrically simple forms available. This will enable students to 'get their eye in';
  - using as full a range of modes /sub-modes of representation as is possible, introducing them deliberately, systematically, and steadily. This will encourage students to engage their knowledge of the codes of representation;
  - maximizing the salience of shapes, edges, shadings, and patterns, within any representation. This will enable students to distinguish the structure of the representation.
  - using a range of degrees of illumination for different sections of the representation. This should enable students to more readily perceive contrasts;
  - making the full use of colour effects, in terms of saturation, hue, and lightness, of a full range of blues, reds, and greens. Again, this will maximize contrasts.

- The use of specific teaching techniques. (Tuckey & Selvaratnam, 1993) identified three approaches, initially within the subject of chemistry but capable of generalisation across the sciences. These involved the use of:

  - stereodiagrams. These consist of pairs of drawings or photographs, one giving the view of a representation as it would appear in the left eye and the other as it would appear in the right eye. The illusion of a three-dimensional image is produced viewing these two images with a device such that the right eye only sees the right-eye view and the left eye only sees the left-eye view.
  - teaching cues. All diagrams, including the virtual mode, that purport to show three-dimensions (virtual or pseudo-3D representations), do so by the use of specific cues e.g. the overlap of constituent entities, the foreshortening /extension of lines of show below-surface / above -surface inclination, the distortion of bond angles, the emphasis of the relative size of constituent entities (atoms, ions, molecules);
  - systematically teaching rotation and reflection through the use of a series of diagrams.
  - the use of virtual representational systems. Investment in 'Geographical Information Systems' has been strongly advocated (N.R.C., 2006) (p. 155)

At the level of curriculum design, two approaches seem to have great potential:

- The explicit use of multi-media approaches to teaching. Mayer has strongly advocated the use of as many media as possible in teaching, on the grounds that accessing information simultaneously both is verbal and visual forms increases the likelihood of effective learning (Mayer, 1997).
- The explicit teaching of the 'master images' of which scientific representations are composed (Mathewson, 2006)

If enquiries are to lead to comprehensive explanations for the phenomenon of 'the visualization of representations' and to outcomes that enable metavisualization more widely and readily attained, then cross-disciplinary enquiries, perhaps associated with 'design experiments', involving natural scientists, cognitive scientists, linguists, educationalists, are called for.

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References

Aberg-Bengtsson, L. (1999). Dimensions of performance in the interpretation of diagrams, tables and maps: some gender differences in the Swedish Scholastic Aptitude Test. *Journal of Research in science Teaching, 36*(5), 565–582.

Bennett, J. (2003). *Teaching and learning science: A guide to recent research and its applications*. London: Continuum Press.

Beveridge, M., & Parkins, E. (1987). Visual representation in analogical problem solving. *Memory and Cognition, 15*(3), 230–237.

Bodner, G. M., & McMillen , T. L. B. (1986). Cognitive restructuring as an early stage in problem solving. *Journal of Research in Science Teaching, 23*(8), 727–737.

Bowen, G. M., & Roth, W.-M. (2005). Data and graph interpretation practices amongst pre-service science teachers. *Journal of Research in Science Teaching, 42*(10), 1063–1088.

Bowen, G. M., Roth, W.-M., & McGinn, M. K. (1999). Interpretations of graphs by university biology students and practicing scientists: Towards a social practice view of scientific representational practices. *Journal of Research in Science Teaching, 36*(9), 1020–1043.

Carr, M., & Oxenham, J. (1985). Model confusion in science. In R. J. Osborne & J. K. Gilbert (Eds.), *Some issues of theory in science education* (pp. 81–88). Hamilton, New Zealand: Science Education Research Unit, University of Waikato.

Chittleborough, G., Treagust, D. F., Mamiala, T., & Mocerino, M. (2005). Students' perception of the role of models in the process of science and in the process of learning. *Research in Science and Technology Education, 23*(2), 195–202.

Cleveland, W. S. (1985). *The elements of graphing data*. Monterey, California: Wadsworth.

Coll, R. K., & Treagust, D. F. (2001). Learners' mental models of chemical bonding. *Research in Science Education, 31*(3), 357–382.

Driver, R., Guesne, E., & Tiberghien, A. (Eds.). (1985). *Children's ideas in science*. Milton Keynes: Open University Press.

Ferk Savec, V., Vrtacnik, M., & Gilbert, J. K. (2005). Evaluating the educational value of molecular structure representations. In J. K. Gilbert (Ed.), *Visualization in Science Education* (pp. 269–298). Dordrecht: Springer.

Gabel, D. (1999). Improving teaching and learning through chemical education research: a look to the future. *Journal of Chemical Education, 76*, 548–554.

Gilbert, J. K. (2005). Visualization: A metacognitive skill in science and science education. In J. K. Gilbert (Ed.), *Visualization in science education*. Dordrecht: Springer.
Gilbert, J. K., & Boulter, C. J. (Eds.). (2000). *Developing models in science education*. Dordrecht: Kluwer.
Gilbert, J. K., Boulter, C. J., & Rutherford, M. (2000). Explanations with models in science education. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education* (pp. 193–208). Dordrecht: Kluwer.
Grosslight, L., Unger, C., Jay, E., & Smith, C. L. (1991). Understanding models and their use in science:conceptions of middle and high school students and experts. *Journal of Research in Science Teaching, 28*(8), 799–822.
Halpern, D. F., & Collaer, M. L. (2005). Sex differences in visuospatial abilities: More than meets the eye. In P. Shah & A. Miyake (Eds.), *The Cambridge handbook of visuo-spatial thinking* (pp. 170–212). Cambridge: Cambridge University Press.
Harre, R. (1970). *The principles of scientific thinking*. London: MacMillan.
Harrison, A. G., & Treagust, D. F. (1998). Modelling in science lessons: Are there better ways to learn with models? *School Science and Mathematics, 98*(8), 420–429.
Harrison, A. G., & Treagust, D. F. (2000). Learning about atoms, molecules, and chemical bonds: A case study of multiple-model use in Grade 11 chemistry. *Science Education, 84*(3), 352–381.
Harrison, A. G., & Treagust, D. F. (2001). Conceptual change using multiple interpretative perspectives: Two case studies in secondary school chemistry. *Instructional Science, 29*, 45–85.
Hearnshaw, H. (1994). Psychology and displays in GIS. In H. Hearnshaw & D. J. Unwin (Eds.), *Visualization in geographic information systems* (pp. 193–211). Chichester: Wiley.
Hesse, M. (1966). *Models and analogies in science*. London: Sheen and Ward.
Hinton, M. E., & Nakhleh, M. B. (1999). Students' microscopic, macroscopic, and symbolic representations of chemical reactions. *The Chemical Educator, 4*(4), 1–29.
Hodson, D. (1990). A critical look at practical work in school science. *School Science Review, 71*(256), 33–40.
Huddle, P. A., White, M. D., & Rogers, F. (2000). Using a teaching model to correct known misconceptions in electrochemistry. *Journal of Chemical Education, 77*(1), 104–110.
Ingham, A. M., & Gilbert, J. K. (1991). The use of analogue models by students of chemistry at higher education level. *International Journal of Science Education, 22*(9), 1011–1026.
Johnstone, A. H. (1993). The development of chemistry teaching: a changing response to a changing demand. *Journal of Chemical Education, 70*(9), 701–705.
Justi, R., & Gilbert, J. K. (2002). Modelling, teachers' views on the nature of modelling, and implications for the education of modellers. *International Journal of Science Education, 24*(4), 369–387.
Kosma, R. (2003). The material features if multiple representations and their cognitive and social affordances for science learning. *Learning and Instruction, 13*, 205–226.
Kosma, R., Chin, E., Russell, J., & Marx, N. (2000). The role of representations and tools in the chemistry laboratory and their implications for chemistry ; learning. *The Journal of the Learning Sciences, 9*(2), 105–143.
Kosma, R., & Russell, J. (1997). Multimedia and understanding: expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching, 34*(9), 949–968.
Kozma, R., & Russell, J. (2005). Modelling students becoming chemists: Developing representational competence. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 121–146). Dordrecht: Springer.
Kress, G., & Van Leeuwen, T. (1996). *Reading images:The grammar of visual design*. London: Routledge.
Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development, 56*, 1479–1498.
Lowe, R. (2004). Interrogation of a dynamic visualization during learning. *Learning and Instruction, 14*, 257–274.
Mathewson, J. H. (2006). The visual core of science: Definitions and applications in education.

In J. K. Gilbert (Ed.), *Science education: Major themes in education.* (Vol. 3, pp. 298–320). London: Routledge.
Mayer, R. E. (1997). Multimedia learning: are we asking the right questions? *Educational Psychologist, 32*, 1–19.
N.R.C. (2006). *Learning to think spatially*. Washington, DC: National Academies Press.
Nakhleh, M., Polles, J., & Malina, E. (2002). Learning chemistry in a laboratory environment. In J. K. Gilbert, O. de Jong, R. Justi, D. F. Treagust, J. H., & van Driel (Eds.), *Chemical education: Towards research-based practice* (pp. 69–94). Dordrecht: Kluwer.
Nelson, T. O., & Narens, L. (1994). Why investigate metacognition? In J. Metcalfe & A. P. Shinamura (Eds.), *Metacognition* (pp. 1–25). Cambridge, MA: MIT Press.
Newberry, M. (2002). *Pupils' understanding of diagrams in science: Progression from key stage 3 (11–14 years) and across key stage 4 (14–16 years).* Fareham, Hants: Cams Hill School.
Newcombe, N. S., & Learmonth, A. E. (2005). Development of spatial competence. In P. Shah & A. Miyake (Eds.), *The Cambridge handbook of visuospatial thinking* (pp. 213–256). Cambridge: Cambridge University Press.
NRC. (1996). *National science education standards*. Washington, DC: National Academic Press.
Perry, W. G. (1970). *Forms of intellectual and ethical development in the college years.* New York: Holt, Rinehart,Winston.
Peters, R. (2006) *Chemical equations*. Retrieved 15 Sept., 2006, from http://www.wissensdrang.com/ auf1ce1.htm
Ploetzner, R., & Lowe, R. (2004). Dynamic visualizations and learning. *Learning and Instruction, 14*, 235–240.
Polya, G. (1957). *How to solve it* (2nd ed.). Princeton, New Jersey: Princeton University Press.
Pozzer, L. L., & Roth, W.-M. (2003). Prevalence, function, and structure of photographs in high school biology textbooks. *Journal of Research in Science Teaching, 40*(10), 1089–1114.
Reisberg, D. (1997). *Cognition*. New York: Norton.
Roth, W.-M., Bowen, G. M., & McGinn, M. K. (1999). Differences in graph-related practices between high school biology textbooks and scientific ecology journals. *Journal of Research in Science Teaching, 36*(9), 977–1019.
Roth, W.-M., & Welzel, M. (2001). From activity to gestures and scientific language. *Journal of Research in Science Teaching, 38*(1), 103–136.
Taber, K. (2002). *Chemical misconceptions – prevention, diagnosis and cure. Volume1: Theoretical background.* London: Royal Society of Chemistry.
Treagust, D. F., Harrison, A. G., & Venville, G. (1998). Teaching science effectively with analogies: An approach for pre-service and in-service teacher education. *Journal of Science Teacher Education, 18* (85–101), 91.
Tuckey, H., & Selvaratnam, M. (1993). Studies involving three-dimensional visualisation skills in chemistry. *Studies in Science Education, 21*, 99–121.
Tufte, E. R. (1983). *The visual display of quantitative information*. Cheshire, Connecticut: Graphics Press.
Unsworth, L. (2001). *Teaching Multiliteracies Across the Curriculum*. Buckingham: Open University Press.

Section A
The Nature and Development of Visualization: A Review of what is Known

Miriam Reiner

How is a visual representation turned into knowledge? What are the mental processes that are involved in attaching a meaning to a picture, a map, a graph? What mental and brain processes are involved in 'seeing'? After all, visual information is transferred through electromagnetic energy, and characterised by features such as intensity and frequency. How does such an electromagnetic energy turned into knowledge? Even more provoking is the process of mental visualization, i.e. 'seeing with the mind's eye. It is well known that learners use images, pictorial representations and mental 'simulations' to run scenarios in the mind. Such is for instance a thought experiment in physics. Thought experiments, a central cognitive tool that lead to major innovations throughout the history of physics, is based on mental processes of 'seeing with the minds' eye (Gilbert & Reiner, 2000; Mach, 1976; Lakoff, 1987). Thus authentication of learning physics, by definition, includes components such as mental visualization.

This section mainly deals with mental processes associated with visualization. The section evolves from a behavioural point of view towards the cognitive functions of memory perception and action as related to visualization, and concludes with brain activities associated with visualization across sensory channels: seeing with the eyes, and 'seeing through touch'. The first two chapters look at the behavioural aspects of visualization, i.e. how is visual information perceived and generalized into a wide range of learning situations. The third paper looks at the neurological processes associated with visualization.

A central topic across all three chapters is the definition of the term 'visualization'. Uttal and O'Doherty as well as Rapp and Kurby define visualizations as any type of physical representation designed to make an abstract concept visible. The third chapter views visualization as the cognitive and brain processes associated with the act of visualizing rather than as a pictorial representation. In this sense the third paper conceptually differs from the first two: a mental-brain process, not a mere picture.

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Rapp and Kurby claim that, based on ‘visualizations’, learners construct mental models. They then look at the relationships between visualizations and corresponding mental models. Mental models are considered the ‘ins’ and visualizations are considered the ‘outs’. The two papers use the word ‘representation’ in a different way: Uttal and O’Doherty define the ‘visualization’ (a picture, a map) as a representation, while Rapp and Kurby define a mental model as a representation. Indeed, both make sense: the first is an external representation, while the second is an internal representation.

The third paper, suggests a further more basic level of visualization, and looks at brain activations correlated with visualization. Normally, areas in the visual brain are said to be activated when the brain processes visual information. What the third paper shows is that some areas in the visual brain are activated when we ‘see’ with our fingers, with closed eyes, providing a physiological;/brain perspective theory of why sensory interaction, such as in the physics lab, is crucial in the learning process. This further explain the high appeal and deep understanding that is associated with manual models such as those of molecules, e-m fields, and mechanics. It is the integration of touch and visual that strengthens the perception and memory of the scientific concept being learnt.

In a sense all three papers talk about representations: One discusses external visual representations and their behavioral correlates, the second discusses internal representations and their behavioral correlates, and the third discusses neurological representations, i.e. brain areas activated during representations. The three chapters thus present a comprehensive view of visualizations from the external physical representation, to the internal mental representation, to the underlying brain activations that are responsible for the whole process of mental visualization.

Frequently the representation is partial, and the ‘visual’ representation refers to partial properties of the source concept. Uttal and O’Doherty, indeed treat visualizations as no more than pictures. Such pictures may be dynamic (e.g. an animation, a film) but still the central assumption is that visualizations are synonyms of different types of pictorial representations, as partial as these may be. Such an assumption logically leads to Uttal and O’Doherty central research question in the paper: how learners grasp the relations between ‘a visualization and what it stands for’, an important question when it comes to studying the relationships between scientific diagrams and the underlying concept, e.g. blue small balls and the concept of an electron . . .

Rapp and Kurby use similar questions from a perspective of memory, perception and action. They look at encoding processes, mental representations, and specifically attend to perspectives that emphasize the perceptual and abstract qualities of mental models. The paper emphasizes theoretical and empirical views that have focused on links between perception and action, and what those links imply for learning. The paper relies especially on the dual processing theory to suggest ways of supporting memory of external representations. In this way, basic research on the nature of memory can provide pragmatic suggestions with respect to the design, implementation, and assessment of visualizations.

While Rapp and Kurby suggest a general theory of perception-action-mental models, Uttal and O’Doherty suggest that the link between what one sees and what one knows can be understood by looking a young children behavior and perception. They provide a developmental view of the relationships between the external representation visualization – and its internal representation, in an attempt to draw implications for science learning. The process of discrimination between a concept and its representations is rooted in developmental aspects. Thus the paper reports on young children, as young as babies that treat a picture of an object as the object itself. Is this context bound, and returns later in complex situations, leading to naïve interpretations of the visual scientific representations, imprinting eternally the concept of an 'electron' into a mere representation of 'blue tiny balls'? A similar question is raised as to scaling. For instance, a well know perceptual distortion relates to the distances and sizes of the earth, sun and other starts. Is it a problem of over generalization of a very limited model of the sun system? The paper really does not answer these questions, but rather suggests some applications to design of learning settings that take these into account.

To summarise, this section provides psychological-educational-neurological basis for visualization, using different points of view:

a. Nature of visualization: visualization is pictures (Rapp and Kurby, Uttal and O'Doherty) vs. visualization is mental-brain processes (Reiner),
b. Types methodologies of research: review of behavioral-cognitive studies vs. fMRI measuring techniques.

All three provides insights into understanding the process of visualization, and into designing the learning environments in a manner that is adaptive to the behavioral and brain processes known data.

References

Gilbert J., & Reiner M. (2000). Thought experiments in science education. *International Journal of Science Education, 22*(3), 265–283.

Johnson, M. (1987) *The mind in the body: The bodily basis of meaning, imagination and reason*. Chicago: The University of Chicago Press.

Lakoff, G. (1987) *Women, fire and dangerous things: What categories reveal about the mind.* Chicago: University of Chicago Press.

Mach, E. (1976). 'On thought experiments'. In J. McCormack (Trans.), *Knowledge and error* (pp. 134–147). Dordrecht: Reidel.

Chapter 2
The 'Ins' and 'Outs' of Learning: Internal Representations and External Visualizations

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Abstract Science classrooms teach complex topics by exposing students to information through a variety of methodologies, including lectures, discussions, readings, lab experiences, and representational experiences. The goal of these activities is to help students build internal representations for course content – information stored in memory that students can retrieve to generate inferences, solve problems, and make decisions. But what are these internal representations like, and what does the nature of these representations suggest for the design of learning methodologies such as external representations? This chapter is an introduction to current and contemporary work on mental representations. In particular, we emphasize theoretical and empirical views that have focused on links between perception and action, and what those links imply for learning. In this way, basic research on the nature of memory can provide pragmatic suggestions with respect to the design, implementation, and assessment of what are commonly called 'visualizations' (i.e., external visual representations of processes) as tools for science learning.

The 'Ins' and 'Outs' of Learning

What remains in student memory after a successful learning experience and how is that information used in future learning situations? Learning is usually defined as acquiring some knowledge and, presumably, being able to use that knowledge to solve problems (e.g., Kintsch, 1998). But this definition tells us little about what students actually represent 'in their heads,' and even less about what constitutes the fabric of that knowledge. Learning, in this way, reveals little as to whether stored memories are composed of images, or words and sounds, or some more abstract form that isn't easily described. The measures we use to assess learning are also of limited utility in describing internal representations of knowledge. While we can evaluate a student's understanding of course content using tests, term papers, or discussion questions, these assessments provide little insight into the *nature* of

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students' knowledge. Even our personal introspections about effective teaching and learning reveal relatively little about the way information is coded in memory.

Nevertheless, philosophers and scientists have discussed, debated, and, using cleverly designed experiments, developed hypotheses about the nature of memory for hundreds of years. Some of these hypotheses have suggested that memory is composed of mental models, conceptual schemas, and semantic networks (Johnson-Laird, 1980; Minsky, 1975; Newell & Simon, 1972). Each of these constructs is useful for suggesting how memory is organized and utilized to generate inferences, solve problems, and make decisions. But each of these constructs has its own inherent ambiguity, and thus the question of what constitutes the 'residue' of learning remains an open one.

We focus on these thorny issues as a means of contextualizing the challenges involved in discussing and investigating mental representations. Despite these challenges, researchers in fields such as cognitive science and the learning sciences have managed to provide important insights into what people retain after a successful learning experience. Beyond epistemological inquiries about the nature of memory, this work also has implications for thinking about the conditions that might facilitate learning. Consider that if we have some notion of how information is represented in memory, we can attempt to design learning experiences that align with and contribute to the development of such representations. An underlying assumption of this view is that external presentations should match, in some way, what we wish students to encode into memory. If information that is gathered from a learning experience is too abstracted from the situation(s) it is related to, it may be too difficult for novice students to recognize that the information is useful for reasoning and problem solving.

Science education is a domain in which teaching methodologies have often relied on matches between learning activities (i.e., external presentations) and the knowledge we wish students to acquire from their lessons (i.e., internal representations). Lab-based activities, active learning assignments, and task-driven coursework all help students learn about scientific topics through active participation rather than passive viewing or listening. External representations ('visualizations') have emerged as a methodology that, in many ways, relies on similar principles to facilitate learning. A visualization can be thought of as the mental outcome of a visual display that depicts an object or event. Science-based 'visualizations' in particular have become ubiquitous in classrooms; by this, we mean there are many 'visualizations' available, and in actual classroom use, for the principles, theories, and concepts that students might learn in traditional k-12, college, and adult education courses. Their popularity and implementation is a function of many factors, but generally, those factors have remained separate from evidence-based assurances of actual learning benefits (e.g., Rapp, 2005; Rapp & Uttal, 2006).

A realization of the need to assess the effectiveness of 'visualizations' in science classrooms has led to increased interest in the impact of their use. We believe, though, that it is possible to tackle the issue using a slightly different approach. Psychological investigations of learning and memory can provide useful suggestions as to when and how 'visualizations' might function as effective learning tools (see

Rapp, Taylor, & Crane, 2003, for similar discussion with respect to digital media). One way to pursue this issue is to consider, as described earlier, whether the mental activity necessitated by visualization-based tasks effectively engenders the construction of mental representations. To adopt this approach, researchers must, necessarily, possess at least a basic understanding of the nature of the mental representations that students may develop during learning experiences.

Thus, the current chapter has two goals. The primary goal is to introduce the topic of mental representations so as to address our initial question: What do students glean from external representations and how do they internalize and manipulate that information? A second, but equally important goal is to relate this work to educational situations, to derive practical implications that can help inform the development of effective visualization experiences, and potentially help students internalize those visualizations. Some of our own work has involved developing such implications for the Earth Sciences, and more generally, for instances involving procedural and skill-based learning; however, these implications, we believe, should be generalizable beyond particular science domains as well as across other content areas.

The chapter is organized as follows. We begin with a general description of mental representations and 'visualizations', to develop common ground for our discussion and to better codify the distinction between internal and external representations. We briefly review attempts to broadly qualify the contents of mental representations, and specifically attend to perspectives that emphasize their perceptual and abstract qualities. We next constrain these perspectives to consider modality-specific representations – those derived from visual- or verbal-only experiences. We also consider work investigating the multi-modal nature of mental representations. These reviews allow us to consider how theories of mental representations might be applied to foster knowledge acquisition. We conclude by deriving some general recommendations for the development and implementation of effective educational methodologies, and specifically for visualizations, in classroom settings, as a function of our review. The chapter, then, is intended as a basis for translating empirical research on mental representations into pragmatically oriented design implications for instructional visualizations.

Internal and External Representations

A representation is a likeness or simulation of some idea, concept, or object. We construct and comprehend representations throughout the day, taking for granted the degree to which the phrase 'what you see is what you get' often fails to ring true. For example, a photo of the Chicago skyline is a representation of that skyline; it is not the actual skyline reduced in size and transposed onto a two-dimensional surface, but only a copy of what the skyline looks like from a particular vantage point. Similarly, if you have ever been to Chicago and can envision what the skyline looks like, from whichever perspective you wish, you are relying on a mental representation of that skyline. The skyline is not physically in your head, but rather a 'mental copy' of the skyline accessed from memory. Some representations can be quite detailed and convey meaning in a very direct way, as exemplified by the intricate renderings of an architectural blueprint or the delicate brushstrokes of a painting. Other representations can be more abstract, and interpretations of such work must be derived in ways that rely less on surface characteristics. Consider the meanings (e.g., views and beliefs) associated with the flags of a nation, or the geometric shapes that, taken together, convey emotion in cubist artwork. Words themselves, whether spoken or written, are also a type of representation. The changes in air pressure that make up speech, and the ink blots and pixels that make up the words we see, are not meaningful things unto themselves but are instead imbued with meaning by cultural groups. These acoustic and visual stimuli are representations of ideas, concepts, and objects, including concrete items (e.g., the word 'chair') and more abstract notions (e.g., the word 'luxury').

These examples allow us to introduce a useful dichotomy for classifying representations – external vs. internal. An external representation is one that is available in the environment, like the aforementioned skyline, flag, or blueprint. These representations often stand for or correspond to additional concepts or notions, such as a flag both being an object itself and a symbol of some geographical region, group of people, or sociocultural perspective. A variety of external representations have been developed specifically to convey particular ideas, and in many situations, to specifically help individuals learn. Maps and graphs are examples *par excellence* of external representations for learning. They organize data into presentations that are more easily interpretable than their raw forms (e.g., the collected numbers that comprise a bar graph) by summarizing concepts in salient, systematic ways.

Internal representations are not available in the environment, but are instead held in the viewer or learner's mind. The traditional term in cognitive science for an internal representation is a mental representation, which designates it as part of our private thoughts, derived through mental activity. Our memory for a happy childhood experience, our recall of the number of windows in our house or apartment, and our expectations for the events that traditionally take place when we visit a restaurant are all examples of mental representations. Unlike external representations, we have no direct evidence for their existence. We cannot physically manipulate mental representations to assess their validity. Nevertheless, our phenomenological experience of mental representations remains quite vivid, and their importance for our moment-to-moment functioning is quite obvious.

With respect to visualizations, internal representations can be divided among at least three categories; visual memory, visual imagery, and knowledge representations. There are at least two forms of visual memory. One is a short lived record of the perceptual experience that persists in working memory for a few seconds (Sperling, 1960) and is essentially a veridical copy of what was seen. Another form of visual memory is memory of what something looks like as recalled from long term memory. The 'mental copy' of the Chicago skyline discussed above is an example of visual memory. This long term visual memory is in many ways similar to visual imagery. A visual image is an internally generated 'visual' experience viewed in what has been metaphorically referred to as the mind's eye. Visual images can be of something mundane such as an apple or something completely novel such as hitting a baseball into outer space. The labeling of these images as visual is appropriate given that, in addition to describing the subjective experience of imagery, visual images are created by partially engaging the brain regions involved in visual perception (Behrmann, 2005; Kosslyn, 1994). Visual images are constructed based on our knowledge of the object or event of interest.

Knowledge representations are in many ways more complex than visual memory and imagery (Barsalou & Hale, 1993; Markman, 1999). In addition to how something looks, knowledge representations for objects contain a variety of attributes and their relationships, and usually also include attributes of the situations in which they are used (e.g., time, location, events, goals; Barsalou & Hale, 1993). Consider a screwdriver for example. Knowledge of this object may include information about category membership (tools), non-visual features such as weight and function (fastening), situational information such as activities associated with use of the object (replacing a broken hinge), and emotions or beliefs linked to the object and its relevant activities. Events are represented in a similar way except that the focus of these representations is typically on situational information such as the agents typically involved in the event (the agent *officer* is typically involved in the event of *arresting*; Ferretti, McRae, & Hatherell, 2001; Wiemer-Hastings & Xu, 2005). It is the student's knowledge representation that we hope to influence in some way with 'visualizations'. For example, by making visually explicit a certain process, we may facilitate a student's ability to make new links between concepts in their knowledge representations, understand new uses for objects, and so on.

The dichotomy between external and internal representations is both theoretically and practically interesting because these two types of representations necessarily interact throughout our daily experiences in a variety of ways. Consider first how often we must convert our mental representations *into* external presentations. Communication, and specifically language, is the best example of this conversion process. When we sit down to write a scientific paper, compose an e-mail, or prepare a grocery list, we are retrieving our internal representations and attempting to reproduce them in some external form. Next, consider that we also continually attempt to develop mental representations *from* external presentations. Readers studying textbook explanations, perusing their e-mail inboxes, and carefully double-checking their shopping lists are transducing external stimuli into mental representations. These activities, the production of internal and external representations, and the comprehension of those internal and external representations, are far from trivial. Many core perceptual and motor processes are necessary for successful language production (e.g., writing) and language comprehension (e.g., reading). Additionally, individual differences across readers and writers, as a function of expertise, learning preferences, and motivation, among other factors, guide those processes (e.g., Chi, Glaser, & Farr, 1988; Dunn & Dunn, 1978; Dweck, 1986; Levelt, 1989). In fact, the degree to which mental and external representations successfully coalesce into mutually-agreed upon, meaningful constructions is quite remarkable (Clark, 1996). Quite clearly, our everyday activities are continually marked by interactions between what is inside and outside our heads.

'Visualizations' as External Representations

Given the above classifications, the 'visualizations' we discuss in this chapter should be thought of as one type of external representation. Science 'visualizations' in classrooms, for example, present data in novel ways to foster student comprehension. These 'visualizations' might include a simulation of a scientific law, a novel grouping of information that makes elements of a scientific explanation more salient, or an innovative method of organizing data that relies on readily familiar grouping principles or conceptual frameworks (e.g., using color as an indicator of temperature). Examples of scientific 'visualizations' include dynamic multimedia demonstrations of physics principles like the swing of a pendulum or gravitational force, animated explanations that use voiceovers to describe the causal antecedents and resulting consequences of seasonal change, and manipulable three-dimensional images of the human brain that can be overlaid with detail to indicate neural and vascular substrates. Each of these visualizations, to name key characteristics, (a) conveys information that would not be easily seen (or is actually impossible to see) with the naked eye, (b) uses symbolic cues like color, icons, and sound to help students identify which elements are key to comprehending the underlying scientific issues (e.g., Tversky, Zacks, Lee, & Heiser, 2000), and (c) likely acts as a simulation that students can review, and in some cases manipulate, to test hypotheses and potentially solve problem sets (e.g., Taylor, Renshaw, & Jensen, 1997). Not all 'visualizations' share these characteristics but we point them out to exemplify some of the elements that may be integral to any potential effectiveness for the methodology.

In line with their label, 'visualizations' are most often visual. However, 'visualizations' can also convey information by necessitating the use of other sensory modalities for their presentations. Sound and proprioceptive feedback, for example, are perceptual cues that could be used to convey critical concepts. Acoustic stimuli might be employed in a 'visualization' of national parks by including songbird calls to indicate the avian species found in local habitats. Raised relief globes rely on touch to deliver scalar information about the surface topography of the Earth. Thus 'visualizations' can include solid physical objects (e.g., desk globes) or immaterial light projections (e.g., holographic images) that utilize images, sounds, text, textures, and other perceptual modifications to convey complex information.

Whatever the format or modality, 'visualizations' depend upon the notion of scaffolding to facilitate learning. Scaffolding is the idea that existing knowledge can be used as a support to guide the understanding of new information. If students know that particular colors are associated with particular temperatures (e.g., red as hot and blue as cold), they can use that information to quickly understand the meaning of color cues in a depth-related water temperature diagram. Or if students want to revisit a particular video demonstration in an interactive 'visualization', the functional controls necessary to rewind or fast forward through the animation would be most effective if they mapped onto those used with traditional VCR and DVD players. 'Visualizations' often rely on interface or content-based metaphors to help students successfully navigate through and understand elements of a novel presentation. In many cases, these scaffolding cues can be quite powerful. Consider that arrows or underlining used to point out key components in a presentation are an excellent method of attracting and maintaining user attention (Heiser & Tversky, 2006). Obviously advertisers use scaffolding cues to promote their products in commercials and in-store displays. For science ‘visualizations’, though, designers and instructors use these cues to help students not just take notice, but to develop a deeper conceptual understanding of scientific principles. These cues can be used to help individuals understand the causal and associative relationships between elements of a ‘visualization’ presentation along with the concepts that underlie their activity, as necessary for comprehending complex explanations and processes in science.

Thinking About Mental Representations (Visualizations)

We now focus on the nature of mental representations, beginning with a broad examination of some of their features. One important thing to consider at the outset is that mental representations are not as complete as one might suspect. Evidence has convincingly demonstrated that, in general, human memory is hardly infallible (e.g., Loftus, Miller, & Burns, 1978; Loftus & Palmer, 1974). Not surprisingly, then, mental representations can be characterized as piecemeal and incomplete (e.g., Franco & Colinvaux, 2000; Norman, 1983; Rapp, 2005; Tversky, in press). What this means is that a student with some knowledge of a concept, like how lightning forms, does not simply retrieve a holistic mental replica of that knowledge from memory (e.g., the text they read or the lecture they attended). Instead, the student retrieves elements of the partial representation he or she has stored of that material, and those fragmented sets of memories must be reassembled in some form. That partial representation, only partially retrieved, is reconstructed during problem solving tasks (e.g., answering a test question about lightning or explaining what one knows about lightning to others).

Besides the limits of our mental representations, a host of other factors constrain our reconstructive processes, and hence our resulting problem solving and decision making activities. Factors such as the nature of a task, the immediate context, our arousal level, and general mood can influence the ways in which we build meaning from our partial knowledge structures. Thinking about mental representations in this way is much different than everyday notions of memory retrieval. Consider the degree to which instructors describe their students as ‘remembering what they studied’ for an exam or ‘calling upon what they had read’ to answer questions in class. It is important to mention that underspecified, piecemeal representations describe both novices’ and experts’ mental representations. The advantages experts enjoy in solving problems derive from qualitative and quantitative differences in what they know, as well as from their practice piecing together important representational elements in their domains of expertise (Chi, Feltovich, & Glaser, 1981; Ericsson, Krampe, & Tesch-Römer, 1993; Reimann, & Chi, 1989).

Understanding the piecemeal nature of mental representations, while useful for thinking about the limits of memory, tells us relatively little about the format of our knowledge. A simple way of conceptualizing this issue is to ask what a memory *looks* like (although the word *looks* should not limit us to thinking about mental representations as visual in nature). While we may feel as if we can build images in our heads, perhaps our mental representations are not visual, or at least not only visual. Surely we can easily imagine the smell of fresh cut grass or our favorite foods. Do these sensory-based phenomenological experiences provide insight into mental representations? Certainly some of our memories appear to resemble complex multimedia presentations. For instance, if you were asked to recall your last argument with someone, or the last time you rode a roller coaster at an amusement park, you might feel as if you could see the situation unfolding like a movie, hear the voices, smell the smells, and even feel your pulse begin to race. Our memories, like this one, can seem quite vivid.

While our introspections about memory suggest certain qualitative features that 'feel right,' we must be careful in ascribing any explanatory validity to them. Consider the following analogy: Computer printers do not contain words and sentences pre-stored in their systems. Rather, computer peripherals like printers rely on a language of binary digits that are translated into the patterns we interpret as printed language. The 'internal representations' of a printer (i.e., 0s and 1s), are quite unlike the external representations that are produced (i.e., words and images). Looking at a printout, we would never gain insight into the units (0s and 1s) comprising the printer's internal programming language. Similarly, we cannot rely on introspections (our verbal productions, or printouts, if you will) to gain insight into the basic components of memory. What, then, does research and theory actually suggest about the underlying nature of our mental representations?

Amodal vs. Perceptual Views of Mental Representations

To date, notions of what mental representations are like can be categorized into two general views. Each view has obtained evidence for their basic proposals, and current debates as to the validity of each view continues unabated (although, as will become clear from our discussion, one view has gained considerable support for its tenets from neural, behavioral, and philosophical investigations). We now discuss these two general perspectives, as they provide the foundation for thinking about how visualizations, and really a broad variety of educational experiences, may be represented in memory.

The *amodal* view of mental representations likens knowledge to a set of nodes in memory. These nodes hold information in some abstract form, composed of arbitrary symbols (which we will refer to as amodal symbols) that are not related in any systematic way to our real-world experiences of them (Anderson & Lebiere, 1998; Graesser & Clark, 1985; Newell & Simon, 1972; Pylyshyn, 1981; Van Dijk & Kintsch, 1983). An appropriate analogy might be to think about the way most words are related to their underlying concepts. Some words have some form of relationship with their associated concept, as in the case of onomatopoeia (i.e., 'pow,' or 'purr'), but the majority of English words do not. The word 'dog' does not have any inherent relationship to the concept of dog, but is set of symbols that, in English, has been selected to convey that concept. Similarly, amodal symbols have no inherent relationship to the concepts they represent. Amodal views, however, go further by suggesting that the underlying 'language' of mental representations need not bear similarity to any known communicative or perceptual form. Amodal theories assume that knowledge is represented as the association of these arbitrary symbols in node-based networks (Newell & Simon, 1972). Thought, then, involves the manipulation of these amodal symbols using rules, propositions, and processing procedures (cf. Harnad, 1990).

Why should we believe that amodal symbols are a viable description of how information is stored in memory? Some researchers have argued that amodal symbols provide a good explanation of abstract thought and reasoning; that is, reasoning that does not or could not involve actual experience (Pylyshyn, 1981). For example, Pylyshyn (2002) argues that people can easily imagine situations they could never experience. Consider, again, a situation wherein a baseball player hits a ball hard enough to launch it into outer space. While we have little difficulty considering such a situation, it is not based on any previously experienced event. Thus, we must somehow be able to store and construct this situation in our heads without any directly suitable perceptual analogs. In addition, many theories of text comprehension assume that the mental representations readers build during reading are, in general, composed of propositions and arbitrary symbols (e.g., Kintsch, 1998; Van Dijk & Kintsch, 1983). The theoretical underpinnings of this issue are beyond the scope of this chapter; however, the general notion is that readers comprehend sentences by decomposing them into their propositional idea units, and those units are amodal in nature.

Amodal symbols, as a description of how we represent knowledge, have much to recommend them. Because of their abstract nature, amodal symbols are amenable to computation, and as such, can potentially describe the ways in which we process information. If all knowledge is stored in an amodal format, it need not matter whether experiences are verbal, visual, or imagined, because in the end, all experiences would be coded in the same abstract format. Additionally, an amodal code could be combined and reconstituted in countless ways. In other words, the 'common code' underlying amodal representations affords an easy way for memory nodes, regardless of how or when they were encoded, to interact and communicate. All that would be required is that the human processing system understand the computations underlying the transformations from real experience to abstract code (e.g., from what we hear to what is stored in memory) and from abstract code to output (e.g., from what is stored in memory to what we say or do).

However, potential problems for amodal accounts quickly emerge when we consider the ontogeny of those symbols. How do our processing systems *learn* an amodal symbols code? Harnad (1990) used the well-known Chinese Room problem, introduced by Searle (1980), to describe one inherent challenge facing purely amodal explanations. Imagine you are in a foreign country and do not speak the language. As an aid, you carry a dictionary published in the language of that country, but unfortunately, you possess no translation of the contents of that dictionary into your own native language. When you hear a word in the foreign language, you attempt to look it up in your dictionary to understand it. Even if you could find the appropriate entry, the dictionary only defines that word using the same incomprehensible (to you) language. How could you hope to eventually figure out that foreign language? The amodal symbols view falls victim to an analogous problem: Without appropriate links to direct meaning, amodal symbols are inherently untranslatable, and hence uninterpretable, to the human processor. One way to solve the Chinese Room problem is to ground some aspect of the dictionary to elements of the real world that are readily understood. For example, the Chinese Room problem could be at least partially resolved by looking at a storefront displaying a sign in the foreign language, assessing what it sells, finding words that were contained in the sign within the dictionary, and assuming that the words and meanings in the relevant dictionary entries are somehow related to the store's wares. Unfortunately, amodal theories in general provide no mechanism for such grounding to occur in memory, as they are based purely on abstract symbols. Thus, a problem for this view of mental representations is that it does not provide an adequate and necessary account of how mental representations are formed.

In response to this problem, recent *perceptual* theories of knowledge representation have suggested that the brain systems involved in perception and action are central to cognition (Barsalou, 1999; Glenberg, 1997; Zwaan, 2004), and hence, knowledge acquisition. Thus, when we think of a concept, we conduct mental simulation (Kahneman & Tversky 1982) that reactivates the brain systems recruited during actual perception. These simulations are, then, mental reenactments of the perceptual experiences associated with some concept or experience. Perceptual theories of knowledge assume that representations are modality specific – visual experiences lead to representations that are imagistic; tactile experiences lead to representations that encode touch in some way. When representations from different perceptual sources are combined, which is nontrivial since different representations presumably have different perceptual codes, they potentially become multimodal. Despite the translation problem inherent to combining representations, perceptual views, unlike amodal views, can describe how representations develop. Our mental representations are embodied, in the sense that they are precisely linked to the real world concepts and sensory perceptions we have experienced (Barsalou, 1999; Glenberg, 1997; Hesslow, 2002; Lakoff & Johnson, 1980; Svensson & Ziemke, 2004; Zwaan, 2004).

Most importantly, a growing body of evidence has supported perceptual rather than amodal accounts of mental representation. This evidence is based on both neuropsychological research and behavioral studies. For example, Martin, Haxby, Lalonde, Wiggs, and Ungerleider (1995) found that the cortical regions proximal to those involved in color perception were activated when participants named the colors associated with objects. In addition, other areas of the cortex associated with the perception of motion were activated when participants were required to name actions associated with objects (see also Martin, Wiggs, Ungerleider, & Haxby, 1996). Similarly, Kellenbach, Brett, and Patterson (2001) found activation in cortical areas associated with audition when participants retrieved information about the sound properties associated with objects. More generally, motor regions of the brain appear to activate when participants are shown pictures of tools and objects that can be manipulated (Chao & Martin, 2000; Gerlach, Law, & Paulson, 2002; Grafton, Fadiga, Arbib, & Rizzolatti, 1997; Kellenbach, Brett, and Patterson, 2001; Martin & Chao, 2001). Across all of these studies, tasks that require individuals to simply think about particular objects or concepts seem to recruit the neural systems responsible for actual perception of those objects or concepts.

Behavioral studies have also provided support for the notion that perceptual simulations underlie cognition, and in particular, language comprehension (Stanfield & Zwaan, 2001; Zwaan, Stanfield, & Yaxley, 2002). For example, Zwaan, Madden, Yaxley, and Aveyard (2004) demonstrated that readers simulate the motion depicted by language. In their experiments, participants were presented with sentences that implied an object was moving either toward or away from the reader. For example, the sentence 'You threw the baseball to the catcher' implies motion moving away from the reader. After reading a sentence, participants were next presented with two sequential pictures of a single object (e.g., a baseball), in which the second picture was either slightly smaller or larger than the first. Consider that objects appear smaller as they move away from us, but larger as they approach. Participants took longer to determine whether the two sequential pictures were of the same object when the pictures depicted movement (as a function of a change in size) in a direction opposite to that suggested by the sentence. For our example sentence, in which the ball is described as moving away, participants were slower to identify the baseball pictures as depicting the same object when the baseballs appeared to grow in size, in contrast to when they appeared to diminish in size. These results, as well as other studies looking at matches and mismatches between text descriptions and their perceptual correlates, suggest that the mental representations responsible for our comprehension of language likely involve perceptual simulation of those descriptions ((Fincher-Kiefer, 2001; Glenberg & Kaschak, 2002; Horton & Rapp, 2003; Kaschak et al., 2005; Pecher, Zeelenberg, & Barsalou, 2003; Stanfield & Zwaan, 2001; Zwaan et al., 2002; Zwaan & Yaxley, 2004, 2005).

Modality-specific Representations

Based on empirical evidence, the prevailing view is that our mental representations are, to a large degree, embodied by our actual experiences with the external world and its external representations. In fact, this general philosophical view has been invoked, if not explicitly then implicitly, in classic theories of memory processes from the cognitive sciences. These earlier theories of memory processing under gird perceptual views of mental representation. But in contrast to perceptual views, which focus on the degree to which mental representations as a group tend to share certain inherent characteristics, these classic memory theories have focused more specifically on how mental representations develop as a function of the particular characteristics of a learning experience. Such theories were intended to describe how different types of memory processes, structures, and products are a function of different tasks, activities, and stimuli. This early work aligns nicely with our interest in what memory looks like as a function of learning methodologies. In this section, we describe how learning modalities influence what we store in memory, by discussing classic theories of memory processes.

Individuals can learn with different types of materials, including descriptive texts, detailed illustrations, engaging verbal descriptions, and immersive multimedia simulations. Not surprisingly though, not all learning experiences are created equal. By this we do not mean to suggest that specific methodologies are always more or less likely to succeed in some objective way (an issue, it turns out, that is particularly important to educational researchers, e.g., Woolfolk, 2004), but rather that these different experiences may result in different types of mental representations. This view derives from research on conditions that improve and impede memory, much of which has focused on the ways in which individuals learn lists of information (e.g., words or word pairs).

One view based on this work suggests that individuals can mentally represent information in at least two different formats: a visual code and a verbal code. Paivio's dual-coding theory (1971, 1986) suggests that when individuals encounter some word, they may elect to store that information in memory by imagining what it looks like (i.e., reading or hearing the word 'tiger' and imagining a tiger) or based mainly on the verbal stimulus (i.e., what the word 'tiger' sounds like or the letters in 'tiger' look like). A dual-coding view suggests that information can be represented in these formats, depending on a variety of factors. In fact, evidence suggests that the nature of the to-be-remembered stimuli often determines, at least in part, the particular format that information might be encoded in, as well as the likelihood that the information will be available for later retrieval (Paivio, 1983). What are some of the critical factors in this process?

Words can differ in a variety of ways, but one oft-studied variable is the degree to which words convey concrete or abstract concepts. According to Paivio, the concrete or abstract nature of concepts influences the ways in which they are encoded. Consider concrete words such as 'cat,' 'telephone,' or 'ball.' These words can be encoded into a visual format, relying on an image-based representation of the objects based on our prior experiences with them in the real world, and/or a verbal format, relying on the phonological, orthographic, and acoustic properties of the words. Abstract words such as 'freedom,' 'perplex,' and 'species,' in contrast, are not easily imagined and are instead encoded in a verbal format. For example, it is harder to establish an exemplary image for the notion of 'freedom' without invoking other concrete objects and thus abstract concepts like this one are less amenable to visual representation.

Evidence for differential memory effects as a function of a concept's concrete-abstract qualities comes from work on the picture-superiority effect (e.g., Nelson, Reed, & Walling, 1976; Paivio & Csapo, 1973). When participants are asked to study words for later recall, they are more likely to remember concrete than abstract words. This is, presumably, at least partially a function of the degree to which concrete words can be represented in visual and verbal formats, while abstract words are restricted to the verbal format. In sum, the degree to which a particular concept is visualizable can confer a memory advantage for later recall. This important evidence reinforces our earlier statement that different stimuli may afford different types of representations, with concomitant effects on memory retrieval as a function of those representations. Again, the dual-coding view aligns nicely with perceptual views of mental representation. Learning benefits accrue as a function of how easily we can develop a visual image of to-be-studied information, a notion that relies directly on the perceptual (in this case, visual) properties associated with some concept.

We note that there has been some criticism of dual coding theory. Some have argued that the picture-superiority effect is mainly due to tendencies to devote deeper processing to pictures than words. That is, it may not be the visual code itself that facilitates memory but rather individuals' propensities for how they elect to process visual information. Indeed, the recall benefits enjoyed by concrete words as compared to abstract ones can be reduced with instructions asking individuals to process abstract words more deeply (Paivio, 1991). Regardless of why memory for pictures is better than words, the dual-coding findings suggest that the use of pictures over words whenever possible may be beneficial in enhancing memory.

Another influential view that has suggested individuals can code information based on modality-specific features is derived from Baddeley's working memory model (Baddeley, 1986). Working memory exemplifies the storehouse in which we maintain attentional focus for things we are currently thinking about, whether those thoughts are driven by information from the environment or concepts we have retrieved from prior knowledge. Baddeley's model of working memory goes further to describe both the underlying mental structures that comprise working memory, as well as the processes involved in its activity (e.g., Baddeley, 1992). According to the model, working memory is made up of three components, each devoted to the operation of the human memory and information processing system (Baddeley, & Lieberman, 1980; Baddeley & Logic, 1999).

Two working memory components, termed subsystems, are devoted to the processing and storage of information in a particular modality (and hence can be considered modality specific). The *phonological loop* is responsible for acoustic stimuli, generally. When we listen to a lecture, and mentally imagine hearing particular words or phrases from that lecture, we are maintaining the spoken stimuli in this storage subsystem. Maintaining information in this loop involves the mental rehearsal of sound stimuli. In contrast, the *visuospatial sketchpad* is responsible for visual and spatial stimuli, generally. We rely on this subsystem to think about the shapes and colors of objects, and their locations in space. This subsystem is the mental workspace necessary for considering the relationship between two spatial regions, such as when we attempt to figure out the fastest route from home to work. Taken together, the phonological loop and the visuospatial sketchpad are structures that allow us to keep information active during moment-by-moment comprehension.

The third working memory component, the central executive, is responsible for coordinating activities between the two subsystems. The central executive acts as a control processor, allocating precious mental resources to each subsystem. An account of how resources are allocated to each subsystem is necessary to explain both the successes and failures of the human processing system. In particular, failures provide important insight into the nature of working memory. In Baddeley's view, and as supported by considerable research evidence, each subsystem can be taxed depending on the qualitative and quantitative difficulty of a particular task (Baddeley & Hitch, 1974). When tasks continue to tap a particular subsystem, the potential for overload increases, and performance suffers. In contrast, when tasks allow individuals to rely on both subsystems, overload can be avoided. So, one way to decrease the likelihood of one type of learning failure is to provide information in multiple formats, allowing individuals to rely on both subsystems during processing.

The views offered by Paivio and Baddeley, while focusing on different elements of everyday experiences, share some critical characteristics for this review. Note, as with Paivio's view, that the subsystems of Baddeley's model are organized around the perceptual qualities of an experience; the acoustic and visual characteristics of stimuli are critical factors in determining whether and how information remains active in working memory (and eventually accrues enough attention and rehearsal to facilitate encoding into more permanent, long-term memory). Also like Paivio's dual-coding model, Baddeley's working memory model suggests that learning benefits can result when information is encoded in more than one format. These theories, while focusing on the modality-specific characteristics of memory, seem to suggest that the construction of a multi-modal representation can foster effective learning. We turn to this issue next.

Mental Representations in Multiple Modalities

Both Baddeley's and Paivio's work on the systems responsible for maintaining mental representations, and the underlying nature of those representations, have been incredibly influential in describing the basic cognitive processes and structures involved in human memory. But just as importantly, this work has had a considerable impact on our practical understanding of conditions that might foster effective learning. That is, these scientific models have had a great degree of applied value for education. Most obviously, both of the views have been taken to suggest that learning experiences should be presented to students in a form that fosters the development of multimodal representations in memory.

Recall that concrete concepts allow individuals to build both verbal and visual representations, and coding information in these two formats increases the likelihood of successful encoding into memory and successful retrieval at a later time point. Similarly, information that is coded in both of these formats can utilize the separate subsystems in working memory, reducing the likelihood of single subsystem overload. Thus, information should be presented in multiple modalities to ensure that individuals will remember the contents of a learning experience.

The complementary nature of a well-designed multi-modal presentation can help consolidate working memory resources, provide conceptual redundancy, and encourage students to make connections across presentation modalities, all in the service of facilitating memory for the material in presentations (Mayer, 2001). For example, students demonstrate better memory for simple procedural tasks (e.g., how to put together a small object) after viewing multimodal (e.g., text and picture) rather than single modality (e.g., text or picture) presentations (Brunyé, Taylor, Rapp, & Spiro, 2006). Multimodal representations presumably result from multimodal or multimedia experiences, and the benefits are quite compelling.

Researchers have built up a considerable literature on this issue by specifically examining both how and why multimedia presentations foster the development of multimodal representations in memory. These investigations have, to a large degree, had a particularly educational focus; they have considered the conditions under which students will most effectively learn complex topics. For instance, Mayer and colleagues (e.g., Mayer & Anderson, 1992; Mayer, Heiser, & Lonn, 2001; Mayer & Moreno, 2003; Mayer & Sims, 1994; Moreno & Mayer, 1999) have focused on the ways in which multimedia presentations that include pictures, sounds, and text can help or hinder students' understanding of complex scientific explanations. In their work, participants are asked to view multimedia presentations that describe, as examples, how lightning forms, how brakes operate, and how air pumps function (Mayer, 2001; Mayer, 2003). By manipulating, again as examples, the degree to which information in one format (e.g., a text description) is complementary or redundant with another format (e.g., an illustration), or whether information in the two formats is presented simultaneously or sequentially, this work has assessed the qualities of multimedia presentations that prove most effective for learning.

Most importantly, the hypotheses generated in these studies have relied directly on theories of mental representations. Again, consider what dual-coding and working memory research suggests about multimedia presentations. Mayer (2001), in line with these views, argues that if individuals experience both visual and verbal presentations, they are more likely to remember that information later, in contrast to single-format presentations. This does not mean that multimedia presentations are a panacea; certainly a poorly designed multimedia presentation is going to have little positive impact on a student's acquisition of knowledge. But the nature of memory is such that, with appropriate design, careful organization of material, and a consideration of the content that would be best presented in a visual or verbal format, we might expect educational methodologies to potentially benefit from multimedia experiences.

The issues inherent to the viability of multimedia presentations as effective learning tools, and the findings derived from the above cited studies, are certainly appropriate for thinking about the conditions that foster learning, and what those conditions suggest for effective educational design and implementation. We now turn to a brief review of current research that examines matches between the perceptual nature of representations, and the activities required to learn various concepts. We follow this discussion with some brief recommendations for the use of educational methodologies, including visualizations, as informed by work on mental representations and memory.

Implications for Learning Experiences

Earlier in this chapter we discussed the nature of mental representations by considering both amodal and perceptual views. Classic theories of memory align with current perceptual views, given their mutual reliance on sensory systems during memory encoding and retrieval. And recent work suggests that perceptual views, as compared to amodal views, provide a better account of the extant biological and behavioral data with respect to performance on memory, decision making, and comprehension tasks. The accumulated findings suggest that participants draw upon perceptual representations to understand situations, and that the mental representations we build from an experience rely on the perceptual features of those situations. One of the most exciting elements of this work is that a framework focused on the importance of the perceptual qualities of experiences obviously suggests the need for an emphasis on such features during learning situations. Simply put, providing learners with perceptually salient experiences that align with sensory-based modalities should increase the likelihood that, all other things being equal (e.g., motivation and interest, arousal level), students will retain what they study.

Of course, the implications of these ideas are hardly new, particularly in science classrooms. Well-worn teaching methodologies including activity-based learning, problem-based assessment, role-playing assignments, and hands-on laboratory activities have historically played an important role in science learning. Each of these methodologies relies on the notion that students will more effectively learn when they actively engage with course material in a direct way. However, these methodologies should also work, as suggested in this review, as a function of aligning with perceptual experiences. Chemistry labs, botany field trips, and in-class physics experiments embody the underlying concepts being taught in their respective classes. For each of these cases, students can build representations as a function of their direct, perceptual experiences with the course content. So a relatively novel expectation for these activities is that building and retrieving memories that are directly linked to our actual perceptual experiences can lead to performance benefits.

Consider some of the existing empirical evidence with respect to this view. When learning how to use a compass, novice students were more successful if presented with instructions to use the compass along with a video depicting a hand operating the compass, as compared to when students simply listened to and read a text on the topic (Glenberg & Robertson, 1999). That is, participants could utilize the perceptual information provided by the video to build an understanding of the object rather than working only with written instructions. The benefits of actually working with material are not limited to the use of specific tools. Second graders' comprehension of narrative events also appears to benefit from physically manipulating objects (Glenberg, Gutierrez, Levin, Japuntich, & Kaschak, 2004). Children demonstrate better memory for narratives and a better understanding of the spatial relationships described in them after acting out story scenarios using toys, or even just imagining using the toys to act out the scenarios, than if they simply read and re-read the stories. Presumably the perceptual information afforded through physical action with the toys, and through mental simulation with those toys, helped the children form conceptually grounded mental models of the events. As another example, even abstract concepts may benefit from scaffolding to well known perceptual activities. Valenzeno, Alibali, and Klatzky (2003) showed that teachers' gestures facilitated children's learning of concepts (e.g., symmetry) when physical movements were used to point out structural differences between objects that exemplified those concepts (also see Alibali, 2005).

To show the benefits of perceptually-relevant activities, we now focus on one particular study from our own labs. This specific line of research focuses on the utility of 'visualizations' for fostering comprehension of topics and procedures in the Earth Sciences. In one of our projects, we have investigated whether enhancing the perceptual features of 'visualizations' can help students develop comprehension-based skills that traditionally require significant study time to acquire. Consider that in most Earth Science classrooms, instructors must spend a significant portion of class time teaching students how to read graphs and maps. These training periods are both critical and necessary, as they set the foundation for understanding the more content-driven topics to be covered as the semester unfolds. Because training on these topics, for novices, is often necessarily extensive, and because failure to acquire these skills is so detrimental to performance in later sections of courses, it is important to determine how to effectively and efficiently help students acquire these skills. Topographic maps are an excellent case example, as they are requisite for studying advanced topics in the Earth Sciences, and because they often present clear difficulty for novices to use. Thus, we examined the degree to which novel visualizations of topographic maps might help students work more effectively with the maps (Rapp, Culpepper, Kirkby, & Morin, in press).

In our experiments, novice Earth Science students studied topographic maps that were presented as traditional flat maps, maps with shading to provide some indication of height, maps printed in 3-D (and viewed as such using polarized spectacles) that more directly embodied the notion of height differences along topographic lines, or maps that contained both 3-D and shading cues. These latter three conditions are relatively novel 'visualizations' for topographic map training coursework. After studying their maps, participants were asked to answer perspective-based questions about the map content, with their studied map visible during the task. These questions asked students to determine whether a person standing at a particular location would be able to see objects at other locations. These types of tasks tap into some of the skills, and exemplify some of the activities, indicative of successful map use (e.g., Eley, 1991; Pick et al., 1995). Results showed that the 3-D map led to the best performance. In fact, the combination of shading and 3-D did not lead to additional benefits beyond those obtained for the 3-D maps alone. Because the 3-D maps contained salient, perceptual cues as to height, depth, and the topography of the map terrain, they presumably helped students more directly envision the relationships between particular map regions than traditional topographic maps or maps that included shading cues. Current studies are investigating the limits of these visualization benefits by assessing topographic map comprehension as a function of other performance measures (e.g., hypothesis testing, predictive inferences), as well as individual differences between map users (e.g., prior knowledge, spatial ability, gender).

An important issue that studies like these will need to assess is whether any learning benefits also result in transfer benefits; that is, whether the skills or knowledge acquired through these perceptually-driven interventions enhance performance on other similar and relatively dissimilar tasks. While some studies have suggested that perceptual experiences may be less effective at fostering transfer than more abstract ones (Sloutsky, Kaminski, & Heckler, 2005), there are also projects that have demonstrated effective transfer across perceptually similar domains of moderate conceptual similarity (Taylor, Renshaw, & Choi, 2004). The relationships between abstract or perceptual symbols to the particular learning domain, the method by which those symbols are directly or indirectly integrated into the learning activity, and the importance of the information conveyed by those symbols to the knowledge or skill being acquired are but a few factors to consider in terms of both acquisition and transfer (e.g., Goldstone & Sakamoto, 2003). Future work should examine the retention and likelihood of knowledge transfer following tasks that embody the perceptual remnants of mental representations.

Implications for Educational Methodologies

Given our introductory presentation on internal and external representations, it should be apparent that educational methodologies, and in particular 'visualizations', might benefit from a consideration of the nature of memory. One way to formalize this is to suggest that the internal representations we wish individuals to acquire should be directly guided by the external presentations we offer our students. For example, 'visualizations' that seek to describe a particular domain should include presentations and activities that engender, and indeed foster, the performance criteria expected from the task. If we wish our students to understand how to read topographic maps, and we understand some of the difficulties those students have with such activities, we can (a) design activities that directly address those difficulties and (b) require performance that aligns with what we desire students to accomplish with those maps. If the mental representations that students build are a direct function of their learning experiences, we should then create learning environments that exemplify what we hope students will be able to do. Some of these activities might rely on perceptual features, while others might focus more on motor activities or deductive reasoning.

In addition, one of the major benefits of 'visualizations' is that they can present information in novel ways. These novel presentations often rely directly on substantially innovative organizations of perceptual features (e.g., 3-dimensional simulations of earthquakes within the Earth's surface; color-coded clusters of geographical regions as a function of underlying mineral compositions; schematic, linear animations of developing weather systems), and thus they might reasonably take advantage of the nature of memory mechanisms and subsystems. As research on memory has suggested, care must be taken to avoid overloading any particular subsystem. In that sense, both 'visualizations' and the classroom or homework activities linked to those visualizations should allow students to allocate resources to multiple memory subsystems. This might involve presentations that carefully utilize both text and images (see Mayer, 2001, for discussion of effective design), to help students to build both visual and verbal representations.

Third, and perhaps most importantly, what we learn from any task, including one that involves 'visualizations', is clearly not restricted to the particular learning methodology itself. Rather, what we learn from a 'visualization' is a function of our prior knowledge, the task, our individual goals (which may or may not be derived directly from the task), the interface, the content of the 'visualizations', the design of the 'visualization', and so forth. Indeed our mental representations are built not just from what we see and hear but from what we already have stored in memory. Careful thought must be put into the design of a complete visualization experience, and not just the visual portion of that experience (Rapp, 2005; Rapp & Uttal, 2006). To ensure students will learn from what they are doing, a preliminary task analysis designed to assess precisely what the instructor wants the student to know, and why (as well as how) the 'visualization' might be a useful tool for doing this, is most beneficial. Careful preparation can provide useful guidance for thinking about and implementing effective educational design.

If 'visualizations' are designed in relation to how we actually process that information in the real world, we can engender internal representations that can be used in the future to solve real world problems. For example, the earlier mentioned research by Glenberg et al. (2004) demonstrated that teaching students an internal visualization procedure (imagery) can foster success for later comprehension experiences. This shows that internal visualizations may be quite useful for dealing with novel situations. By designing 'visualizations' that better match how humans represent the world, we may be able to facilitate a student's ability to mentally manipulate that information (e.g., via imagery). This, then, may enhance a student's ability to recognize when the concept learned during the visualization process is relevant to other situations.

These implications, derived from our general understanding of mental representations, may not necessarily be surprising. But time and again 'visualizations' are designed predominantly as a function of technological availability or designer interest in a topic, rather than as a function of technological validity or designer-informed goals for a particular learning experience. By taking into account what we know about the conditions that foster learning, the mechanisms that underlie such learning, and the degree to which we can align particular methodologies with those research literatures, we can better address instructional challenges. 'Visualizations' on their own are not a panacea, but we contend that by coupling what we know about 'visualization' design with research on how students learn, we can improve the likelihood of students acquiring core competencies in their science coursework.

Conclusion

In this chapter we have described the underlying nature of memory. We have focused specifically on what remains after learning by considering some perspectives from cognitive science on the perceptual attributes of knowledge. Internal representations, those memories we hope to engender in our students, are directly influenced by the external stimuli they experience. ‘Visualizations’, as an educational methodology, are one type of experience that might be useful for teaching complex scientific concepts. By designing ‘visualizations’ in ways that align with the nature of memory, it may be possible to more effectively help students understand those challenging concepts. In addition to finding better ways for students to learn complex concepts, ‘visualizations’ may also aid students in dealing with unfamiliar, but potentially related, problem solving situations.

Research evidence is really only beginning to show the utility of such alignments. We hope that researchers will continue to make connections with basic research on learning pedagogy in their examinations of the effectiveness of science ‘visualizations’. Such connections can be useful for developing implications that improve the effectiveness of visualizations as tools in science classrooms, as well as explaining the nature, and mechanisms, of any potential learning benefits (Rapp, 2006).

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References

Alibali, M. W. (2005). Gesture in spatial cognition: Expressing, communicating, and thinking about spatial information. *Spatial Cognition and Computation, 5,* 307–331.

Anderson, J. R., & Lebiere , C. (1998). *The atomic components of thought.* Mahwah, NJ: Lawrence Erlbaum Associates.

Baddeley, A. D. (1986). *Working memory*. Oxford, UK: Clarendon Books.

Baddeley, A. D. (1992). Working memory. *Science*, 255, 556–559.

Baddeley, A. D., & Hitch , G. J. (1974). Working memory. In G. H. Bower (Ed.), *Recent Advances in learning and motivation* (Vol. 8, pp. 47–90). New York: Academic Press.

Baddeley, A. D., & Lieberman , K. (1980). Spatial working memory. In R. S. Nickerson (Ed.), *Attention and performance VIII* (pp. 521–539). Hillsdale, NJ: Lawrence Erlbaum Associates.

Baddeley, A. D., & Logic, R. H. (1999). Working memory: The multiple-component model. In A. Miyake & P. Shah (Eds.), *Models of working memory* (pp. 28–61). Cambridge, UK: Cambridge University Press.

Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral & Brain Sciences, 22,* 577–660.

Barsalou, L. W., & Hale, C. R. (1993). Components of conceptual representation: From feature lists to recursive frames. In I. Van Mechelen, J. Hampton, R. Michalski, & P. Theuns (Eds.), *Categories and concepts: Theoretical views and inductive data analysis* (pp. 97–144). San Diego, CA: Academic Press.

Behrmann, M. (2005). The mind's eye mapped onto the brain's matter. In B.A. Spellman & D.T. Willingham (Eds.), *Current Directions in Cognitive Science. Readings from the American Psychological Society* (pp. 11–18). Upper Saddle River, NJ: Pearson Education.

Brunyé, T. T., Taylor, H. A., Rapp, D. N., & Spiro, A. B. (2006). Learning procedures: The role of working memory in multimedia learning experiences. *Applied Cognitive Psychology*, 20, 917–940.

Chao, L.L., & Martin, A. (2000). Representation of manipulable man-made objects in the dorsal stream. *Neuroimage, 12*, 478–484.

Chi, M. T. H., Feltovich, P., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science*, 5, 121–152.

Chi, M. T. H., Glaser, R., & Farr. M. (Eds.). (1988). *The nature of expertise*. Hillsdale, NJ: LEA.

Clark, H. H. (1996). *Using language*. Cambridge: Cambridge University Press.

Dunn, K., & Dunn, R. (1978). *Teaching students through their individual learning styles*. Reston, VA: National Council of Principals.

Dweck, C. (1986). Motivational processes affecting learning. *American Psychologist*, 41, 1040–1047.

Eley, M. G. (1991.) Selective encoding in the interpretation of topographic maps. *Applied Cognitive Psychology*, 5, 403–422.

Ericsson, K. A., Krampe, R. T., & Tesch-Römer, C. (1993). *Psychological Review, 100,* 363–406.

Ferretti, T. R., McRae, K., & Hatherell, A. (2001). Integrating verbs, situation Schemas, and thematic role concepts. *Journal of Memory and Language, 44*, 516–547.

Fincher-Kiefer, R. (2001). Perceptual components of situation models. *Memory & Cognition, 29*, 336–343.

Franco, C., & Colinvaux, D. (2000). Grasping mental models. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education* (pp. 93–118). Boston, MA: Kluwer Academic Publishers.

Gerlach, C., Law, I., & Paulson, O. B. (2002). When action turns into words: Activation of motor-based knowledge during categorization of manipulable objects. *Journal of Cognitive Neuroscience, 14*, 1230–1239.

Glenberg, A. M. (1997). What memory is for. *Behavioral and Brain Sciences, 20*, 1–55.

Glenberg, A. M., Gutierrez, T., Levin, J. R., Japuntich, S., & Kaschak, M .P. (2004). Activity and imagined activity can enhance young children's reading comprehension. *Journal of Educational Psychology, 96*, 424–436.

Glenberg, A. M., & Kaschak, M. P. (2002). Grounding language in action. *Psychological Bulletin & Review, 9*, 558–565.

Glenberg, A. M., & Robertson, D. A. (1999). Indexical understanding of instructions. *Discourse Processes, 28*, 1–26.

Goldstone, R. L., & Sakamoto , Y. (2003). The transfer of abstract principles governing complex adaptive systems. *Cognitive Psychology, 46*, 414–466.

Graesser, A. C., & Clark, L. F. (1985). *Structures and procedures of implicit knowledge.* Norwood, NJ: Ablex.

Grafton, S. T., Arbib, M. A., Fadiga, L., & Rizzolatti, G. (1996). Localization of grasp representations in humans by positron emission tomography – 2. Observation compared with imagination. *Experimental Brain Research, 112*, 103–111.

Harnad, S. (1990). The symbol grounding problem. *Physica D, 42*, 335–346.

Hegarty, M. (2004). Mechanical reasoning by mental simulation. *Trends in Cognitive Sciences, 8*, 280–285.

Heiser, J., & Tversky, B. (2006). Arrows in comprehending and producing mechanical Diagrams. *Cognitive Science*, 30, 581–592.

Hesslow, G. (2002). Conscious thought as simulation of behaviour and perception. *Trends in Cognitive Sciences, 6*, 242–24.

Horton, W. S., & Rapp, D. N. (2003). Out of sight, out of mind: Occlusion and the accessibility of information in narrative comprehension. *Psychonomic Bulletin & Review, 10*, 104–109.

Johnson-Laird, P. N. (1980). *Cognitive Science, 4*, 71–115.

Kahneman, D., & Tversky, A. (1982). The simulation heuristic. In D. Kahneman, P. Slovic, & A. Tversky (Eds.), *Judgment under uncertainty: Heuristics and biases* (pp. 201–208). New York: Cambridge University Press.

Kaschak, M. P., Madden, C. J., Therriault, D. J., Yaxley, R. H., Aveyard, M., Blanchard, A. A., et al. (2005). Perception of motion affects language processing. *Cognition, 94*, B79–B89.

Kellenbach, M. L., Brett, M., & Patterson, K. (2001). Large, colorful, or noisy? Attribute- and modality-specific activations during retrieval of perceptual attribute knowledge. *Cognitive, Affective, & Behavioral Neuroscience, 1*, 207–221.

Kintsch, W. (1998). *Comprehension: A paradigm for cognition*. Cambridge, UK: Cambridge University Press.

Kosslyn, S. M. (1994). *Image and brain: The resolution of the imagery debate.* Cambridge, MA: MIT Press.

Lakoff, G., & Johnson, M. (1980) *Metaphors we live by.* Chicago: University of Chicago Press.

Levelt, W. J. M. (1989). *Speaking: From intention to articulation*. Cambridge, MA: MIT Press.

Loftus, E. F., Miller, D. G., & Burns, H. J. (1978). Semantic integration of verbal information into a visual memory. *Journal of Experimental Psychology: Human Learning and Memory*, 4, 19–31.

Loftus, E. F., & Palmer, J. C. (1974). Reconstruction of automobile destruction: An example of the interaction between language and memory. *Journal of Verbal Learning and Verbal Behavior*, 13, 585–589.

Markman, A. B. (1999). *Knowledge Representation.* Mahwah, NJ: Lawrence Erlbaum Associates.

Martin, A., & Chao, L. L. (2001). Semantic memory and the brain: Structure and processes. *Current Opinion in Neurobiology, 11*, 194–201.

Martin, A., Haxby, J. V., Lalonde, F. M., Wiggs, C. L., & Ungerleider, L. G. (1995) Discrete cortical regions associated with knowledge of color and knowledge of action. *Science, 270*, 102–105.

Martin, A., Wiggs, C. L., Ungerleider, L. G., & Haxby, J. V. (1996) Neural correlates of category-specific knowledge. *Nature, 379*, 649–652.

Mayer, R. E. (2001). *Multimedia learning*. New York: Cambridge University Press.

Mayer, R. E. (2003). The promise of multimedia learning: Using the same instructional design methods across different media. *Learning and Instruction*, 13, 125–139.

Mayer, R. E., & Anderson, R. B. (1992). The instructive animation: Helping students build connections between words and pictures in multimedia learning. *Journal of Educational Psychology*, 84, 444–452.

Mayer, R. E., Heiser, J., & Lonn, S. (2001). Cognitive constraints on multimedia learning: When presenting more material results in less understanding. *Journal of Educational Psychology*, 93, 187–198.

Mayer, R. E., & Moreno , R. (2003). Nine ways to reduce cognitive load in multimedia learning. *Educational Psychologist*, 38, 43–52.

Mayer, R. E., & Sims, 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, 389–401.

Minsky, M. (1975). A framework for representing knowledge. In P. H. Winston (Ed.), *The psychology of computer vision* (pp. 211–277). New York: McGraw Hill.

Moreno, R., & Mayer, R. E. (1999). Cognitive principles of multimedia learning: The role of modality and contiguity. *Journal of Educational Psychology*, 91, 358–368.

Nelson, D. L., Reed, U. S., & Walling, J. R. (1976). Picture superiority effect. *Journal of Experimental Psychology: Human Learning & Memory*,2, 523–528.

Newell, A., & Simon, H. A. (1972). *Human problem solving.* Englewood Cliffs, NJ: Prentice-Hall.

Norman, D. A. (1983). Some observations on mental models. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 7–14). Hillsdale, NJ: Lawrence Erlbaum Associates.

Paivio, A. (1971). *Imagery and verbal processes*. New York: Holt, Rinehart & Winston.

Paivio, A. (1983). The empirical case for dual coding. In J. C. Yulle (Ed.), *Imagery, memory and cognition* (pp. 307–332). Hillsdale, NJ: Erlbaum.

Paivio, A. (1986). *Mental representations: A dual-coding approach*. New York: Oxford University Press.

Paivio, A. (1991). Dual coding theory: Retrospect and current status. *Canadian Journal of Psychology, 45*, 255–87.

Paivio, A., & Csapo, K. (1973). Picture superiority effect: Imagery or dual coding? *Cognitive Psychology, 5*, 176–206.

Pecher, D., Zeelenberg, R., & Barsalou, L. W. (2003). Verifying properties from different modalities for concepts produces switching costs. *Psychological Science, 14*, 119–124.

Pick, H. L., Heinrichs, M. R., Montello, D. R., Smith, K., Sullivan, C. N., & Thompson, W. B. (1995). Topographic map reading. In P. A. Hancock, J. M., Flach, J. Caird, & K. J. Vicente (Eds.), *local applications of the ecological approach to human-machine systems* (pp. 255–284). Hillsdale, NJ: Erlbaum.

Pylyshyn, Z. W. (1981). The imagery debate: Analogue media versus tacit knowledge. *Psychological Review, 88*, 16–45.

Pylyshyn, Z. W. (2002). Mental imagery: In search of a theory. *Behavioral & Brain Sciences, 25*, 157–238.

Rapp, D. N. (2005). Mental models: Theoretical issues for visualizations in science education. In J. K. Gilbert (Ed.), *Visualization in Science Education* (pp. 43–60). The Netherlands: Springer.

Rapp, D. N. (2006). The value of attention aware systems in educational settings. *Computers in Human Behavior, 22*, 603–614.

Rapp, D. N., Culpepper, S. A., Kirkby, K., & Morin, P. (in press). Fostering students’ comprehension of topographic maps. *Journal of Geoscience Education*.

Rapp, D. N., Taylor, H. A., & Crane, G. R. (2003). The impact of digital libraries on cognitive processes: Psychological issues of hypermedia. C*omputers in Human Behavior*, 19, 609–628.

Rapp, D. N., & Uttal, D. H. (2006). Understanding and enhancing visualizations: Two models of collaboration between earth science and cognitive science. In C. Manduca & D. Mogk (Eds.), *Earth and mind: How geologists think and learn about the Earth* (pp. 121–127). Boulder, CO: Geological Society of America Press.

Reimann, P., & Chi, M. T. H. (1989). Expertise in complex problem solving. In K. J. Gilhooly (Ed.), *Human and Machine Problem Solving* (pp. 161–192). New York: Plenum Press.

Searle, J. R. (1980). Minds, brains, and programs. *Behavioral & Brain Sciences, 3*, 417–424.

Sloutsky, V. M., Kaminski, J. A., & Heckler, A. F. (2005). The advantage of simple symbols for learning and transfer. *Psychonomic Bulletin & Review, 12*, 508–513.

Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs: General and Applied, 74*, 1–30.

Stanfield, R. A., & Zwaan, R. A. (2001). The effect of implied orientation derived from verbal context on picture recognition. *Psychological Science, 12*, 153–156.

Svensson, H., & Ziemke, T. (2004). Making sense of embodiment: Simulation theories and the sharing of neural circuitry between sensorimotor and cognitive processes. In *Proceedings of the 26th annual meeting of the Cognitive Science Society.* Mawhah, NJ: Erlbaum.

Taylor, H. A., Renshaw, C. E., & Choi, E. J. (2004). The effect of multiple formats on understanding complex visual displays. *Journal of Geoscience Education*, 52, 115–121.

Taylor, H. A., Renshaw, C. E., & Jensen, M. D. (1997). Effects of computer-based role-playing on decision making skills. *Journal of Educational Computing Research*, 17, 147–164.

Tversky, B. (in press). Mental models. In A. E. Kazdin (Ed.), *Encyclopedia of Psychology*. Washington, DC: APA Press.

Tversky, B., Zacks, J. M., Lee, P. U., & Heiser, J. (2000). Lines, blobs, crosses, and arrows. In M. Anderson, P. Cheng, & V. Haarslev (Eds.), *Theory and application of diagrams* (pp. 221–230). Edinburgh: Springer.

Valenzeno, L., Alibali, M. W., & Klatzky, R. (2003). Teachers’ gestures facilitate students’ learning: A lesson in symmetry. *Contemporary Educational Psychology, 28,* 187–204.

Van Dijk, T. A., & Kintsch, W. (1983). *Strategies of discourse comprehension*. New York: Academic Press.

Wiemer-Hastings, K., & Xu, X. (2005). Content differences for abstract and concrete concepts. *Cognitive Science*, 29,719–736.

Woolfolk, A. (2004). *Educational psychology* (9th ed.). Boston, MA: Allyn and Bacon.

Zwaan, R. A. (2004). The immersed experiencer: Toward an embodied theory of language comprehension. In B. H. Ross (Ed.), *The psychology of leaning and motivation,* (Vol. 4, pp. 35–62). New York: Academic Press.

Zwaan, R. A., Madden, C. J., Yaxley, R. H., & Aveyard, M. E. (2004). Moving words: Dynamic mental representations in language comprehension. *Cognitive Science, 28,* 611–619.

Zwaan, R. A., Stanfield, R. A., & Yaxley, R. H. (2002). Language comprehenders routinely represent the shape of objects. *Psychological Science, 13*, 168–171.

Zwaan, R. A., & Yaxley, R. H. (2004). Spatial iconicity affects semantic-relatedness judgments. *Psychonomic Bulletin & Review, 10*, 954–958.

Zwaan R. A., & Yaxley, R. H. (2005). Lateralization of object-shape information in semantic processing. *Cognition, 94*, B35–B43.

Chapter 3
Comprehending and Learning from 'Visualizations': A Developmental Perspective

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The use of '*visualizations'* has become nearly ubiquitous in the practice, teaching, and learning of mathematics, science, and engineering. We define '*visualizations'* as any type of physical representation designed to make an abstract concept visible. These include but are not limited to concrete items such as photographs, 2-D graphs, diagrams, charts and 3-D models. It is almost impossible to imagine working in complex visual-based sciences such as chemistry or geoscience without the insights that 'visualizations' can afford.

What makes 'visualizations' useful for learning and thinking? Why do they help students learn? Part of the answer is obvious: 'visualizations' help because they make complex information accessible and cognitively tractable. 'Visualizations' highlight the portions of the information that the designer intends for the learner to see and hence support both learning among novices and new discoveries among experts. They allow us to perceive, and to think about, relations among items that would be difficult to comprehend otherwise.

Consider, for example, the 'visualization' shown in Fig. 3.1. This very simple map of the relative locations of a few United States cities makes accessible and tractable what is actually a very complex set of relations. Imagine the difficulty of describing this same set of relations in words (Taylor & Tversky, 1992; Uttal, Fisher, & Taylor, 2006). A great deal of work in a variety of disciplines, including psychology (e.g., Hegarty, Carpenter, & Just, 1991; Larkin & Simon, 1987; Novick & Hurley, 2001), computer science (Allwein & Barwise, 1996; Ferguson & Forbus, 2000; Glasgow, Narayanan, & Chandrasekaran, 1995) and geography (MacEachren, 1995) has focused on the value of 'visualizations' for depicting scientific phenomena that may otherwise remain opaque or inaccessible.

Put simply, much of the power of 'visualizations' stems from their ability to make us think in visual rather than in abstract, symbolic terms. We do not have to describe in words, for example, the complex relations that allow an enzyme or drug to bond at a specific location on a molecule. With a 'visualization', we can instead see and

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Fig. 3.1 Very simple map of USA in terms of some major cities

think about this complex relationship and location in terms of spatial relations. The 'visualizations' become tools for thinking about the underlying structures and the relations among them.

In this chapter we argue that there is an important prerequisite for learning from 'visualizations'. Before students can benefit fully from the visual-spatial properties of visualizations, they must understand that, and how, 'visualizations' stand for or *represent* particular concepts or complex objects. The fact that 'visualizations' have a visual-spatial nature does not guarantee that the student will comprehend the intended relation between the 'visualization' and what it stands for (the referent).

We begin by developing the argument that 'visualizations' must be conceived as representations. Borrowing from work in developmental psychology and the philosophy of symbols (e.g., Goodman, 1976; Hecht, Schwartz, & Atherton, 2003), we develop the case that grasping the representational relation between a 'visualization' and what it stands for is an interesting and at time difficult challenge. Next, we discuss the development of young children's understanding of simple 'visualizations' and suggest that this development can shed important light on older (i.e., adolescent and adult) students' understanding of more complex visualizations. We then consider the implications of the developmental work for understanding how older students understand and learn from scientific 'visualizations'. Finally, we discuss research questions that follow from our discussions of 'visualizations' and representations.

Understanding 'Visualizations' as Representations

Our work in this area arose from discussions with colleagues who teach geology and chemistry. They told us that their students often struggle to master the basic correspondence between 'visualizations' and what they represent. Students' errors sometimes revealed that they did not seem to grasp fully that the 'visualization' was intended to represent something. For example, colleagues have said that their students saw visual representations of proteins only as 'red dots or green circles' or complex geology maps as 'a bunch of blobs on paper'. These anecdotal reports are interesting because they reveal that the students focused only on the 'visualization' itself, not on what it is intended to represent. The students saw only what was displayed on the paper or the computer screen and failed to grasp what the 'visualization' was intended to represent.

We believe errors such as these are indicative of a general challenge in using 'visualizations' or any representations. To the expert user or professor, the intended purpose of the 'visualization', and its relation to the referent, is obvious. For example, a chemistry professor may look at a 'visualization' of a molecule and think *as if* they were looking at the molecule itself. But to novices, the relations that are so obvious to the expert may be totally opaque.

As an example of what we mean, consider how people understand and use what might be considered a relatively simple 'visualization', a road map. Many adults may assume that the relation between the map and what it represents is immediately clear or obvious. But on second thought, we realize that this sense of easy understanding belies the many years of development and learning that support our understanding. Upon reflection, we may realize that the map really doesn't look much like the world at all. For example, a road map is two-dimensional and is often drawn on white paper. The world isn't. In addition, the map uses various colors, to represent aspects of the world that are not immediately visible. Red may be used to represent a superhighway, and yellow may be used to indicate that a city has more than 100,000 residents. The road is not red in the world, and the city is not yellow (see Wood, 1992, for a discussion of the non-obvious properties of maps).

The point of this analysis is to show that maps (and all visual representations) are not copies of the world; they are instead representations of some aspect of the world. The relation between a 'visualization' and its referent is seldom obvious to novice learners. The visual nature of 'visualizations' does not obviate the basic prerequisite to understand what the 'visualization' represents. Reading a map first requires that people understand that it represents a particular space in a particular way.

The same is true of more complex scientific 'visualizations'. To the experienced user, and to advanced students, the relation between the 'visualization' and what it is intended to represent is obvious. But again, the feeling of simplicity takes for granted the years of development and learning that supported the understanding of the 'visualization'. For example, in representing the orbit of electrons, a choice is made, of necessity, to distort scale. The electrons would actually be *much* further away than is suggested by the 'visualization'. The author of the 'visualization' thus has decided to sacrifice accuracy of scale in order to represent the path of an orbit, or the number of electrons. In addition, the 'visualization' often includes colors that, of course, do not correspond to actual colors in the represented molecule. For example, representations of molecules may use colors to represent positive or negative charges. This can be useful information, but it is useful only if the learner understands what the colors represent. He or she can not simply look at the 'visualization' and comprehend this information, in part because the visualization is not simply a copy of the molecule.

This analysis raises the question of how we define representations. The answer to this question is rarely, if ever, given by the object itself. One cannot say a priori what is and is not a representation. People create representations, through their intention to have one thing stand for something else (Bloom & Markson, 1998; Deacon, 1997; DeLoache, 2000; Tomasello, Striano, & Rochat, 1999). Anything can be a representation of something else if the intention to use it as such becomes clear. For example, consider two people sitting at a dinner table, with one giving directions to another. It would not be surprising to see the interlocutors using silverware, glasses, or candlesticks to stand for various locations. All that has to happen is for one person to say, 'This glass is the Sears Tower, and this fork is the John Hancock building.' From that point on, the glass and fork become representations (in this case, of the locations of important landmarks in Chicago), because someone intended for them to be. The spatial relations between the glass and fork *now* become meaningful information, but only because the individuals have met the prerequisite of understanding that the items are intended to be a representation of something else.

We refer to the critical understanding of the relation between a representation and its referent as *representational insight.* It is the process of coming to understand that, and how, a representation stands for something else. Our central thesis is that representational insight is always required when one learns from a representation. This is true even for highly visual representations such as maps or models; to understand or learn from them, we have to know what they are intended to stand for. The fact that visualizations are visual in nature is not sufficient to guarantee representational insight.

As mentioned above, expert users are so accustomed to using 'visualizations' that they may forget how much we had to learn before they could use them. However, when we look at children's struggles to grasp the intended meaning and use of seemingly simple visualizations, we are reminded of the challenges that we faced, and that our students may be facing today. Therefore, in the next section, we suggest that a developmental perspective can help us to understand the important requirement of obtaining representational insight. Research on the development of children's understanding of 'visualizations' has very important implications for understanding people's initial grasp of the crucially important relation between a 'visualization' and its intended referent.

Towards a Developmental Perspective

In this section we examine the development of children's understanding of simple 'visualizations'. Our focus is on the development of children's understanding of the 'stands for' relation between 'visualizations' and what they are intended to represent. We will consider how children come to understand the simplest 'visualizations', such as photographs, scale models, pictures, etc. In each case, we see that part of the challenge involves learning to understand that, and how, the visualization stands for something.

Grasping at Photographs of Bottles: Infants and Toddlers' Understanding of Photographs

The developmental story begins with very young children, infants in fact. Several interesting studies involving the development of young children's understanding of photographs shed light on the role of representational insight into understanding even the simplest 'visualization'.

One could easily argue that a photograph is the simplest possible 'visualization' in that it looks almost like a copy of the represented object, person, or space. But even in this very simple case we see that gaining representational insight into the relation between photographs and their referents is not a straightforward or simple development. Researchers have examined how and when young children come to understand or appreciate *both* the similarities and differences between photographs and their referents in the world.

In reviewing this work, we need to consider two different sets of questions that are reflected in two different bodies of literature. The first set of questions concerns young children's *perception* of the similarity and differences between photographs and their referents. Do young children recognize objects that are pictured in photographs? And if they do, can they tell the difference between what is shown in the photograph and its real-world referent?

The second set of question concerns children's *use* of photographs as 'visualizations'. When and how do young children use photographs as tools for learning or solving problems?

Before addressing these questions, we need first to discuss briefly how developmental psychologists can ask (and answer) questions about perception and cognition in infants. One frequently used technique is called *habituation.* It relies on the simple fact that events become less interesting the more we see them. When we first see something new, we attend to it, perhaps looking at it for a long time. But if the event is repeated, we quickly get used to it, and it no longer grabs our attention. This basic fact can be used to assess what children know or don't know about their world (e.g., Hespos & Spelke, 2004). Researchers present one stimulus to an infant until she or he *habituates* to the presentation. For example, a researcher might show a photograph or a doll, or play a particular sound. The researcher measures some aspect of the infant's behavior that is thought to indicate interest. One common example is *looking time*, the amount of time an infant's eyes are focused on a particular object or event. When a new event or stimulus is presented, infants tend to look at it, often for several seconds. The researcher would then keep presenting the same stimulus. After a few presentations of the event, most infants become bored with the event, and consequently will look at the additional presentations for a shorter length of time. The researchers will notice that the looking time (a) has decreased substantially, and (b) that the looking time is now fairly stable. Put simply, the infant is now *habituated* to the presentation of the stimulus and looks at the event only for a brief moment.

The basic fact that infants become habituated can be used as a means of determining whether they can tell the difference between two objects, events, or other stimuli. For example, a researcher could habituate children to the presentation of a particular object such as a doll and then switch to a new doll or a realistic photograph of the doll. The critical question is whether the child *dishabituates* to the presentation of the new stimulus. That is, do the children now start to pay attention again, looking at the new stimulus for a relatively long time? If they do, then the researchers can conclude that the children *must* have perceived the difference between the prior and new stimulus.

This basic technique has been applied to the question of whether children understand the similarities and differences between photographs and their referents in the world. Researchers (e.g., DeLoache, Strauss, & Maynard, 1979) have, for example, exposed children to a doll until they are habituated, and then presented them with color or black-and-white photographs of the same doll. Most of the babies failed to dishabituate to either type of photograph, indicating that they recognized the similarity between the photographs and their real-world referents. It is important to note that the failure to dishabituate was not due to babies being unable to discriminate between the photographs and the doll. Additional studies showed that when babies viewed a photograph and its referent side by side simultaneously, they looked longer at the more realistic of the two stimuli—the doll. Taken together, these results indicate that young babies recognize that photographs correspond to live objects but that they are not identical to live objects.

Understanding Photographs as Representations

One might think that once children can perceive both the similarities and differences between photographs and their referents, then they would be able also to *understand* or use this relation. But this is not necessarily the case. Further explorations of young children's understanding of and interaction with photographs highlight clearly the important distinction between perceiving an object that is intended to be a representation and understanding that intention. Even though young babies can perceive similarities and differences between photographs and their referents, this knowledge is not enough to *understand* and to use the representational relation between photographs and their referents. An ongoing line of research suggests that even when children can perceive the difference between a photograph and its referent, they still may not fully grasp what this relation means. In other words, they do not understand that the photograph is intended to be a representation.

In this work (DeLoache, Pierroutsakos, Uttal, Rosengren, & Gottlieb, 1998), we presented photographs, in the form of simple picture books, to 9- and 18-month-olds. For example, children were given a very simple book with one realistic-looking photograph on each page. The photographs showed objects with which infants would typically interact, such as a bottle and a rattle. We placed the picture book in front of the children, turned to the first page, and observed what the children did with the photographed object. After 15 seconds, we turned the page to the next photograph.

We were struck by a very consistent result: Nine-month-olds often attempted to pick up or otherwise grasp the photographed objects. The children's hand motions were directly and specifically aimed at the objects in the photographs. For example, they put their thumb and index finger together, as if they were trying to pick up a small object. Some of the children were quite persistent, attempting to pick up many of the depicted objects. For these reasons we concluded that the infants were not simply trying to pick up the photograph; they were trying to pick up the specific object that was shown in the photograph.

The grasping behavior decreased significantly with age; 18-month-olds did not attempt to grasp the photographed objects very often. Instead, these children pointed to the photographed objects and made noises. Developmental psychologists call this behavior *proto-labeling*; it involves what is probably an attempt to label an object before the child knows the noun. Thus, within a span of about 9 months, children's thinking about photographs develops substantially. Initially, they seem to treat photographed objects as if they were the objects themselves, but with development, they treat the photographs as representations of something in the real world. They are now more focused on the photographs as representations.

Why can babies perceive the difference between photographs and their referents yet still treat photographs as if they were the objects themselves? We believe that the babies note a similarity between the object and the referent. They also see that it doesn't look quite like the typical object does. But not knowing precisely what to make of this difference, they do what they normally do with an object: attempt to pick it up; put it in their mouths, etc. Thus they are attempting to explore the photographic depiction of the object to determine whether it differs from the actual object, and if so, how. However, 18-month-olds have much greater experience in reading picture books with their parents or caretakers. When the picture book reader points to and labels a picture rather than treating the picture as they would the actual object, the children learn about the representational relation between the photograph and what it stands for. They learn that photographs are intended to be treated as representations, not as objects.

This finding is particularly important because it highlights, in a simple and direct way, the central distinction that motivates much of this chapter. The 9-months-olds *perceived* the spatial and perceptual similarities between the photograph of the objects and the real objects. However, they did not *conceive* of the photographs as representations. They had not yet gained representational insight into the relation between the photographed object and the object itself.

Learning from 'Visualizations'

The research discussed thus far has focused on the development of very young children's understanding of photographs as representations. We next address a different, although obviously related, question: When and how do children *use* 'visualizations' as tools for learning or problem solving? Recognizing the similarity (and difference) between a 'visualization' and its intended referent is a necessary condition for using the 'visualization' as a tool for learning, but this alone is not sufficient. Children need to understand *that,* and *how*, a 'visualization' stands for what it represents.

We review a series of studies on the development of children's *use* of simple visualizations as tools for acquiring information. These studies illustrate very well the challenges of interpreting a 'visualization' as a representation. In addition, they help to provide a theoretical foundation for further explorations of learning from 'visualizations'.

Children's Use of Scale Models

Perhaps the most thoroughly researched topic in this area is the development of young children's understanding of scale models (DeLoache, 1987, 1989, 2000; Uttal, Schreiber, & DeLoache, 1995). This work has shed substantial light on the importance of gaining representational insight. The studies all use a very simple task: Children are asked to use a simple scale model of a room to find a toy that is hidden in the room. The model and search task seem so simple to adults that it is astonishing to see young children having trouble establishing a correspondence between the model and the room. That young children often do experience difficulty again highlights the very important role of representational insight in using 'visualizations'. Even though the model and room look very much alike, this visual-spatial correspondence does not guarantee that children will gain representational insight.

The scale-model task also provides further insight on an issue that is of great interest to science educators (and the focus of this chapter), that is: Learning from visualizations. The children need to use the model to learn where the toy is hidden in the room. Note that this way of learning differs greatly from young children's typical way of learning about the world. Usually, when children look for a missing object (e.g., a favorite toy), they do so on the basis of their prior experiences, looking at places where they remember last seeing the toy or where they typically put it (e.g., Wellman, 1985). But to succeed in our scale-model task, they must do something very different; they must rely on information gained purely from a 'visualization' (the scale model). The development of this skill and its challenges for young children is very illustrative of some of the challenges that older students and adults may encounter when using a new 'visualization' , particularly in the early stages of instruction.

In the original studies (e.g., DeLoache, 1987), the children were 2.5- and 3.0-year-olds. Both the room and the model were rather sparsely decorated, with only a few items of furniture in the room (and the corresponding miniature versions in the model). The task began with a detailed explanation that was designed to help the child grasp the correspondence between the model and the relevance of this correspondence for finding the hidden toy in the room. The experimenter pointed out correspondences between the model and the room. For example, the experimenter said that 'Little Snoopy's room was just like Big Snoopy's room.' The experimenter also pointed out correspondences between individual items of furniture in the model and in the room and told the child that Little Snoopy and Big Snoopy liked to hide in the same places in their respective rooms.

The child watched as the experimenter hid the toy behind, under, or in one of the pieces of furniture in the model. The experimenter then asked the child to go into the larger room and find the toy. He or she was reminded that the toy was hidden in the same location in the room as the miniature toy was located in the model. Of course, the experimenter was careful not to label the location (e.g., by saying 'it's behind the couch') because then the child could solve the problem without needing to think about the relation between the model and the room. The child searched the room until he or she found the toy, but a search was scored as correct only if the child's first search was at the correct location. The procedure was repeated several times, and the experimenter kept track of the number of correct searches.

The results revealed a dramatic developmental change. The 2.5-year-olds performed poorly; their searchers in the room were essentially random, indicating that they did not use the information from the model as a guide to search in the room. In contrast, the 3.0-year-olds performed much better, averaging approximately 75% correct searches, far greater than would be expected by chance. These children were able to use what they saw in the model as a guide for searching in the room.

After the children found the toy in the room, the participants returned to the model for an important check on their memory. The experimenter asked the child to show where the toy was hidden in the model. This ensures that forgetting the location of the toy cannot be the cause of the younger children's problem in finding the toy in the room. If the children are able to point out the location of the toy in the model, then they clearly knew and remembered the model location. Most of the children had no trouble with this memory check; the 2.5-year-olds remembered where the toy was hidden in the model, regardless of whether they could find it in the room.

In summary, then, the data indicate that the young children fail not because they cannot remember where the toy is in the model, but because they do not see a connection between the model and the room that it represents. When they entered the room, they knew the location of the miniature toy in the model. But this information was of no value to them once they entered the room. Thus we see that the presence of a strong perceptual relation between a visualization and what it stands for does not guarantee that children (or adults) will be able to use the visualization. We should not be surprised when older students do not immediately grasp the relation between a more complex visualization and what the teacher or scientist intended for the visualization to represent.

The results discussed thus far establish that 3.0-year-olds are capable of using a visualization to solve a simple search task, but this is not the end of the story. Subsequent research established that 3.0-year-olds' understanding of this relation is quite fragile; ostensibly minor changes had dramatically negative effects on children's use of the model as a representation. For example, giving sparser instructions, in which the experimenter did not explicitly point out the correspondence between the model and the room, led to dramatically lower performance (DeLoache, deMendoza, &

Anderson, 1999). Likewise, inserting a delay between the time when the child saw the toy in the model and when he or she was asked to search for it in the room also led to substantial declines in performance (Uttal, Schreiber, & DeLoache, 1995). Importantly, the declines observed were more than children getting a bit worse; they were dramatic shifts in performance, from very good to nearly-random searching. Once the task was tweaked so that children had to think a bit more about the relation between the model and the room, the 3.0-year-olds performed like the 2.5-year-olds. What seems to have been lost is the understanding either that the model stood for the room or that this relation was relevant for finding the toy. These findings again highlight the importance of gaining representational insight and demonstrate its fragility; even if children initially do grasp the representational relation between the model and the room, they can easily lose sight of this relation. Similarly, it seems possibly that a novice student might at times lose sight of what the visualization he or she is using is intended to represent and become overwhelmed by the many new colors and shapes.

The Dual Representation Hypotheses

Based on this pattern of results, DeLoache and colleagues formulated the *dual representation hypothesis* to account for children's success and failure in the model-search task and in understanding representations more generally. Central to this account is the notion that all representations have a dual nature; they are intended to stand for something else, but at the same time, they are also objects in their own right. For example, the scale model is intended to be a representation of the room, but it is also an interesting object, regardless of its connection to the represented room. Each visualization (i.e. pictorial chart, graph, 3-D model, etc.) has this dual nature; it is an object in its own right with its own visual properties but it is *also* an intended representation of something else (i.e. a cell, photo-synthesis, the human brain, etc.). As adults, we are so accustomed to thinking about what common visualizations represent that we may forget that they are also objects in their own right. But sometimes we are reminded. For example, when someone uses an unusual or garish font in a PowerPoint presentation, we may then focus on the letters themselves, rather than on the words that the letters represent. Likewise one would not be surprised if an adult initially interpreted the Tokyo subway map shown in Fig. 3.2 as 'strands of yarn or spaghetti'. The many different colors, combined with a lack of a clear referent, may lead people at least initially to focus on the object itself rather than what it is intended to represent.

Similarly, when a teacher first introduces a scientific visualization to his or her class, the students may see only its object properties (e.g., different colors, ribbons, lines, etc.) because they have not learned yet what the teacher intends for the visualization to represent.

One way to think of the dual representation is as a balance scale. On one side of the scale are factors that lead children (or adults) to interpret 'visualizations'

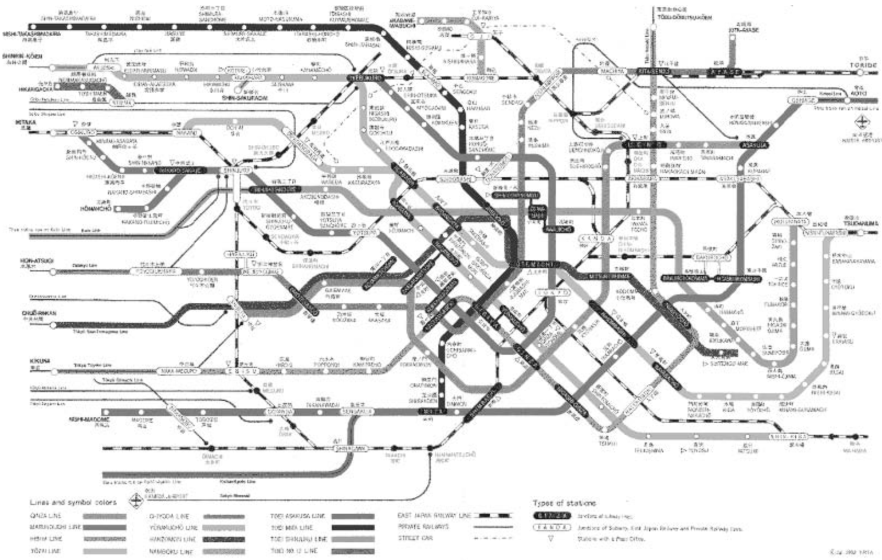

Fig. 3.2 The subway map of Tokoyo
(Source: http://web.yl.is.s.u-tokyo.ac.jp/jp/map.gif)

as objects in their own right. On the other side are factors that lead people to interpret the ‘visualization’ as a representation. To use a model (or map, or photograph, or any ‘visualization’) as a representation of something else, we must focus on what it is intended to represent not on its properties an object in its own right.

In support of this theory, DeLoache and colleagues have conducted a fascinating series of studies on factors that influence children’s use of scale models as representations. For example, in one series of studies (DeLoache, 2000), children were allowed to play with the model before they were later asked to use it as a representation of the room. Many people might assume that allowing children to play with the model beforehand would facilitate their performance, perhaps by helping them become familiar with it. However, note that the dual representation hypothesis predicts the opposite; playing with something that is intended to be a representation may focus children’s attention on the object itself, rather than on the intended referent. The results confirmed this counterintuitive prediction: children who played with the model first actually had more trouble using it as a representation of the room.

Additional research also confirmed the opposite prediction: That restricting children’s access to the model would make it *easier* for them to use it as a representation of something else. In this research (DeLoache, 2000), the model was placed behind a pane of glass so that children could not touch it or otherwise interact with it. In this case, 2.5-year-olds, who normally fail the task completely performed much better. In terms of the dual representation hypothesis, restricting access helped to *decrease* the children's attention to the properties of the model as an object in its own right and hence allowed the children to focus more on what the model represented.

Perhaps the most convincing work to date in support of the dual-representation hypothesis comes from a series of studies in which the dual nature of the model is made irrelevant. In this line of work (DeLoache, Miller, & Rosengren, 1997), the children were convinced that the model was a shrunken version of the room. A magic trick was used to give the appearance that a room (this time composed of fabric supported by PVC tubing) could be made to shrink or expand. The experiment began with an introduction to a 'shrinking machine', which was actually a sham device with many dials that emitted strange sounds. The child was told that the machine was capable of shrinking any object. As a demonstration, the experimenter 'shrunk' a toy troll; he or she placed a troll doll on the top of the machine, activated the 'machine', and left the room. The child could hear the noises of the machine 'working' as he or she stood outside. Unknown to the child, a confederate quietly substituted a miniature version of the troll doll, making it appear as if the doll had shrunk dramatically. When the noises stopped, the experimenter and child then entered the room, and the experimenter pointed out that the troll had shrunk.

The troll-shrinking demonstration was used to motivate the possibility of the room shrinking. After the child was convinced of the 'functionality' of the shrinking machine, he or she was then introduced to the standard search task. The child watched as the experimenter hid the toy in the large-sized portable room. The experimenter and child then reactivated the shrinking machine and both left the room. Several confederates worked quietly to substitute a miniature version (i.e. miniature versions of the furniture were substituted for the full-size furniture) of the room. This smaller version of the room was stored behind curtains so that the child did not know that there were two versions of the room. When the child and experimenter returned to the space, it appeared as if the larger room had been shrunk. The critical question was whether the child could find the toy after the shrinking transformation.

The answer to this question was a decisive yes. 2.5-year-olds, who normally fail, performed much better. In interpreting this result, it is important to note that all elements of this task, save one, remained the same. For example, the child still had to use the location of the toy in one space (the larger room) to find the toy in the other space (the miniature room). The only difference is that the shrinking room procedure eliminated the need for the child to think about the model as a representation of the room. In the mind of the child, the small and large rooms were one and the same.

The results of this experiment provide strong evidence in support of the dual representation hypothesis. The children succeeded because the problem of dual representation was eliminated by the 'shrinking' procedure. Even though the basic requirements remained the same, the way the child needed to think about those requirements changed. The child no longer had to think about a representational relation between the model and the room. In their minds, the shrunken room and the full-size room were one. Removing the need to think about the two different components allowed 2.5-year-olds to succeed when they normally would fail.

Learning from Video

A related series of studies involved understanding representations and learning from television and video. What children see on television does not (usually) correspond to something specific or even necessarily real in the world. Many, if not most, children's television shows involve fantasy characters, cartoon, or other fantastical notions. Thus it would not be surprising to find that young children do not associate what they see on a television screen with a particular or specific scene in reality.

This point is demonstrated in a series of studies in which children were asked to use information provided in a brief video clip to find a toy that was hidden in a room (Troseth, 2003; Troseth & DeLoache, 1998). The video showed a room with several hiding locations and was similar in design and layout to the space that was used in previous studies of children's understanding of scale models. In this case, however, the children watched a video that showed the experimenter hiding a toy in the room. After watching this vignette, the child was asked to enter the room and find the toy.

This task proved particularly challenging for 2.0-year-old children. They did not think of the video vignette as a source of information for finding the hidden toy. Further research established again the specific importance of understanding a representational relation between the video scenes and the hiding event in the room. As in the 'shrinking room' experiments described above, removing the need to think of the video as a *representation* of the room allowed children to succeed when they otherwise would fail. The researchers (Troseth & DeLoache, 1998) placed a video screen in a custom-fit window pane between the two rooms which led children to believe that they were actually observing the specific hiding event in the room, when in reality they were looking at a video of the hiding event. As in the shrinking room experiment, children who had trouble using the relation between the video and the room now performed well. Once again, removing the need to think about a representational relation led children to succeed when they would otherwise fail, providing clear evidence that the challenge for the young children was thinking about the video as a representation of the room.

Understanding Maps

The development of children's appreciation of geographic maps both illustrates and extends the points that we mentioned above. A variety of methods have been used to investigate the development of children's understanding of maps. Some studies have used methods similar to those that were used in the studies described above. For example, young children have been asked to use a simple map to find a hidden toy (Blades & Spencer, 1987), to navigate a route (e.g., Uttal & Wellman, 1989), or to plan a trip. However, what is perhaps most interesting here is studies of children's understanding of 'real', geographic-scale maps, like those that typically adorn the walls of classrooms. When kindergartners or young elementary school children are asked to interpret these maps, they often demonstrate some of the same errors that younger children do when interpreting simple 'visualizations'. For example, when children were asked to interpret a map that showed roads represented in various colors (e.g., red to show major freeways, gray to show two-lane highways, etc.), some said that a red line could not represent a road because the line was too narrow for a car to fit on it. Other children said the line could not represent a road because there are no red roads in the real world (Liben, 1999, 2001; Liben, Kastens, & Stevenson, 2002). Children also made errors of scale, such as correctly identifying a body of water (Lake Michigan, on an aerial photograph of Chicago) as water, but then claiming to see fish in the lake.

These examples are important because they demonstrate a more sophisticated but at times nevertheless incorrect understanding of the relation between 'visualizations' and their referents. The children clearly know that there is some sort of relation between the map and the space, and they readily identify features that look like their referents in the real world. Yet, young children sometimes make mistakes that illustrate how fragile this understanding can be. The children seem to believe that there must be a literal correspondence between the map and the space that it represents. These errors again illustrate that visual correspondence is not enough to promote representational insight. The children do grasp the notion of a visual correspondence, but their strong belief in the *necessity* of visual correspondence actually gets in the way of their comprehension of the map as a representation. These young children may hold a 'copy theory' of the relation between maps and the world, believing incorrectly that the map should be a literal copy of the world.

Summary

The studies that we have reviewed thus far have covered a range of 'visualizations', including photographs, models, video, and maps. Of central importance in all of these studies has been the need to understand, and to exploit, a representational relation between the 'visualization' and what it represents. Initially, young children need to perceive a similarity between a 'visualization' and what it represents, but this alone is not enough if we want them to use a 'visualization' for learning. In fact, in the case of photographs, a high degree of visual similarity can lead babies to treat a photograph as if it were an actual object. Likewise, a belief in the necessity of visual similarity seems to interfere with, rather than to facilitate, elementary school children's understanding of maps. All of the examples that we have reviewed clearly indicate the centrality of understanding the intention to use a 'visualization' to represent something. In the next section we consider the implications of these findings for older students' use of more complex visual representations, such as those used in a typical organic chemistry class.

Implications for the Use of 'Visualizations' in Education

To what extent are the results and theoretical perspective that we have presented thus far relevant to understanding the use of 'visualizations' in high school or college classrooms? One could argue that the results we have described here are directly and immediately relevant to high school or university students’ learning from ‘visualizations’ in fields such as chemistry, biology, geoscience, or engineering. On this view, novice learners face the very same challenges that young children face when they first see a new ‘visualization’. They may simply fail to recognize that the new ‘visualization’ represents something else, and thus they may sometimes say they see ‘blobs’ or ‘dots’ when they are asked to explain the ‘visualization’. Put simply, the novice learner may fail to obtain representational insight when interpreting a new ‘visualization’

Clearly, students do need to appreciate that ‘visualizations’ are representations. Instructors are often so accustomed to thinking about the ‘visualization’ as a representation that they may easily forget that students may not understand the correspondence between the ‘visualization’ and its referent. What may seem obvious to the instructor may be totally opaque to the student. In such extreme cases, it is possible to imagine that students might literally behave like children; they may fail to grasp the intended representational relation between the representation and its referent.

We think, however, that a second, more nuanced interpretation of the implications of the developmental work is more informative. Adolescent and adult learners differ from young children in a very important way, one that influences greatly whether, and how, they learn from ‘visualizations’ At least by middle school, most students have developed what DeLoache (2000, 2004) and others have termed *symbolic sensitivity.* They can bring knowledge and experience gained from many prior learning experiences to new learning experiences. Over time, working with a variety of ‘visualizations’ and graphics helps students to *expect* that a new ‘visualization’ stands for something, although they still may have great difficulty bringing this to bear in a new learning situation. Put another way, adolescent and adult learners have acquired some degree of what diSessa and colleagues (e.g., diSessa & Sherin, 2000) have termed *meta-graphical* awareness, which is a general understanding of the purposes of visual representations and of the value of different kinds of ‘visualizations’ for solving different types of problems. There is at least the possibility that adults have acquired a more general understanding of the purposes of ‘visualizations’ and of the match between ’visualizations’ and problems. The younger children in the experiments described earlier were, in essence, ‘blank slates’ when it came to learning from the ‘visualizations’. In the case of adolescents and adults, this is unlikely to be true.

In addition, there is another important difference between the examples we have discussed from research with children and the challenges that adolescent or adult learners face in the classroom. In most science or mathematics classrooms, ‘visualizations’ or visual-based learning is important but not sufficient for mastery of the topic. Students must also master more abstract, written symbols. For example, students may need to learn to understand and use equations or written representations of chemical reactions. ’Visualizations’ are designed in part to facilitate conceptual understanding that can provide a basis for understanding and learning these more abstract representations. Researchers and educators must therefore consider the relation between the use of ‘visualizations’ and students understanding of written symbols.

Despite these differences between child and adult learners, the issue of dual representation is still relevant for understanding how adults learn from 'visualizations'. For example, visualization designs that lead students to focus more on the properties of the visualization itself, rather than on what it is intended to represent or teach, can be counterproductive even in adult learners. In the mind of the expert, the intended representation is clear, but in the mind of the novice, the properties of the 'visualization' as an object may be much more salient than the teacher realizes. Students may initially understand that the map or other 'visualization' is a representation, but they may get consumed with the local, physical properties of the object and fail to focus on what the 'visualization' is intended to represent. Therefore, garish or highly attractive 'visualizations' may actually make it harder for students to grasp what the visualization is intended to teach specifically because they will focus more on the properties of the visualization as an object in its own right.

A particularly poignant example of the costs and benefits of using interesting or concrete visualizations comes from the work of Goldstone & Sakamoto (2003). Their specific focus was on transfer of knowledge. It is extremely important that students be able to transfer principles that they acquire from using a 'visualization' to other learning situations that depend on the same general concept. To do so, they must be able to look beyond the properties of a particular 'visualization' to learn about, retain, and ultimately transfer their knowledge to a new domain. Unfortunately, this has often been difficult to accomplish. 'Transcending superficial appearances to extract deep principles is as critical to science as it is difficult to achieve.' (Goldstone & Sakamoto, 2003, p. 415).

Goldstone and colleagues have used 'visualizations' to teach college students a variety of scientific principles. One example is the notion of competitive specialization, which is the idea that adaptation in a competitive environment can be facilitated by adopting specialized strategies. This principle is relevant to many different scientific domains, including evolutionary biology, perceptual pattern learning, and the economics of business growth. It is therefore an ideal way in which to look at transfer of knowledge and the relevance of different kinds of 'visualizations' for promoting (or inhibiting) transfer.

Goldstone and colleagues systematically manipulated the visualizations they used to investigate the influences of attractive, interesting, or concrete representations on students learning and transfer of knowledge. For example, in one experiment (Goldstone & Sakamoto, 2003), students learned the concept of competitive specialization either from a concrete 'visualization' in which they had to help 'ants' select 'food' (both depicted pictorially in the 'visualization') or from a more idealized 'visualization' in which the food and ants were simply represented by small dots and larger blobs. The results indicated that the concrete 'visualization', which showed pictures of ants and food, helped students learn initially. However, some students who learned from the concrete 'visualization' found it *more* difficult to transfer their knowledge to other domains than did students who learned from the more idealized representation. Of particular interest was that students who initially had trouble learning the concept were much more likely to transfer what they did learn when they used the idealized 'visualization'. These results have been replicated and extended in a series of experiments that indicate that in general, concrete representations may facilitate initial learning but make transfer more difficult than more idealized representations that do not focus students’ attention on the particular characteristics of the ‘visualization’ (Goldstone & Son, 2005).

The results of this research clearly reveal that the dual representation hypothesis is relevant to learning from complex visual representations of the kind that are used in modern science instruction. Even though adults are quite familiar with many ‘visualizations’, educational designers still need to balance the attractiveness or concreteness of the visualization with the desire to help students learn from it. The putative assumption that highly interesting or attractive visualizations enhance learning may not be true, either for children or adults. More generally, what we need is a more detailed consideration of the benefits and costs of learning from concrete and idealized visualizations. The research reviewed here clearly indicates that even for very simple visualizations, there is always a tradeoff between making something interesting in its own right and helping people learn from it.

Towards a Research Agenda

The research and theoretical perspectives that we have reviewed here raise several important questions that could be explored in future research. In this final section we consider the questions that future research could address and suggest methods by which they could be approached.

Applying the Developmental Model

The first, and most general, suggestion is that the developmental model that we have outlined here can be used as a framework even for studying the development of ‘visualization’ use among college students. Of course, as discussed above, there are important differences between children and adults, but when it comes to understanding new or complex ‘visualizations’, there may also be important similarities. Most of what we do know about differences between novice and expert users of visualizations is based on anecdotes or is part of the cultural lore of teaching.

Accordingly, the first research recommendation we have is that we should study adolescents‘ and adults’ learning from new ‘visualizations’ from a developmental approach. We should investigate what knowledge they bring to bear when first interpreting a new representation and how this knowledge changes as they learn more both about the representation itself and what it stands for. What do students first think about when they encounter a new ‘visualization’? Does their prior experience in interpreting other ‘visualizations’ influence their interpretation of the novel one, and if so, how? Researchers in education and the learning sciences have already begun to answer questions like this (e.g., Lee & Sherin, 2006) through intensive studies of the process of learning through visualizations. But what is missing, for the most part, is how such understanding develops over time, across courses, and whether knowledge gained in one class transfers to other classes. This kind of research is neither easy nor inexpensive to do, but it is very much needed if we are to understand how, when, and why students learn from 'visualizations'.

A second important question concerns the process of abstraction and role of attractive or highly concrete 'visualizations'. Goldstone and colleagues' work is a very important beginning, but we still know very little regarding what type of information should be depicted at various stages in the learning process. For example, we do not know how or when students transform their knowledge or make connections among different forms of representations, nor do we know how or when instructors should switch representations. One can imagine a tradeoff between the misunderstanding that might arise from the frequent use of different 'visualizations' and the difficulties in transfer that might arise from repeated use of the same visualization or other model or representation. Given that students will be exposed to an increasingly large number of visualizations, we need more research on how they relate one 'visualization' to another (See Ainsworth, 2006 for a review of this issue).

A third set of questions concerns the possibility of helping students to develop a more general understanding of visual representations. It may be possible to develop meta-graphical awareness that is at least in part domain general. That is, students could learn to think *about* 'visualizations' in a manner that is not completely tied to a content domain. The work of Novick & Hurley, (2001) suggests that students may already understand the appropriate uses of different types of relatively simple visual representations, such as matrices, networks, and hierarchical diagrams. It may be possible, therefore, to create classes or instructional units that emphasize visual-spatial thinking and 'visualizations'. Such courses already exist in some engineering schools (See Sorby, 2001 for discussion of an example), and they seem to be highly successful. Facilitating the development of meta-graphical awareness might help to minimize the chances that students will focus on the concrete properties and hence fail to grasp what the 'visualization' is intended to represent. One important question that will arise in designing such a course or intervention will be where to begin: One could imagine teaching relevant concepts at a variety of ages or grades. The ultimate goal will be to make visual-spatial fluency as important as linguistic fluency.

Conclusion

'Visualizations' have transformed both the practice and teaching of science, engineering and mathematics. High-speed, inexpensive computers have made it possible for even beginning students to have access to rich representations of highly complex phenomena. Most textbooks in the natural sciences now come with CDs, DVDs, or links to web sites that allow students to learn from these 'visualizations' without even leaving their homes. Research on the process of learning from visualizations has lagged behind the creation of 'visualizations', but there are some signs that it is beginning to catch up. One example is this volume, which focuses specifically on the process of learning from 'visualizations'.

Perhaps the most important conclusion that can be drawn from this chapter is that 'visualizations' are representations. Indeed, much of the trouble that children, and perhaps adults, have in learning to use 'visualizations' involves recognizing that the person who created the 'visualization' intended it to represent something. Once this basic insight is gained, the spatial properties of the 'visualization' become available and useful for learning. But these properties remain useless until this basic prerequisite is met. The effective design of visualizations therefore must focus on how to facilitate, rather than to obviate, the need to think about them as representations.

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References

Ainsworth, S. E. (2006). DeFT: A conceptual framework for learning with multiple representations. *Learning and Instruction, 16*, 183–198.

Allwein, G., & Barwise, J. (1996). *Logical reasoning with diagrams.* Oxford: Oxford University Press.

Blades, M., & Spencer, C. (1987). The use of maps by 4–6-year-old children in a large scale maze. *British Journal of Developmental Psychology, 5*, 19–24.

Bloom, P., & Markson, L. (1998). Intention and analogy in children's naming of pictorial representations. *Psychological Science, 9*, 200–204.

Deacon, T. W. (1997). *The symbolic species: The co-evolution of language and the brain.* New York: Norton.

DeLoache, J. S. (1987). Rapid change in the symbolic functioning of very young children. *Science, 238*, 1556–1557.

DeLoache, J. S. (1989). Young children's understanding of the correspondence between a scale model and a larger space. *Cognitive Development, 4*, 121–139.

DeLoache, J. S. (2000). Dual representation and young children's use of scale models. *Child Development, 71*, 329–338.

DeLoache, J. S. (2004). Becoming symbol-minded. *TRENDS in Cognitive Science, 8*, 66–70.

DeLoache, J. S., deMendoza, O. P., & Anderson, K. (1999). Multiple factors in early symbol use: Instructions, similarity, and age in understanding a symbol-referent relation. *Cognitive Development, 14*, 299–312.

DeLoache, J. S., Miller, K. F., & Rosengren, K. S. (1997). The credible shrinking room: Very young children's performance with symbolic and nonsymbolic relations. *Psychological Science, 8*, 308–313.

DeLoache, J. S., Pierroutsakos, S. L., Uttal, D. H., Rosengren, K. S., & Gottlieb, A. (1998). Grasping the nature of pictures. *Psychological Science, 9*, 205–210.

DeLoache, J. S., Strauss, M. S., & Maynard, J. (1979). Picture perception in infancy. *Infant Behavior and Development, 2*, 77–89.

DiSessa, A., & Sherin, B. (2000). Meta-representation: An introduction. *Journal of Mathematical Behavior, 19*, 385–398.

Ferguson, R. W., & Forbus, K. D. (2000). *GeoRep: A flexible tool for spatial representation of line drawings.* Paper presented at the National Conference on Artificial Intelligence, Austin, TX.

Glasgow, J., Narayanan, N. H., & Chandrasekaran, B. (Eds.). (1995). *Diagrammatic reasoning: Cognitive and computational perspectives.* Menlo Park, CA: AAAI Press/ The MIT Press.

Goldstone, R., & Sakamoto, Y. (2003). The transfer of abstract principles governing complex adaptive systems. *Cognitive Psychology, 46*, 414–466.

Goldstone, R., & Son, J. Y. (2005). The transfer of scientific principles using concrete and idealized simulations. *Journal of the Learning Sciences, 14*, 69–110.

Goodman, N. (1976). *Languages of art.* Indianapolis, IN: Hackett Publishing.

Hectht, H., Schwartz, A., & Atherton, A. (2003). Looking *into Pictures: An Interdisciplinary Approach to Pictorial Space.* Cambridge, MA: MIT Press.

Hegarty, M., Carpenter, P. A., & Just, M. A. (1991). Diagrams in the comprehension of scientific texts. In R. Barr, M. L. Kamil, P. Mosenthal, & P. D. Pearson (Eds.), *Handbook of reading research* (Vol. 2, pp. 641–668). New York: Longman.

Hespos, S., & Spelke, E. (2004). Conceptual precursors to language. *Nature, 430*, 453–456.

Larkin, J. H., & Simon, H. A. (1987). Why a diagram is (sometimes) worth a 1000 words. *Cognitive Science, 11*, 65–99.

Lee, V. R., & Sherin, B. (2006). Beyond transparency: How students make representations meaningful. *Proceedings of the Seventh International Conference of the Learning Sciences*, 397–403.

Liben, L. S. (1999). Developing an understanding of external spatial relations. In I. E. Sigel (Ed.), *Development of mental representation: Theories and applications* (pp. 297–321). Mahwah, NJ: Erlbaum.

Liben, L. S. (2001). Thinking through maps. In M. Gattis (Ed.), Spatial schemas and abstract thought (pp. 44–77). Cambridge, MA: MIT Press.

Liben, L. S., Kastens, K. A., & Stevenson, L. M. (2002). Real-world knowledge through real-world maps: A developmental guide for navigating the educational terrain. *Developmental Review, 22*, 267–322.

MacEachren, A. M. (1995). *How maps work: Representation, visualization, and design.* New York: Guildford Press.

Novick, L R., & Hurley, S. M. (2001). To matrix, network, hierarchy: That is the question. *Cognitive Psychology, 42*, 158–216.

Sorby, S. A. (2001). A Course in spatial visualization and its impact on the retention of women engineering students. *Journal of Women and Minorities in Science and Engineering, 7*, 153–172.

Taylor, H. A., & Tversky, B. (1992). Spatial metal models derived from survey and route descriptions. *Journal of Memory and Language, 31*, 261–292.

Tomasello, M., Striano, T., & Rochat, P. (1999). Do young children use objects as symbols? *British Journal of Developmental Psychology, 17*, 563–584.

Troseth, G. L. (2003). TV guide: Two-year-old children learn to use video as a source of information. *Developmental Psychology, 39*, 140–150.

Troseth, G. L, & DeLoache, J. S. (1998). The medium can obscure the message: Young children's understanding of video. *Child Development, 69*, 950–965.

Uttal, D. H., Fisher, J. A., & Taylor H. A. (2006). Words and maps: Developmental changes in mental models of spatial information acquired from descriptions and depictions. *Developmental Science, 9*, 221–235.

Uttal, D. H., Schreiber, J. C., & DeLoache, J. S. (1995). Waiting to use a symbol: The effects of delay on children'ns use of models. *Child Development, 66*, 1875–1889.

Uttal, D. H., & Wellman, H. M. (1989). Young children'nns mental representation of spatial information acquired from maps. *Developmental Psychology, 25*, 128–138.

Wellman, H. M. (1985). *Children'nns searching: The development of search skill and spatial representation*. Hillsdale, NJ: Erlbaum.

Wood, D. (1992). *The Power of Maps.* New York: Guilford Press.

Chapter 4
Seeing Through Touch: The Role of Haptic Information in Visualization

Miriam Reiner

Abstract This chapter presents evidence for the development of visualization through touch when in circumstances where no visual information is provided. Results reported here show that local touch is translated into gestalt whole visualized patterns. It further shows that haptics, perception through touch, has semantics and that specific force patterns that constitute haptic interactions act as elements of information that are translated into visual images. It is shown that regions in the occipital brain, especially the Lateral Occipital Tactile-Visual Area, are activated when subjects attempt to recognize a shape haptically. Visualization of haptic patterns provides holistic gestalt views based on local haptic sensory cues. Haptic information contributes the micro details to visualization while the macro details are contributed by the human-visual system. It is further concluded that these findings about the processes of touch – visualization have major implications for design of cognitive technology with the intention of improving learning. A combination of touch and visual cues is advantageous to learning, providing more than each for the construction of a meaningful image of the world.

Introduction

Visualization is traditionally associated with what we see, grounded in images we perceive. Yet recent research reveals that one can generate an image without seeing (visuals), mainly through touch. This suggests that visualization processes can be enhanced by adding or replacing visual information with other sensory modalities. Indeed many instances in everyday life link touch with the identification of shapes. Almost everybody is familiar with finding a keyhole in the dark. Touching is indeed helpful in identifying the shape of the keyhole, discriminating the texture of the metal from the texture of the wood, feeling and controlling the orientation of the key, and finally inserting the key. This is done by being attentive to the forces acting on the key, then feeling that it is has a fit into the lock, and turning it. Yet what is the process behind the touch? How does the pressure on the skin of the fingers and

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fine movements of the hand help in identifying the shape of keyhole? Is this process inherent to touch or, is this particular kind of touch somehow associated with the visual system?

This chapter deals with visualization through touch. Four studies are reported: the first brings evidence that, based on touch only, students were capable of constructing visual representations of fields of force. The second looks at touch as a communication system and shows semantic interference takes place between touch patterns and verbal-visual patterns. The third shows that touch is constituted of elements of information, similar to ‘words’. The last study asks what is activated in the brain when touching an object in order to explore its shape. The assumption is that, if shape is indeed recognized through touch, some parts of the visual cortex should be activated. I start defining the properties of touch and then review the literature of the several studies that show the link between visualization and touch.

What is Touch?

At this point it may be helpful to the reader if to introduce the terminology used in the touch literature:

- -tactile feedback
  ‘is a sensation applied to the skin, typically in response to contact or other actions in a virtual world. Tactile can be used to produce a symbol, like Braille...’ (Burdea, 1996).
- -kinesthetic (proprioceptive) movement
  This is the sense of a relationship between force and motion. It includes force-feedback: a sensation of force, exerted on the body as a response to a particular force exerted by the body (Newton’s third law). Sensations such as that of weight while holding an object, resistance to pressing a flexible ball, friction while dragging an object, walking against strong wind or swimming against a strong stream, are all examples of force feedback. It should be noted that force feedback is always present when there is a response to a force exerted by the hand.
- -haptic feedback
  This is an umbrella term that is often used to include both tactile and kinesthetic feedback. It is sometimes used as being synonymous to tactile feedback only (Burdea, 1996)

Touch, unlike any other sensory channel, is unique: it is used for both collecting touch information such as textures and shapes and simultaneously used to act on the environment. For instance, a surgeon, when carrying out an incision, while actually inserting the tip of the instrument, is aware of a feedback force – is the feedback force that of a bone? of muscles? of fat? of blood vessels? Based on the information received through the feedback force, the surgeon may change the position, location or pressure exerted on the surgical instrument. This is not typical of surgical

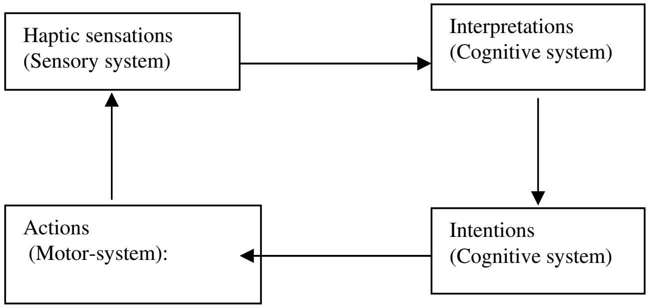

Fig. 4.1 Active exploration – a cyclic process

procedures only: when one lifts a cup of coffee towards ones lips, a person forms an initial estimation of the force needed. The muscles of the hand 'are prepared' for the estimated weight. Fine adjustment are made while lifting the cup. Yet, sometimes we make a mistake – we all know the awkward feeling of lifting a seemingly heavy cup, full of coffee, that turns out to be three quarters empty. The force exerted is too high, the resulting acceleration is not appropriate and the coffee which is still inside is sprayed into the immediate environment. Thus the sense of touch may be viewed as an *environmental adaptive* sense. The touch system feels the environment and finely tunes the action to fit both the information collected through touch from the environment and at the same time to fit the intentions in the person's mind (Fig. 4.1). In this 'sense', the sense of touch may be viewed as 'intelligent'. Indeed I show later that touch shares some features with primitive languages. It conveys a meaning and is used to express a meaning. If information is collected from the environment and intentions are achieved through touch, it makes sense to assume that some kind of learning happens through touch. The first study shows indeed that learning one of the most difficult concepts in physics is attained by naïve students through visualization of touch.

How is Touch – Sensory Input Translated into Visual – Sensory Output

The question is not just that of the translation of signals from one sensory modality into a different one. There are several intriguing questions related to visualization through touch that motivated this study: is it at all possible to transfer/represent/translate pressure on the finger into visual signals, something that is normally correlated with electromagnetic radiation acting on the retina of the eye? The two are totally different physiological systems, different physics processes. Although it seems intuitively plausible, this is at all not obvious. The second question is: what is the added value of the visual representations? Why is it beneficial to transfer touch representations into visual representations? The third question is that of meaning: the 'qualia' of the linked touch and visual representations. Qualia are qualities or properties as perceived or experienced by a person. Do touch and vision share the same qualia? Is there a difference in the qualia? The following study is a behavioral study into the feasibility that subjects construct visual representations on the basis of touch experience.

Results suggest that indeed visuals are constructed on the basis of touch although the two sensory systems are totally physiologically different and employ different physics signals, which further suggests that corresponding brain regions may be connected. They also suggest that visualization has a unique and powerful qualia advantage – *qualia are constructed through visualization*. It is the visual representation that provides the user/learner with the corresponding qualia by that adding *meanings and structure to the touch experience*.

Not much has yet been written on learning through a tactile interface. Bach-y-Rita et al., 1998 found that letter in a form of pin arrays of letter shapes attached to the skin on the back were recognized by subjects. In general there is a wide literature on recognition of shapes, but not on how touch is used for constructing concepts (e.g. Biggs & Srinivasan, 2001; Basgadan, Ho, Srinivasan, & Slater, 2000; Lederman, Klatzky, Hamilton, & Ramsay, 1999). Kilpatrick (1976) used kinesthetic feedback as an aid to 2D and 3D force field understanding respectively. He showed that kinesthetic feedback improved user perception and manipulation in a simple 3D virtual world, even more so than did three-dimensional stereo viewing. Similarly, Brooks, Ouh-Young, Batter & Kilpatrick (1990) found that an understanding of the binding energy of a drug molecule was much clearer when achieved through the medium of forces than those achieved through a visual display. Project Grope (ibid) summarize their findings over twenty years of research on tactile interface as follows: haptic display as an augmentation to visual display can improve perception and understanding; chemists using GROPE III can readily reproduce the valid docking positions for drugs and have a better understanding of why a particular drug docks well or poorly.

In a learning experiment, twelve subjects used a virtual environment that includes a screen and a tactile interface, a spherically shaped 'tactile trackball' which was developed by Haakma and Engel (For details see Engel, Goossens, & Haakma, 1994). This was commercially applied to a car's wheel and used for navigation in multimedia environments. The trackball was a 5cm ball that rested on a ring supported by four wheels. Two of the wheels were attached in such a way that, under particular conditions, they may create a torque on the trackball. When such a torque is applied, if not held by the user, the trackball rotates freely. Thus the user experiences a force exerted on his hand while trying to rotate the trackball. The torque was controlled by manipulating the difference in voltage of the two motors keeping all other parameters equal. The software ('Tactool'^{R}) simulates a field of forces. Thus an object presented on a screen is subject to forces applied by an invisible field. The learner may manipulate objects in the field by rotating the tactile trackball. This requires the user to apply a force on the tactile trackball. This feel of force corresponds to the simulated forces 'applied' by the field on the object. The stronger the simulated forces are, the stronger the force the learner needs to apply on the trackball. For instance, suppose that an invisible point O is the center of attraction, (e.g., a field of a positive charge) and an object is located at point B. Further suppose that the user wishes to move the object further away from O, the center of attraction. In order to rotate the trackball, the learner has to exert a force. This force varies according to the features of the field. If the user 'releases' the trackball, the 'object' will move towards the invisible point O, and the trackball rotates freely. In order to hold the 'object' in its place, the user must apply a force to hold it in its position.

Three force fields were designed for the study: An attraction field of forces, of a concentric shape, similar to forces exerted on an object that falls into a symmetrical 'hole'; A repulsion field of forces, also of a concentric shape, similar to the gravitational force exerted on a ball that moves towards the top of the hill. The top of the 'hill' is a non stable point of equilibrium; A repulsion field of forces, similar to the gravitational forces exerted on a ball that moves towards the peak of an infinitely sharp, point-sized top. The top of the peak is impossible to reach since it requires an infinite force. The repulsive forces drive the object away. Subjects were asked to freely explore the environment and draw the structure of each of the above three fields. In addition, subjects were asked to design, that is to draw, a field that generates particular motion of the charged particle.

Fields of forces are among the more complex and difficult to conceptualize. Unlike concepts such as force, temperature or light, fields are not sensed in any direct way. Fields are often represented through mathematical formulation or graphical representation only. Sensory experience of field forces in the laboratory is often impossible, due to the low magnitude of the forces involved. Thus the sensation of force is rarely involved in the construction of the concept of field.

The results showed a rich array of visual representations that share core features and convey similar core information: There was not even one case of failing to understand the structure of the field totally. The visualizations differed, in size, in dimensions e.g. 2D, and were sometimes drawn with a perspective that generated a 3D object. Fig. 4.2a and 4.2b describe two-dimensional visual representations of the force fields as drawn by the subjects. The radial lines describe the direction of force, the co-central lines describe the lines along which the force is perceived as constant, similar to the physics notion of equal-force-lines. Fig. 4.2c and 4.2d describe a three dimensional concept of fields as drawn by the subjects:

In addition subjects were able to visually design a field that 'traps a particle' that 'creates linear motion of a particle' that 'create parallel motions of multiple particles' that 'direct a particle to a target point'. Out of the 60 images produced by the subjects for all stages of the study, (24 were produced for the first stage only, 36 were produced for the later stages), 50 were two dimensional, and ten were three dimensional. None were uni-dimensional, none were irrelevant or totally erroneous. Visual representations were imagined in the resulting force patterns. Thus the translation of touch-visuals is bidirectional. Force patterns are translated into visuals to generate an enriched qualia of the concept, and visuals are translated into force patterns to generate situations that target a particular function. (for additional details please see Reiner, 1999)

The above results have implications for understanding haptic interactions. Is the touch action indeed uni-sensory or does it involve repeating cycles of touch-visuals translated to and fro to generate progressively enriched understanding of the environment and action on it? The results suggest that at least in some of the part of the haptic action cycle suggested in Fig. 4.1, visualization is involved in constructing

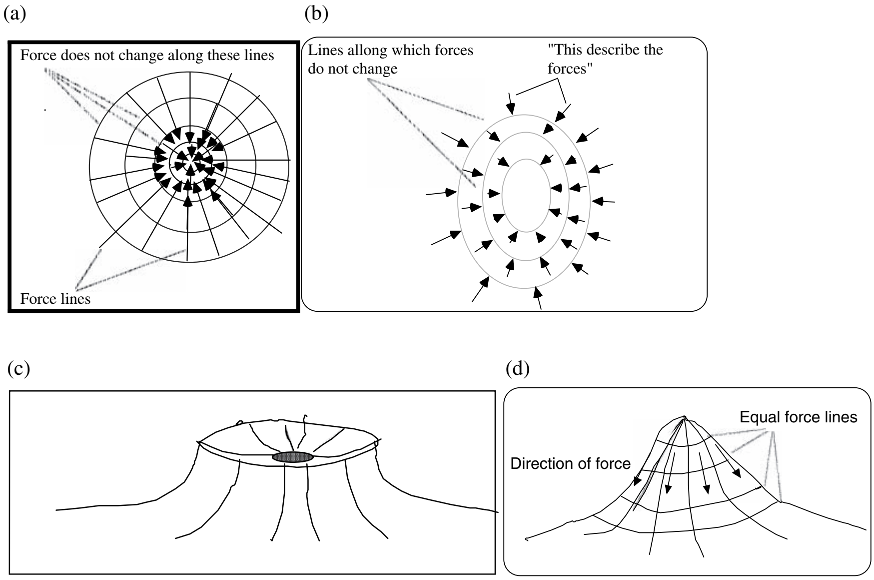

Fig. 4.2 Two dimensional and three dimensional visualization of force fields based on the sensation of force only, with no visual representations present

interpretations applied to action. This process is cyclic: situations are visualized through the feel of force patterns and force patterns are imagined and generated based on visualizations.

This study was limited in its results as it only suggest that visuals and haptics are in some situations linked, and that equivalent haptic and visual representations can be constructed. Yet these results give no clue as to the underlying mechanism. Does indeed haptic carry semantics? If so, what are the constituents of haptic interactions? What are the minimal patterns that conveys information? i.e. what is the minimal haptic unit that may be considered as an item of information? Two studies will be reported in the section on haptic language: the first uses a known effect – Stroop effect – that has previously tested semantic interference for non-congruent visual representations. This was applied to haptics to show that haptics has a semantic aspect too. The second study within the section of ‘haptic language’ shows that there is a haptic primitive language, which includes haptic patterns that may be considered to be elements of information.

Haptic Semantics and Visualization

The Stroop Effect was originally designed to test behavior when non-congruent cues were provided. In its original ‘Color-Word’ version, Stroop (1935) asked his participants to: name the color of colored squares, and name the color of the ink of written words. The meaning of the words was either congruent or incongruent – for instance

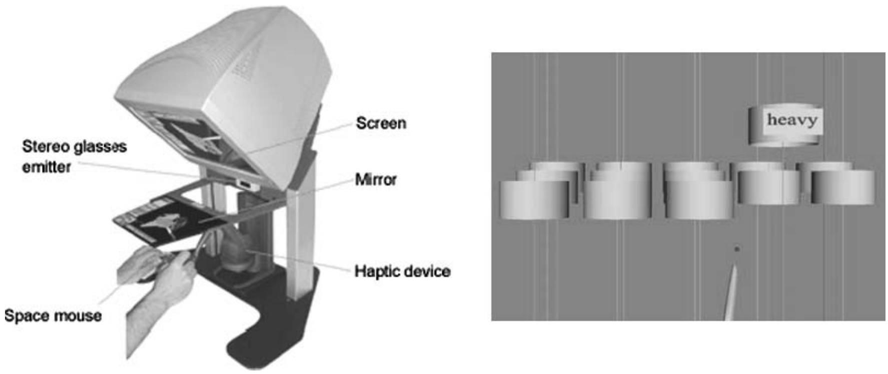

Fig. 4.3 The left hand figure shows the virtual world. The subject wears ‘active goggles’, which when synchronized with the graphics of the system show an immersive 3D virtual world. The room is darkened and the virtual objects are vivid and touchable. The figure on the right, displays the screen, which unlike here, is visualized in three dimensions

the word blue was written in red ink. Reaction Time (RT) was found to be longer in the incongruent color-word condition (Stroop, 1935)

The same effect was tested for hapto-verbal interference. A virtual world that includes both visuals and touch capabilities through touch capabilities through haptic interface – a PHAntom (Masey et al., 1994) (Fig. 4.3), in which participants had a visual display of virtual cylinders which they could ‘lift’ with a haptic device.

Half the cylinders were of a light weight and the other of a half heavy weight. The task was to discriminate the cylinders according to their weight. Lifting a cylinder, activated a label on it, containing the word ‘light’, ‘heavy’ or ‘###’ (neutral condition). Thus, participants experienced a haptic sensation either congruent with the label on the cylinder, incongruent or neutral. Two parameters were measured: Reaction Time (RT) and Error Rate (ER). Results show that both, RT and ER were significantly in the following order: congruent < neutral < incongruent. These results suggest that there is a dissonance between the meaning conveyed by the haptic sensation and the meaning conveyed by the text, further suggesting that haptics are somewhat similar to words, and indeed carries semantics. Whether this haptic semantics is translated into visualization, i.e. is obtained through means of visualization is not clear. However this study shows that there is interference between visual constructs and haptic constructs. (for full details please see Reiner, Hecht, Halevy, & Firman, 2006).

Elements of Haptic Information

How is haptic semantics conveyed? What are the haptic units of information? In analyzing the haptic interaction cycle in a tele-manipulation task it was found that particular force patterns exerted on the fingers and arm convey a particular meaning (Reiner, 2000). A sequence of force patterns conveys a ‘story’. This extends the previous finding suggesting that haptic elements constitute haptic meanings, somewhat analogously to letters that constitute a word. The experimental procedure was based on a telesurgery system that was carried out at SRI Int. in Menlo Park. The SRI telepresence system is extremely intuitive and highly immersive; thus all the acts are similar to everyday acts. The purpose of this experiment is to test the ability to identify invisible properties of visible objects on the basis of both visual and force feedback information. Subjects were asked to use two actuators, of a bi-manual telesurgery system to identify the shape and internal structure of a remotely positioned silicon breast model. Three invisible lumps were inserted inside the model. The subjects palpated the model by using the actuators. Remote robotic arms tracked the subjects' hand position and fed back haptic information. The normal and tangential forces applied on the robotic arm were transferred and exerted on the hand by the haptic interfaces.

The users were asked to explore the shape of the object then the inner structure of the object based on touch patterns only. Results showed that all subjects identified the shape, texture and inner structure of the silicon breast model. Although the context was identical for all subjects, completion time varied greatly, suggesting that personal factors may be involved. It was hypothesized that visualization, the task of constructing an image out of the haptic cues, was of varying level of difficulty for different subjects, and that other personality factors may be involved.

In addition, the recurring force patterns exerted on the hand were analysed and the time of occurrence was taken. Recurring verbal descriptions that were videotaped during the experiment were also identified and their time of occurrence was also taken . Force patterns were than correlated with verbal description in order to find out whether particular patterns correlate with particular verbal description. The results of analysis showed four such force patterns that were consistently coupled with the same four verbal descriptions. These corresponded to collision of the handle and the metal tray, sliding down and up along a 'dip' in the object, sponginess, and edge of the object. *Consistency* was measured by the number of events in which the subject mentioned a similar verbal description for a similar force-sensation pattern. The word edge (synonymous) was mentioned in 91% of the cases in which a particular pattern of force was exerted on the hand.); spongy –99.5%, bumping into hard material – 99.8% dip – 87%.

The results suggest that not only that haptic sensations have semantic features, they also include elements that are integrated by the brain to visualize a 'shape', for a particular sequence of sensed haptic cues. It supports the idea that the haptic sensory system interferes with the visual system to allow visualization of the touched objects. Visualization seems to be supported by the haptic elements of information, which when integrated over time, allow visualization of a shape (for full details please see Reiner, 2000).

The Visual Brain is Correlated with Haptic Shape Recognition

None of the above studies provided information as to how the two physiologically different physiological sensory systems, visual and haptics, are involved in way such the system A represents signals perceived by system B. The plausible way to support the idea that haptics is indeed correlated with visuals is to show that some visual-signal processing parts of the brain are activated when subjects touch to recognize a shape and no visual information is provided. The results described above suggest that there is interaction between the haptic system and the visual system at the brain level. This was studied in a fMRI study that hypothesized that the occipital (visual) cortex is activated when touch is used for shape recognition.

To answer the question concerning neural aspects of interaction across the touch and visual sensory systems, an fMRI experiment was conducted that examined brain activations during haptic and visual shape and texture recognition (Reiner, Korsnes, Feldman, Glover Gabrieli, in preparation). The unique supporting brain areas that correlate with recognition of shape/texture were sought. The main goal of this study was to explore neural correlates of recognition of shape and recognition of textures. The working hypothesis was that haptic exploration of shape activates in the visual cortex, but haptic exploration of texture does not. Scanning was done while subjects touched an object on a disk set by his/her hand. The disk included objects with different shapes and textures. The results show that shape recognition indeed activates areas in the occipital cortex in addition to areas in the motor cortex (also supported by results from Amedi, Malach, Henlder, Peled, & Zohary, 2001) (see Fig. 4.4). This further suggests that visualization is supported by touch, by

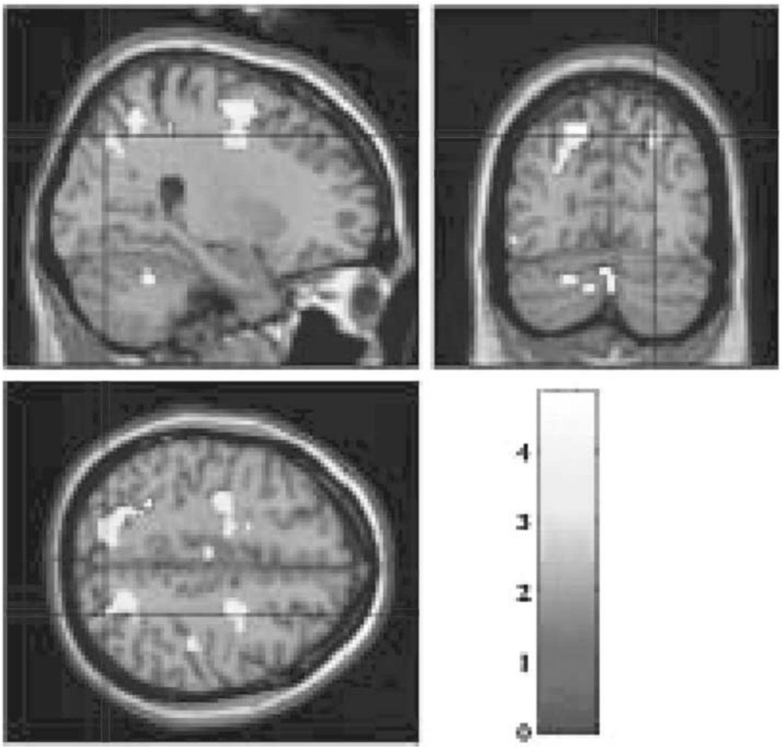

Fig. 4.4 Regions with higher activation for shape recognition than texture recognition include somato sensory regions and visual regions

activations in the motor area (responsible for the movement of the hand while touching an object) and by activations in the visual regions of the brain. The visual regions activated are also activated for actual 'seeing'. Thus touch and visualization are somewhat overlapping. Touch is an additional channel for providing details for visualization.

Summary and Discussion

I have shown that haptic interaction supports and can be translated into visualization on several levels: when sensing forces the sensory information is translated into a visual patterns, supporting visualization of a gestalt pattern. While touch provides local information, visualization provides an entire pattern. There is inherent difference between touch information and visual information: for instance suppose you need to describe the shape of an object, say an apple. You close your eyes, and try to get the information through touch. You touch one point then go to a second point. Over time, by collecting consecutive cues, you may be able to integrate those into a shape. Seeing an apple is totally different – the whole apple is seem at once. Thus it seems safe to suggest that a major benefit of translating touch into visualization is in the capability to see a whole pattern, a gestalt pattern, while touch provides local information both in space and in time. This major advantage of visual information may be the reason why whole visualized patterns contribute to constructing a meaning.

Further support has brought the haptic semantics studies and the brain correlates studies closer together. It was found that there are elements of information that provide information within the haptic modality, and also may, but do not have to, be translated into a visual gestalt that corresponds to the touch interaction. And it was showed that the hypothesis raised about interaction across the two sensory modalities is indeed correct: parts of the visual system are activated when no visual information is provided, eyes are closed, yet the hand is exploring a shape. These are the 'eyes in the fingers'.

Why is this important at all – because this provides a way to enhance learning. Visualizing is a central and immensely important in science learning. Cognitive mechanisms of science innovations and learning at all levels are based on visualization. Thought experiments have changed the way physicists think, and they way children learn physics. (Reiner, 1999, 2006; Reiner & Gilbert, 2000; Reiner & Burko, 2003; Reiner & Gilbert, 2000, 2004; Sorensen, 1992, 2006; Klassen, 2006). Visualization is crucial in thought experiments. How do we enhance visualization? How can we use other sensory modalities to design new technologies to empower children with the ability to see beyond the immediate visuals?

Some information is hardly perceived through the naked eye, and touch provides the micro details. For instance, texture is hard to perceive through visual information only. Medical doctors touch the skin in order to feel the rough texture that may provide additional information about the state of the skin. This suggest that visualization with the naked eye provides the macro details, touch increases the 'resolution' of possible visualization by providing micro details, by that enhancing visualization for learning.

The touch-visual link suggest design of learning environments: mental models of fields are mentally constructed through touch. Understanding of equilibrium and docking positions in space are understood through touch. All these suggest that learning environments need to include both visual and sensory interaction to support processes of construction of mental models of the environment.

References

Amedi, A., Malach, R., Henlder, T., Peled, S., & Zohary, E. (2001). Visuo-haptic object-related activation in the ventral visual pathway, *Nature Neuroscience, 4*(3), 324–330.

Bach-y-Rita, P., Kaczmarek, K. A., Tyler, M. E., Garcia-Lara, J. (1998). Form perception with a 49-point electrotactile stimulus array on the tongue: A technical note. *Journal of Rehabilitation Research and Development, 35*, 427–430.

Basgadan, C., Ho, C. H., Srinivasan, M. A., & Slater, M. (2000). An experimental study on the role of touch in shared virtual environments. *Computer-Human Interactions, 7*(4), 443–460.

Biggs, J., & Srinivasan, M. A. (2001). Haptic Interfaces. In K. M. Stanney (Ed.), *Handbook of virtual environment technology*. Lawrence Erlbaum Associates, Inc.

Brooks, F. P., Ouh-Young, M., Batter, J. J., & Kilpatrick, P. J. (1990). Project GROPE – Haptic displays for scientific visualization. ACM Computer Graphics, 24(4), 177–185.

Burdea, G. C. (1996). *Force and touch feedback for virtual reality.* New York: John Wiley & Sons Inc.

Engel, F. L., Goossens, P., & Haakma, R. (1994). *Improved efficiency through I and E feedback: a trackball with contextual force feedback.* Manuscript 1013. Institute for Perception Research, Eindhoven University of Technology, the Netherlands.

Gilbert, J., & Reiner, M. (2000). Thought experiments in science education. *International Journal of Science Education, 22*(3), 265–283.

Kilpatrick, P. J. (1976). *The Use of kinesthetic supplement in an interactive system.* Ph.D dissertation, Computer Science Department, University of North Carolina at Chapel Hill.

Klassen, S. (2006), The science thought experiment: How might it be used profitably in the classrom?, *Interchange 37(1)*, 77–96.

Lederman, S. J., Klatzky, R. L., Hamilton, C. L., & Ramsay, G. I. (1999). Perceiving surface Roughness via a rigid probe: Effects of exploration speed and mode of touch. *Haptics-e Journal, 1*(1), October 7 http://www.haptics-e.org.

Masey, T. H., & Salisbury, K. (1994). The PHANToM haptic interface: A device for probing virtual objects. *Proceedings of the ASME Winter Annual Meeting, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, Chicago, IL, Nov 1994.

Reiner, M. (1999). Conceptual construction of fields with a tactile interface. *Interactive Learning Environments, 6*, 1–25.

Reiner, M. (2000). The validity and consistency of force feedback interfaces in telesurgery. *Journal of Computer Aided Surgery*, 9, 69–74.

Reiner, M. (2006). The context of thought experiments in physics learning. *Interchange, 37/1*, 99–117, Springer.

Reiner, M., & Burko, L. (2003). On the limitations of thought experiments in physics and implications for physics learning. *Science and Education,* 12, 365–385.

Reiner, M., & Gilbert, J. (2000). Epistemological resources for thought experimentation in science learning. *International Journal of Science Education, 22*(5), 489–506.

Reiner, M., & Gilbert, J. (2004). The symbiotic roles of empirical experimentation and thought experimentation in the learning of physics. *International Journal of Science Education, 26*(15), 1819–1834.

Reiner, M., Hecht, D., Halevy, G., & Firman, M. (2006). Semantic interference and facilitation in haptic perception. *Proceedings of the Eurohaptics conference*, Paris.

Sorensen, R. (1992). *Thought experiments*. Oxford: Oxford University Press. Paper given at Eurohaptics 2006, Paris, France, July 2006.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*, 643–662.

Section B
The Design of Units and Courses Focused on Visualization

Mary Nakhleh

This section emphasizes how instructors can select and use appropriate external representations for their courses. As we have seen in the previous section, external representations are powerful tools, but in an educational setting they must be used appropriately within the context of the goals of a course, the students' backgrounds, and even the structure of the particular science discipline. Such representations can be very useful in helping students understand some of the "invisible" aspects of a discipline. For example, in chemistry it is often useful to personally visualize molecular behavior, while in biology representations of ecosystems are often valuable tools in capturing the patterns that arise when many variables interact in complex ways. In addition, instructors must remember that multiple external representations, such as audio and video or video and line graphs, must positively reinforce each other rather than compete with each other for the students' time and attention.

In fact, external representations can be evaluated along at least six different dimensions in thinking about how to use them effectively in your teaching. For example, one dimension to evaluate would be abstract to realistic. Along this dimension, external representations can be abstract (maps, systems diagrams, graphs), semi-abstract (molecular models, cell models, cross-sections of stars), or realistic (photographs of rock formations, movies of an egg hatching). Then there is the animation dimension, ranging from static representations, such as a model of a molecule, to simple motion, such as rotating a molecular structure, to complex motions, such as a molecular-level representation of the process of dissolving. Of course, motion implies a time dimension, ranging from an instantaneous snapshot of a phenomenon to a complete display of the time history of an event, such as a titration graph. Fourth, one can consider where a representation falls along the simple to complex dimension, or fifth, the dimension which goes from simple observations and data collection to full-blown interpretation and model building. Finally, a dimension that Liliana Mammino's chapter clearly highlights is the idea of assessing the visual literacy of the students, which might range from no ability to interpret and understand representations to full visual literacy.

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However, these dimensions are not the only ways in which one must evaluate representations for pedagogical purposes. These dimensions interact with three different levels that exist within most science disciplines: the macroscopic, the microscopic and the symbolic. Often the objective is to use students' understanding on one level to increase their understanding on another level. And often that movement is from the macroscopic level to the microscopic level, using the symbol structure of the discipline as a tool for interpretation and model building. On the macroscopic level, most science disciplines are concerned with what can be seen and measured, such as physical and chemical properties and changes. However, most science disciplines also deal with a microscopic level, such as the chemist's molecular level or the physicist's quantum level. Students are usually expected to take all of the observations and measurements they make on the macroscopic level and then process and interpret these data on the microscopic level. Also every science discipline has a symbol structure that it uses to calculate, interpret data and build their models. For example, chemistry has formulas and chemical equations; Newtonian physics has its vector diagrams. Therefore, students have to master their science courses along many dimensions and at different levels, a formidable task. Fortunately, research is showing that external representations have great potential for helping students in this task, but research is also showing that poorly chosen representations can actually hinder students in their learning as well. Therefore, this section presents four studies that might help other educators think about how to harness the power of representations for their own courses.

Yvonne Rogers' chapter discusses two projects that investigate how students can use mobile sensing tools to collect data in the field (woodlands in this case) and then pool their data and create complex representations using large computer-based displays. One study was with young children, and the other study was with university students. Both groups benefited from the representations, and in both groups students were able to use them to expressly link their observations to physical, graphical and numeric representations. In the process, students were able to engage in "a rich tapestry of experiential and reflective activities." This project uses the macroscopic and symbolic levels in its representations and employs the simple/complex, abstract/real and observation/interpretation dimensions in its data display and data analysis procedures. Students in this project would need to possess a high level of visual literacy.

The chapter by Roy Tasker and Rebecca Dalton focuses on dynamic animations of molecular level structures and processes in chemistry. They discuss how these animations can be embedded in instruction to allow students to collect data on the macroscopic level (the real world) and then interpret that data using their understanding of molecular level behavior. Along the way, they target specific misconceptions that students often hold about the molecular level. This study focuses on the molecular level (microscopic) and on learning how to relate this molecular-level model of matter to the observations of nature that are made on the macroscopic level. To do this, students must be fluent in chemistry's symbol structure and must have good visual literacy. Their project concentrates on the dynamic end of the static/dynamic dimension and uses the full range of the observation/interpretation dimension.

Debbie Reese's chapter focuses how digital game world theories can be used to build and analyze teaching metaphors that can help students bridge the gap between novice and expert thinking. Using the idea of a balanced chemical equation as an example, she discusses how to transform the target domain (balanced equations) to a source domain (a grid of tiles) in a virtual environment. She also discusses the design issues and research agenda associated with the idea of metaphor-enhanced learning objects within a virtual environment. A metaphor is basically a symbolic device, and in fact the source domain, the tile grid, seems to depend almost entirely on the symbolic level. Interestingly, the target domain, the balanced chemical equation, largely depends on a molecular-level understanding of atoms and molecules and on a macro-level understanding of moles. The chapter also depends heavily on the abstract/realistic dimension in that it tends strongly to the abstract.

Finally, Liliana Mammino's chapter describes teaching chemistry in environments with limited resources and to students whose traditional culture is largely orally transmitted. The chapter illustrates both the challenges and opportunities afforded by representations. She reports that one the one hand, representations can be a bridge to help the students take their data from the macroscopic level and interpret it on the molecular level. On the other hand, she discovered that many of her students had low levels of visual literacy and therefore could not benefit as much from the representations. She discusses strategies for overcoming these difficulties but warns that

> "searching for optimal encounters and convergences of the use of visualization (representation) in science teaching and the use of culturally inherited oral learning resources... could constitute one of the challenging pathways for the overall enhancement of science literacy and acquisition of science knowledge in developing/emerging contexts."

This chapter clearly communicates the important role of visual literacy in teaching and learning using representations.

Chapter 5
Using External Visualizations to Extend and Integrate Learning in Mobile and Classroom Settings

Yvonne Rogers

Abstract Advances in mobile technologies and pervasive computing provide new opportunities for supporting and enhancing learning that goes beyond that which has been made possible using the desktop PC. "Visualizations" can be presented or accessed via mobile devices or ambient displays at opportune times that can be pertinent to an ongoing physical activity. This chapter examines how external representations can be designed, accessed and interacted with to facilitate scientific inquiry processes, through using pervasive and mobile technologies. It begins by providing an overview of how different technologies have been used to support learning about and the practicing of scientific inquiry. Next, it describes the kinds of representations that are considered most effective to use. Two case studies are then presented that show how small-scale and large-scale representations were successfully integrated and used by students to understand and hypothesize about habitats and environmental restoration.

Introduction

Advances in mobile technologies and pervasive computing are providing new opportunities for supporting and enhancing learning that goes beyond that which has been made possible using the desktop PC. Various kinds of information can be presented or accessed via mobile devices (that are worn or carried) or ambient displays (situated in the environment) at opportune times that can be pertinent to an ongoing physical activity. For example, the physical activities associated with scientific inquiry, e.g., measuring, recording, can be augmented with contextually-relevant digital information making it possible for higher level analysis and synthesis of the "live" data being observed and collected to occur in the same location and time. Abstract representations ("visualizations") can be brought to the centre of students' attention at critical moments in the context of the ongoing physical action – which

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is usually not possible when on a field trip – that can facilitate deeper and more integrated understanding. By this is meant making connections between ideas and observations, across both abstractions and physical environments.

"Visualizations" can also bridge learning experiences through linking and representing disparate data collections. Real-time logging, recording and collating of data in the field can be revisited, either in situ or later in the classroom, using a variety of representational formats. Furthermore, students can collect data within their local environment, using various sensing technologies and handheld computers that can be combined with similar kinds of data collected by other students, who are in different locations. The accumulating data sets can be analyzed and comparisons made. For example, bird's eye dynamic "visualizations" can be created that depict the distribution of environmental readings taken from a range of students in different locations (Rogers et al., 2005). Having a personal relation to and interest in the data (i.e. having collected some of it and experienced the physical environment from where it came from) provides an experiential dimension to data analysis that can make the visualization more meaningful than when compared with looking at and analyzing others' datasets. At the very least, it can be motivating as students examine their contribution relative to others' and its significance.

Ackermann (1996) points out how in order to learn from experience, it is necessary to step back and reflect momentarily before diving back into the experience. Collecting data and revisiting it as different forms of visualizations is well suited to supporting such diving in and out. However, it requires students to be able to switch their attention between different perspectives, activities and foci of interest and to be able to make sense of them. A central concern, therefore, is can students learn effectively when switching between ongoing physical activities, such as measuring, and interacting with multiple digital representations?

This chapter examines how external "visualizations" can be designed, accessed and interacted with to facilitate scientific inquiry processes, through using pervasive and mobile technologies. It begins by providing an overview of how different technologies have been used to support learning about and the practicing of scientific inquiry. Next, it describes the kinds of visualizations that are considered most effective to use. Two case studies are then presented that show how small-scale and large-scale visualizations were successfully integrated and used by students to understand and hypothesize about habitats and environmental restoration.

Background

Information visualization is a growing field concerned with the design of computer-generated graphical representations of complex data that are typically interactive and dynamic. The goal is to amplify human cognition, enabling scientists and other researchers to see patterns, trends and anomalies in the visualization and from this to gain insight in ways that is much harder to accomplish from numerical datasets or textual descriptions (Card, Mackinlay, & Shneiderman, 1999). It follows on from earlier research on graphical representations, where it has been found that diagrams are easier to make inferences from compared with informationally equivalent sentential forms, since less computation is required to use them to reason (e.g., Larkin & Simon, 1987; Scaife & Rogers, 1996). Likewise, it is assumed that visualizations can be designed to enable people to readily switch their attention from one component to another to draw conclusions in ways that are difficult, if not impossible, to do with a sequence of sentences. "Visualizations" also provide simultaneous information about the location of components in a form that enables objects and their relations to be easily tracked and maintained. The best "visualizations" – as with other forms of graphial representations – are those that make it obvious where to look to draw conclusions.

There has been little research on which are the most effective ones for supporting learning. A few science educational tools have been developed that include data "visualization" as a component. For example, PC-based software tools that have been developed for learning about scientific inquiry, include the Progress Portfolio (Loh et al., 2001) and ScienceWare (Soloway et al., 1996) – that support the different phases of investigation, including data gathering and data "visualization". Studies have shown them to be effective at helping students build and understand dynamical models of complex phenomena (e.g., Stratford & Finkel, 1996) but not as good at enabling them to transfer this knowledge to the practice of scientific inquiry. An alternative approach has been to create combined simulation and measuring tools with the aim of facilitating more experiential-based learning activities. For example, Probeware was designed to enable students to perform hands-on scientific experiments (e.g., measuring parameters such as temperature and light) and to be able to view the probed readings in real-time on a computer display in the form of graphical representations (e.g., Laws, 1997; Layman & Krajcik, 1990). The TEEMMS project found that investigation, exploration, and reflection could be enhanced using such combined tools and representations (Metcalf & Tinker, 2003).

Mobile computers have also been developed for use on field trips with the primary aim of allowing groups of students to organize and share data they collect from the environment (e.g., Gay, Rieger, & Bennington, 2002; Grant, 1993; Hine, Rentoul, & Specht, 2004; Rogers et al., 2005; Roschelle & Pea, 2002; Soloway et al., 1996; Sharples, Corlett, & Westmancott, 2002; Soloway et al., 2001). One of the main findings from this body of research is to show how context is powerful at helping students understand and question: in particular, being able to collect and analyze data in the same location enables them to relate the changes they see in numerical and graphical data with the changes they see in the environment.

The focus of much of the research on mobile learning has been on collaborative interactions; pairs or small groups of students use mobile devices, such as PDAs or mobile phones, to communicate their discoveries and ideas with others, who are beside them or at a distance. The external representations that are updated or the information accessing is relayed to others, via voice or text messaging, during and after the activities. One of the main benefits of encouraging this form of peer-to-peer communication, while engaged in hands-on physical activities, is to promote reflection (e.g., Ackermann, 1996; Boud, Keough, & Walker, 1985; Scaife &

Rogers, 2005). Students are encouraged to express their opinions, seek clarification, interpret, explain, dispute, generate, test and elaborate ideas. Moreover, by "self explaining" to themselves and others, they become aware of their own discrepancies in understanding, enabling them to revise their understanding (Chi, 1997). "One way in which learners may gain from working closely on a problem is by being required to make their thinking public and explicit" (Crook, 1994, p. 133). Rather than just consider how to design visualizations to be used by individual students to support their learning, it is important to think about how they can be accessed, shared and verbalized in a collaborative setting.

Designing Visualizations for Supporting Collaborative and Mobile Learning

One design principle that has been promoted for using external representations in learning is dynalinking (Rogers & Scaife, 1998). By this is meant changes made to elements in one representation are designed to co-vary with elements in another. Physical measurements can be "dynalinked" with numerical and graphical representations that make their dynamic relationship explicit. For example, as a physical entity changes (e.g., the level of CO2 in the environment) so, too, do the dynamic measurements collected; these can be conveyed using numerical and graphical representations that co-vary to reflect the changes. Hence, one of the main cognitive benefits of dynalinking is to allow the relationships between a complex concept to be dynamically and explicitly displayed via different forms of external representations. In so doing, it can help students integrate multiple representations at different levels of abstraction, enabling them to understand and reason with them more readily.

Specific objectives when designing information "visualizations" are to enhance discovery, decision-making and explanation of phenomena. Most have been developed for use by experts to enable them to understand and make sense of vast amounts of dynamically changing domain data or information (e.g., satellite images, research findings). They are usually presented via high resolution large displays, enabling the zooming in and out of more or less detail depicted in the visualisations. There has been less research, however, on how "visualizations" can be designed, specifically to help students understand and practice science in situ. Here, we are interested in how external representations can be designed, initially, to help groups of learners understand and hypothesize about the environment when experiencing and observing it, and, subsequently, when revisiting and working with them in other settings, away from the field trip experience but with additional tools and visualizations at hand. A goal is to enable more analysis and synthesis to take place outdoors while at the physical site of observation and more consolidation and reflection to take place when revisiting and combining data and visualizations in a classroom setting. An assumption is that having more opportunties to analyse, synthesize and reflect will enable learners to understand better the connections betweeen different inquiry processes and the various representations that are collected and used in the different contexts.

So what kinds of external "visualizations" are effective for supporting scientific inquiry activities – that can be accessed in mobile settings via small displays? How should they be collated and re-presented when revisited later in a lab or classroom setting to enable students to build upon their observations and analyses in the field and compare them with other datasets? We suggest that "visualizations" that are intended to be used in situ (i.e. when in the field) should be designed to be relatively simple and easy to read. Moreover, students should be able to readily view and understand dynamically changing data and trends as a result of their onoging measuring and recording activities, allowing them to further detect in real time patterns or anomalies. To this end, we propose using simple canonical forms, such as trend graphs, cyclical diagrams or bar charts, that are 2D in form – rather than more complex techniques that have been developed for depicting information visualizations, such as 3D interactive maps that can be zoomed in and out of and which present data via webs, trees, clusters, tiling or scatter plot diagrams (Bederson & Shneiderman, 2003; Chen, 2004). My reasoning is that complex "visualizations" take too much time to parse and extract meaning from, interfering with the ongoing activity. Hence, "visualizations" that are intended to be used in situ should provide just enough information to enable students to be able to readily connect with what they are doing, e.g., measuring or observing and from this mapping to make inferences and generate hypotheses about why something is or is not the case.

When back in a lab or classroom setting, students will have more time to reflect on their initial musings and analyses of the data they collected in the field. They can be combined with existing datasets, and and so further information can be depicted through using more complex "visualizations" using large computer-based displays. However, it is important that the "visualizations" viewed in the outdoor setting are able to be revisited and explicitly linked with the new ones to enable students to continue to map their personal experience of where and how the data was collected (and any discussions and hypothesis generation arising from this) with the new representations. To illustrate how this can be accomplished, an overview of the Ambient Wood Project (Rogers et al., 2005) and the LillyPad projects are presented below (Rogers, Connelly, Tedesco, & Hazlewood, 2006).

The Ambient Wood Project

One of the motivations behind the Ambient Wood Project was to enable children intermittently to switch from their "here and now" experiences of the physical world (e.g., observing a butterfly drinking nectar from a thistle) and to reflect upon the ecological processes that lie behind this interdependency (e.g., pollination). Often field trips and computer-based indoor learning activities are performed separately; children may go on a field trip and observe and collect data that, on another occasion, they will input into a software simulation package back in the classroom. This separation of interlinked activities can make it difficult for children to see and understand the connections between what are essentially the same representations and processes being studied, albeit in different contexts. To this end, a learning experience was designed to encourage children to hypothesize more about different aspects of a woodland habitat while they were exploring it. They were provided with mobile sensing tools to probe the environment that resulted in real-time visualizations being depicted on a handheld device that were revisited later in a different format via large shared displays.

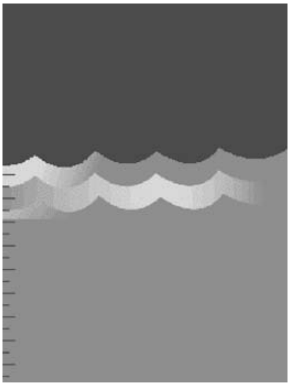
The probe tool was designed to allow children to collect real time measurements of light and moisture in the woodland (see Fig. 5.1). Readings of the probes appeared on the PDA display as simple representations that varied in intensity of light or level of water to indicate their relative levels. It was decided not to provide exact readings but relative ones of the data being collected when being used in situ. The reason for this was to provoke the children into hypothesizing about what they meant with respect to their surroundings and ongoing activities. The probe tool was also designed to transmit and store all of the readings taken and the location at which they were collected in the woodland (using GPS).

Reflection tools were developed to enable the children to analyze their outdoor discoveries more extensively (see Fig. 5.2). These comprised an interactive large scale "visualization" showing a bird's eye view of the woodland, overlaid with all the children's collected probe readings in the location (as dots that could be opened to reveal the actual probe readings collected and observed earlier) and an interactive tangible board that was designed to allow the children to reconstruct what they had observed and collected at a higher level of abstraction, using various graphical representations that were embedded with RFID tags. Feedback was provided on an adjoining display in response to certain combinations of tagged tokens (that represented correct interrelationships) being detected by the board.

Two field studies were carried out with 20 pairs of children, aged 11–12 years, taking part. The pairs of children were asked to discover as much as possible about a different part of the environment, initially by looking, touching, smelling and listening. They were then provided with the probing devices to find out more. To facilitate reflection, the children were encouraged to talk with one another and a remote facilitator, via the use of walkie-talkies, reporting on what they had discovered, what its significance was and what they planned to do next. They were asked to discover and observe different aspects of the habitat and to generate hypotheses about their relationships and their interdependencies.

Findings from the logged use of the probe tool and video data of the children in the woodland showed much evidence of them integrating the findings obtained from the probe devices with their own observations of the physical environment. All the children probed many different aspects of the woodland (and themselves), taking it in turns to either probe or read the outcome on the PDA. On average each pair took about 80 readings, of which half were for light and half were for moisture. This frequency of probing indicates the collaborative activity to be highly successful at provoking further exploration. Often, after taking a reading, the pairs of children would suggest to each other another place to go to confirm or disconfirm their hypothesis about what the new reading would be. They also suggested to each other where to take the most extreme readings, and again, this involved them making and

(i)



(ii)

(iii)

Fig. 5.1 (i) Examples of the simple, real-time "visualizations" depicting high intensity light and medium level moisture on the PDA screen immediately after being collected, (ii) a boy using the probe tool to measure moisture of a tree and (iii) a pair looking at the visualization of their latest probe measurement

Fig. 5.2 Shared visualizations analyzed and reflected upon in a makeshift classroom: on the left is a tangible board for placing external representations of parts of the ecosystem visited and recorded and on the right is a display showing a bird's eye visualization of all the pairs of student's data collected

then testing predictions about the environment. The following is an example of a pair of girls hypothesizing where next to probe to find a similar reading or the opposite:

A: "Shall we try a dry leaf?"

<A puts the probe tool onto a leaf of the tree>

B: "That didn't do much at all – not very wet at all"

B: "Try it in this grass"

B: "That's much wetter"

A: "This is really dry, shall I try it over here?"

There was also evidence of the children integrating their probe readings with their understanding of the habitat. For example, after taking a probe showing a dark reading under a tree, one boy observed that "the grass grows where it is light and moist, but it is dry and leafy under the trees". The spontaneous conversations that took place suggest that this method of interacting with the environment together with the information provided via the simple "visualizations" enabled the children to initiate and practice scientific inquiry. Furthermore, there was much evidence of them diving in to take the readings and stepping back to interpret them in the context of what they were doing and what next to do.

The pairs of children then all came together to reflect on and share their explorations in a makeshift classroom, housed in a tent, in another part of the woodland. Our aim was to allow them to reflect while their experiences of being in the woodland were still fresh in their minds. They were fascinated that all of their own and the other children's probe readings were now available to them as interactive data points on the bird's eye visualization display. By clicking on the data points the children were able to bring up the same readings they had seen before on their

PDAs. This caused much interest, especially when trying to find the data points of where they had probed parts of their bodies. Being able to see each other's data in this personalized way, enabled the children to develop an overall picture of the different distributions of moisture and light in the two areas and to make generalizations about the contrasting habitats as to why different types of organisms lived in each habitat and why they would not survive so well in the other. In so doing, they abstracted and explained to each other what the patterns of their personalized data points represented.

The combination of viewing real-time, simple visualizations that subsequently could be revisited in the form of a large-scale visualization of all the data collected by the children was successful at facilitating analysis and other scientific inquiry processes. In particular, the children were able to integrate their here and now understanding of the woodland, derived from their individual probes of it, with their subsequent reflections on the patterns appearing in the bird's eye visualization.

The LillyPad Project

Similar to Ambient Wood, the goal of the LillyPad project was to facilitate the practice of more integrated scientific inquiry in the field, using a mobile learning application, but for older learners, namely, university students, working in teams, rather than pairs. Accordingly, the type of data collected, the tools used and the "visualizations" developed were more sophisticated, intended to be at an appropriate level for that student group.

A main assumption was that having relevant datasets and "visualizations" ready at hand could provide the necessary external support to enable students to answer their own and other's questions, leading them to probe further and, in so doing, support the transition and progression between different inquiry processes. The goal was to determine if the teams of 5–6 students could actively participate at different times in the various inquiry processes by: making connections between their observations, understandings, and analyses of aspects of the physical environment; comparing these with previously collected data stored on the mobile device; interpreting and making inferences at higher levels of abstraction using various graphical representations on the mobile device, and generating hypotheses and drawing conclusions.

An experimental field research site, called Lilly Arbor, was the focus of the study. This was created as part of an investigation into ecological restoration of urban riverbanks. A 1.8 km stretch of riverbank in the US mid-west was restored, a number of years ago, using three of the most common methods for reforestation to determine the best strategies for forest restoration. Over 1400 native trees of 12 different species were initially planted using the different methods for different plots. The site has now evolved into a wildflower meadow and shrub/sapling habitat as the trees grow and other species gradually recolonize the area. Twice a year, in spring and autumn, teams of environmental scientists and students have conducted an assessment of the restoration site, measuring the survival and growth of trees and noting, among other things, any predator damage to the trees and the impact of the recolonization of other trees and plants in the plots.

The students are immersed in an apprenticeship approach to learning: discovering what is involved in being an environmental scientist by practicing how to observe, collect, record and analyze data in an authentic setting. They work alongside the scientists and are made aware that the data they collect will contribute directly to the accumulating scientific databases and analyses. Initially, they have to locate and identify a tree to assess its health. Various measurements are then taken, including the diameter and height of the tree.

The students have tended to focus on the task of measuring the tree's dimensions, finding it difficult to reason subsequently about the implications of these with respect to environmental issues. Part of the problem seems to be that they did not have the information available at hand to help them make the leap from data collection to analysis and synthesis. Hence, the LillyPad application was designed to provide them with the necessary forms of external representations that would enable them to reason and reflect more when engaged in the measuring activities. These included functions for entering observations, connecting these with previous recordings and finding and using relevant information to enhance their understanding of what they were observing. It was assumed that these would allow the students to begin to reflect more upon their measuring activities and make inferences about them with respect to relevant environmental and restoration issues.

To encourage analysis and reflection, "visualizations" depicting growth trends and patterns of the actual trees that were in the environmental restoration site were provided. These were in the form of line graphs, that students are familiar with, conveying the growth rate of the individual trees and species over five years (see Fig. 5.3). An assumed benefit was that it would enable students to interpret more generally the significance of growth patterns over time in the context of their ongoing observations and measurements for a particular tree.

Three line graphs were presented showing, first, the growth of a particular tree over time, second, the average growth for that tree species within the plot they were currently in and third, the average across all of the plots in the restoration site and

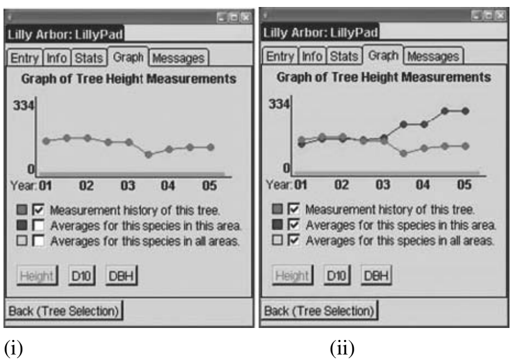
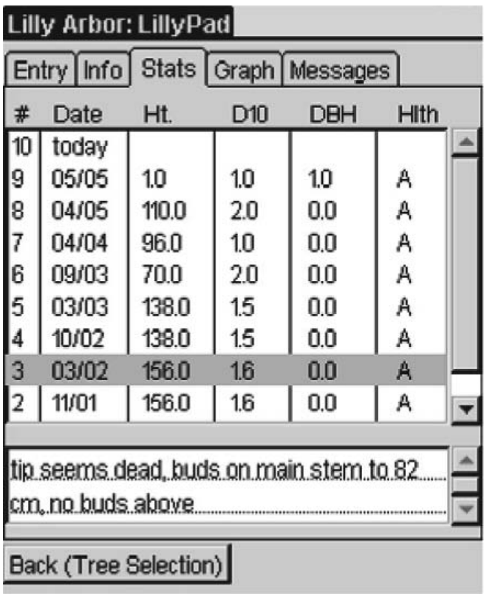


Fig. 5.3 Graphs depicting tree growth over five years designed for the LillyPad application: (i) default data representing a single tree and (ii) all checkboxes clicked on to show the trends for the species for that area and for the whole site

therefore all of the planting styles. The three line graphs are built up interactively by clicking on adjacent checkboxes for each level of abstraction. The default is for a relatively simple, single line graph to be presented for the growth pattern of an individual tree. Providing the three levels of abstraction in this way was intended to help the students incrementally build up their understanding of why a tree for a particular species may be performing well or poorly in a given area and the causes for this; these could be species-specific, local factors (e.g., predation competition), environmental factors (e.g., flooding), or experimentally induced factors (e.g., initial type of tree planting method). Numerical data was also provided showing the dimensions of each tree's growth for the measurements taken over five years (see Fig. 5.4). In contrast to the line graphs, they provide the students with an exact reading that allowed them to determine how many centimeters a tree has grown or shrink in the last six months – providing a different kind of representation from which to make inferences from.

The graphical "visualizations" were intended to support the reasoning about why a particular measurement of a tree was found to be less than previous measurements – that was revealed through the numerical data. Switching between dynamically updated numerical and graphical representations of a physical entity that is being observed and measured, provides a powerful form of dynalinking. It enables the students to appreciate the value of having different representations and when best to use one or the other to further their scientific inquiry processes.

Two measuring days were conducted where teams of 5–6 university students used the LillyPad application. From the logged and video data collected, several instances were found of the groups alternating between accessing and interpreting



#	Date	Ht.	D10	DBH	Hlth
10	today				
9	05/05	1.0	1.0	1.0	A
8	04/05	110.0	2.0	0.0	A
7	04/04	96.0	1.0	0.0	A
6	09/03	70.0	2.0	0.0	A
5	03/03	138.0	1.5	0.0	A
4	10/02	138.0	1.5	0.0	A
3	03/02	156.0	1.6	0.0	A
2	11/01	156.0	1.6	0.0	A

Fig. 5.4 The historical data represented in tabular form of each tree's measurements over five years. Ht stands for height, D10 and DBH are two measures of the diameter of each tree and Hlth stands for health of the tree (A means alive)

the numerical and graphical representations when locating and measuring trees. For example, they looked up the numerical data for the previous measurements of a tree they were currently measuring, and if any of these were less would start to question why. They would then switch over to the graphical visualization to see if this anomaly was a one off or part of a pattern. On several occasions, the students tried to decide whether the anomaly was species-related (e.g., common to all oaks) or environmentally-related (local to that area) by collaboratively working through a series of interrelated inferences and differing conclusions. In one group – who had observed an oak tree to have shrunk – two of the students concluded that it was most likely to be caused by a local environmental factor, e.g., the reed grass smothering the oak preventing this tree from growing. But another student in the same group refuted this, pointing out how their observations of the physical site meant that the reed grass was only covering a small portion of the area making up the plot. To support her claim she looked back at the graph of all the oak trees in the plot and was able to use the information to further argue that it would have meant that all the trees would have to have been smothered by the grass to show the same trend. She was able to reject the other's hypothesis by clicking on the third level of the graph that showed the growth trend of the oak across all the plots and convincingly conclude that it was a species-related phenomenon.

This example and others show how having dynamically updated representations ready at hand can enable students to participate in more complex and integrated inquiry practices. They can be used to reason about observations made in the physical world especially when discovering something that is puzzling or anomalous with what is normally expected. Importantly, it means that the students do not have to hold back from pursuing analysis and synthesis processes but can begin making inferences based on the various digital representations they have access to in the field.

Conclusions

This chapter has outlined how different kinds of external "visualizations" can be designed to support the learning and practice of scientific inquiry processes, when moving between the field and other indoor settings. An emphasis was on the personalization and experience of "visualizations" – where data and representations are explicitly linked through a process of dynalinking the physical, the numerical and the graphical. It was found that this form of mapping enabled the students to answer their own and other's questions, which in turn lead them to probe the environment more and, in so doing, support the transition and progression between different inquiry processes.

Having a range of opportunities to revisit and re-present their ongoing activities and observations, both physical and digital, to others in verbal and visual modalities can also lead to a deeper understanding. When external "visualizations" are interacted with in this way they help learners integrate and construct their knowledge. In particular, the switching between the here and now, the past and the present, helps learners reflect upon their immediate experiences, enabling them to make relevant connections (Rogers & Price, 2006). Furthermore, recording and adding data to a collective dataset enables learners to build and construct personal meaning during a learning activity that can be revisited to see how their contribution compares with others over time and to see how it fits in to the larger whole.

In sum, by expanding the contexts in which visualizations are used, computer technology-enhanced learning can be transformed into a rich tapestry of experiential and reflective activities; students can move in and out of overlapping physical, digital and communicative spaces.

References

Ackermann, E. (1996). Perspective-taking and object construction: Two keys to learning. In Y. Kafai & M. Resnick (Eds.), *Constructionism in practice: Designing, thinking and learning in a digital world.* NJ: Lawrence Erlbaum.

Bederson, B., Shneidemann, B. (eds.) (2003). *The craft of information visulization: Readings and reflections.* San Francisco: Morgan Kaufmann.

Boud, D., Keough, R., & Walker, D. (1985). *Reflection: Turning experience into learning*. London: Kogan Page.

Card, S. K., Mackinlay, J. D., & Shneiderman, B. (1999). *Readings in information visualization. Using vision to think.* San Francisco, CA: Morgan Kaufmann Publishers, Inc.

Chen, C. (2004). *Information visulization.* London: Springer Verlag.

Chi, M. (1997). Why is self explaining an effective domain for general learning activity? In Glasser, R. (Ed.), *Advances in instructional psychology.* Lawrence Erlbaum Associates.

Crook, C. (1994). *Computers and the collaborative experience of learning*. London: Routledge.

Gay, R., Rieger, R., & Bennington, T. (2002). Using mobile computing to enhance field study. In N. Miyake, R. Hall, & T. Koschmann (Eds.), *CSCL 2: Carrying forward the conversation* (pp. 507–528). Mahwah, NJ: Lawrence Erlbaum.

Grant, W. C. (1993) Wireless coyote: A computer-supported field trip. *Communication of the ACM, 36*(2), 57–59.

Hine, M., Rentoul, R., & Specht, M. (2004). Collaboration and roles in remote field trips. In J. Attewell & C. Savill-Smith (Eds.), *Learning with mobile devices: Research and development*. London, UK: Learning and Skills Development Agency.

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

Laws, P. (1997). Millikan lecture 1996: Promoting active learning based on physics education re-search in introductory courses. *American Journal Phys*ics, 65(1),13–21.

Layman, J. W., & Krajcik, J. S. (1990). The use of microcomputer-based laboratories in constructing science concepts. *Presentation at the National Science Teachers Association, Area Convention,* December 13–15, Washington, DC.

Loh, B., Radinsky, J., Gomez, L., Reiser, B., Edelson, D., & Russell, E. (2001). Developing reflective inquiry practices: A case study of software, the teacher and students. In S. K. Crowley, C. S. Chunn, & T. Okada (Eds.), *Designing for science: Implications from everyday, classroom, and professional settings.* Mahwah, NJ: Erlbaum.

Metcalf, S. J., & Tinker, R. (2003). TEEMSS: Technology Enhanced Elementary and Middle School Science. *Annual Meeting of the National Association for Research in Science Teaching,* March 23–26, Philadelphia.

Rogers, Y., & Scaife, M. (1998) How can interactive multimedia facilitate learning? In Lee, J. (Ed.), *Intelligence and multimodality in multimedia interfaces: Research and applications*. Menlo Park, CA: AAAI. Press.

Rogers, Y., Price, S., Randell, C., Stanton-Fraser, D., Weal, M., & Fitzpatrick. G. (2005). Ubi-learning: Integrating outdoor and indoor learning experiences. *Communication of ACM, 48*(1), 55–59.

Rogers, Y., & Price, S. (2006). Using ubiquitous computing to extend and enhance learning experiences. In M. van t'Hooft & K. Swan (Eds.), *Ubiquitous computing in education: Invisible technology, Visible Impact*. LEA.

Roschelle, J., & Pea, R. (2002). A walk on the wild side: How wireless handhelds may change CSCL, In Proceedings of CSCL 2002, LEA, NJ, 51–60.

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

Scaife, M., & Rogers, Y. (2005). External cognition, innovative technologies and effective learning. In P. Gardenfors & P. Johansson (Eds.), *Cognition, education and communication technology.* LEA.181–202.

Sharples, M., Corlett, D., & Westmancott, O. (2002). The design and implementation of a mobile learning environment. *Personal and Ubiquitous Computing,* 6, 220–234.

Soloway, E., Jackson, S. L., Klein, J., Quintana, C., Reed, J., Spitulnik, J., et al. (1996). Learning theory in practice: case studies of learner-centered design. *Proceedings of CHI, Conference on Human Factors in Computing Systems,* ACM Press, 189–96.

Soloway, E., Norris, C., Blumenfeld, P., Fishman, B., Krajcik, J., & Marx, R. (2001). Log on education: Handheld devices are ready-at-hand. *Communication of the ACM, 44*(6), 15–20.

Stratford, S. J., & Finkel, E. A. (1996). The impact of ScienceWare and Foundations on student's attitudes towards science and science classes. *Journal of Science Education and Technology, 5*(1), 59–67.

Chapter 6
Visualizing the Molecular World – Design, Evaluation, and Use of Animations

Roy Tasker and Rebecca Dalton

Abstract The research literature clearly indicates that many student misconceptions in chemistry stem from an inability to visualize structures and processes at the molecular level. A selection of these misconceptions was targeted in the *VisChem* project by producing a suite of molecular-level animations. The animations were produced with care to balance the often-competing demands of scientific accuracy, technical constraints, and clarity of communication.

The effectiveness of a selection of these animations was evaluated when used in a conventional lecture context to assist students to build useful mental models of structures and processes at the molecular level. This research revealed that, if used appropriately, students perceived most of the intended 'key features' and incorporated them in their mental models. There was evidence that students could transfer their ideas to similar situations, but no evidence of transfer to new topics. This indicated that these key features were not 'internalised'.

With this background we then embedded the animations as learning objects in learning activities, within a constructivist learning design. The *VisChem Learning Design* was developed to 1) motivate students to focus attention on the key features of their own prior mental model to explain test-tube level observations, 2) produce cognitive dissonance if their model fails, 3) actively look for new features in *VisChem* animations to reconcile any dissonance, and 4) then apply their refined model to new chemical topics.

Introduction

Why is Chemistry so Difficult?

A seminal paper by Johnstone (1982) offered an explanation for why science in general, and chemistry in particular, is so difficult to learn. He proposed that an expert in chemistry thinks at three levels; the *macro* (referred to as the *observational* level in this chapter), the *sub-micro* (referred to as the *molecular* level in

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this chapter), and *representational* (referred to as the *symbolic* level in this chapter). The observational level involves chemistry that is visible and tangible, incorporating what we can perceive with the senses. The molecular level of understanding consists of mental images that chemists use to imagine and explain observations in terms of atoms, ions and molecules. Observed phenomena and molecular-level processes are then represented in terms of mathematics and chemical notation at the symbolic level.

Figure 6.1 summarizes these three levels for the chemical reaction that occurs when silver nitrate solution is added to solid copper. Dendritic silver crystals growing on the surface of the copper can be perceived at the observable level. At the molecular level an animation can portray the dynamic, but imperceptible, formation of silver atoms adhering to a growing cluster of silver atoms. An equation only summarises the reaction at the symbolic level.

Questions addressed later in this chapter are – *can a molecular-level animation help students to build an accurate mental model to explain laboratory observations, and understand chemical symbolism with deeper understanding? Are students able to use their mental model to visualise analogous reactions and understand new topics in chemistry more deeply?*

One of the authors first used these levels *explicitly* in his chemistry teaching in the late 1980s (Tasker, 1992), allocating different parts of the lecture stage to different levels (Fig. 6.2). Reactions at the observable level were demonstrated on one side, often on an overhead projector, and an attempt to model the processes occurring at the molecular level on the other side. Only after these perspectives

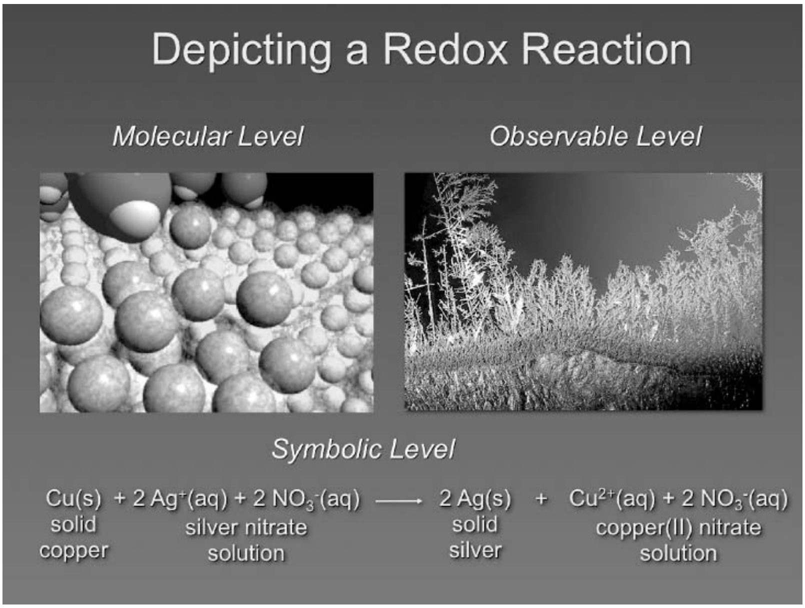


Fig. 6.1 Chemical equilibrium presented at the three thinking levels

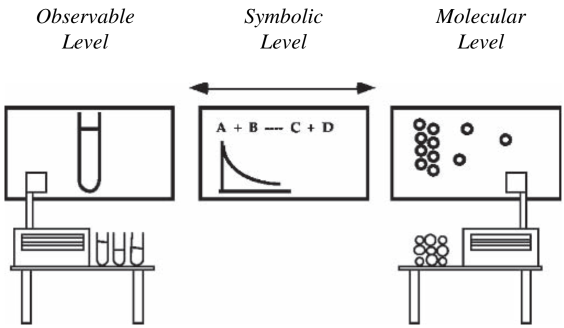


Fig. 6.2 Dividing the lecture stage into the three thinking levels. This approach was also reinforced explicitly in the laboratory notes, tutorials and assessment

were these phenomena depicted at the symbolic level on the board. This three-level approach was reflected in the laboratory manual, study activities, and exam questions, to encourage students to integrate laboratory work and theory at each level. Other researchers have also recommended teaching at the different levels of thinking, and helping students to draw links between the levels (Tasker, Bucat, Sleet, & Chia, 1996; Russell et al., 1997; Hinton & Nakhleh, 1999).

Johnstone (1991) suggests that much of the difficulty associated with learning science occurs because 'so much of teaching takes place . . . . where the three levels interact in varying proportions and the teacher may be unaware of the demands being made on the pupils'. Many students find it difficult to see the relationships between the levels (Kozma & Russell, 1997) and therefore, find it practically impossible to switch their thinking spontaneously between them. Understanding the relationships between the three levels does, however, vary from student to student, regardless of academic success (Hinton & Nakhleh, 1999). When students fail to see these relationships their knowledge is ultimately fragmented (Gabel, 1999) and many concepts may have only been learnt at a superficial level.

Gabel (1999) also suggests that problems arise because chemistry teaching has traditionally concentrated on the abstract, symbolic level and that teachers often have not considered the three levels in their own thinking. It is likely that teachers do not realise that they are routinely moving from one level to another during their teaching. However, presenting the three levels simultaneously to a novice is likely to overload his or her working memory (Johnstone, 1991; Gabel, 1999). If the levels are introduced together, numerous opportunities should be given to relate them, so that linkages are formed in the long-term memory.

Why is Visualisation at the Molecular Level so Important?

Nakhleh (1992) defined the term 'misconception' as 'any concept that differs from the commonly-accepted scientific understanding of the term'. There is convincing evidence in the literature (e.g., Kleinman, Griffin, & Kerner 1987; Lijnse, Licht, Waarlo, & de Vos (1990) and references therein) that many student difficulties and misconceptions in chemistry result from inadequate or inaccurate models at the molecular level. Moreover, many of the misconceptions are common to students all over the world, and at different educational levels. Lack of meaningful learning is demonstrated by the fact that many students can solve traditional-style chemistry problems without understanding the underlying molecular processes (Nurrenberm & Pickering, 1987; Nakhleh, 1993; Nakhleh & Mitchell, 1993; Niaz, 1995). The most important finding is that many misconceptions are extraordinarily resistant to change.

How can we Help Students to Visualise the Molecular Level?

Until the early 1990s there was a shortage of resources that portrayed the molecular level so teaching and learning was restricted to the observable and symbolic levels, in the hope that students' mental models of the molecular world would 'develop naturally'. Students were then left to construct these models from the static, often oversimplified, two-dimensional diagrams in textbooks, or from their own imaginative interpretation of chemical notation—for example, did the formula 'NaCl(aq)' mean that sodium chloride contained dissolved 'NaCl molecules' in water?

Physical models (e.g., ball-and-stick) are static, and can be misleading models of substances like

- solid sodium chloride, that does not have directional bonds or significant spaces between ions
- ice, where the distinction between *intra*-molecular and *inter*-molecular bonds is not clear because both are shown with sticks (albeit of different lengths).

However, physical models do provide a tactile, kinaesthetic dimension to appreciation of shape and angles. This can be more convincing than 2-D representations (perspective or orthogonal) of 3-D models on a computer screen, particularly without any previous experience with physical models. This can be likened to failure to navigate efficiently in virtual gaming environments without enough physical experience in the real world.

Since the molecular world is always dynamic it would be reasonable to assume that computer animations would be a more effective medium for depicting this world. However, animations often have a number of weaknesses, some obvious (use of 'artistic license' such as colour, and slow motion), some not so obvious but revealed through interviews with students, as described in the next two sections.

Can Animations be Effective Learning Resources?

A preliminary study by Greenbowe (1994) suggested that when animations are used during lectures to teach electrochemistry, they are most effective when 'coupled with live demonstrations of electrochemical cells' (p. 556). A follow-up study conducted by Sanger and Greenbowe (1997) examined the effects of animations, coupled with live demonstrations and a balanced equation, on students' conceptual understanding of electrochemistry. Sanger and Greenbowe looked specifically at the common misconception that electrons move as isolated species through the solution and the salt bridge in an electrochemical cell. Results suggested that viewing the animation helped students to visualise the process and significantly decreased the number of students consistently demonstrating this misconception, as compared with students in a comparison study.

Williamson and Abraham (1995) asked whether two- and three-dimensional computer animations have any effect on college-level students' visualisation of chemical concepts and whether they enhanced their understanding more than static drawings. Instruction using animations was found to have no effect on course achievement or attitudes but the animation group demonstrated greater conceptual understanding and reduced misconceptions compared with the control. The animations seemed to encourage a particulate view of matter, as indicated by the conservation of particles between drawings and fewer 'continuous matter' drawings. The authors concluded that animations helped students build dynamic mental models of chemical phenomena, whereas pictures either encouraged the formation of static mental models or failed to help students build any form of mental model.

Russell et al. (1997)developed an interactive chemistry multimedia program to address misconceptions and enhance mental models in the topic of equilibrium. The program (4M:Chem – *M*ulti*m*edia and *M*ental *M*odels) draws explicit links between the four different levels of representation (laboratory, symbolic, molecular animation, graphs and diagrams), which can be shown individually or in combination. An initial evaluation showed significant improvement in understanding of the nature of equilibria and the effects of temperature on these systems following two one-hour presentations of 4M:Chem. This program was not successful, however, in improving students' understanding of the effects of pressure on equilibria (Kozma, Russell, Jones, Marx, & Davis, 1996). Furthermore, there were still a significant percentage of students that did not demonstrate an understanding of equilibrium reactions after instruction.

In 1998, Burke, Greenbowe and Windschitl published a paper outlining the effective use of animations. They advised that animation sequences should be short (20–60 s) and focused, have 'accurate' chemistry content, address misconceptions in the literature and allow for some student interactivity with appropriate feedback. Animations should be used in conjunction with lecture demonstrations to help students draw connections between the macroscopic, symbolic and molecular levels of representation. Also, when animations are used in a classroom instructional sequence, the teacher or lecturer should provide a verbal narrative. Access to animations outside the lectures was also considered important. The authors concluded that when care is taken to design and use animations appropriately, students' understanding should improve as a result.

Garnett and Hackling (2000) explored the use of a multimedia tool entitled 'Balancing and Interpreting Chemical Equations', in improving Year-10 students' understandings of the molecular level of chemical reactions. A pre-test and post-test examined the students' abilities to translate (or transform) from symbolic to particulate representations and *vice versa*. Results indicated an improvement in the students' understandings of the symbolic notation of chemical equations and representations of chemical reactions at the molecular level.

Clearly, the use of animations for teaching chemistry holds promise. However, animations are inherently more visually complex than diagrams (Lowe, 2001). The potential for this complexity to reduce their effectiveness is one concern. Moreover, there is potential for animations to cause new and resistant misconceptions (Tasker & Dalton, 2006).

Sanger, Phelps and Fienhold (2000) reported the use of an animation to help students develop an understanding of the molecular-level processes involved in a can-crushing experiment. Their results suggested that students who viewed animations of the molecular-level process were more able to discuss the relevant details relating to water condensation and pressure in their explanations of the phenomena, and were less likely to apply gas laws algorithmically, without understanding.

Jones, Jordon and Stillings (2001) advocate the use of animated or simulated visual representations for 'helping students understand the dynamics involved in chemistry' (p. 6), to 'provide a means of helping students improve their conceptions' (p. 6) and to portray simply and directly 'the effect of subtle interactions between molecules, which are complex and difficult to describe simply' (p. 6). Animations, after all, are able to provide more detailed and accurate representations by showing movement (Lowe, 2001).

Velazquez-Marcano, Williamson, Ashkenazi, Tasker and Williamson (2004) demonstrated that molecular-level animations combined with videoclips of macroscopic phenomena better enabled students to predict the outcome of effusion and diffusion problems, than animation or video alone. They concluded that the combination of animation and video allowed students to interpret a concrete phenomenon in terms of an abstract concept.

These studies all indicate that molecular-level animations can be effective if presented in a context where students were rewarded for demonstrating an understanding of molecular-level structures and processes. The problem is that in many teaching situations students can perform well in tests and exams because few questions probe understanding at this level, and even fewer are designed to identify common misconceptions.

The VisChem Project – Visualising the Molecular Level with Animations

In the early 1990s the *VisChem* project was funded to produce a suite of molecular animations, depicting the structures of substances and selected chemical and physical changes (Tasker et al., 1996; also see vischem.cadre.com.au for a complete list), to address student misconceptions identified in the literature. Table 6.1 lists many

Table 6.1 List of selected *VisChem* animations, each with a key frame, description, and the misconceptions or difficulties addressed

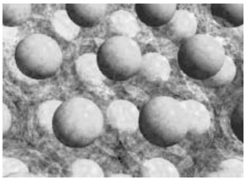
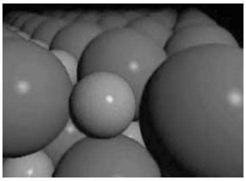
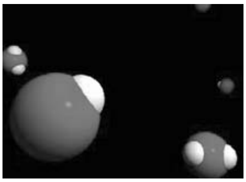
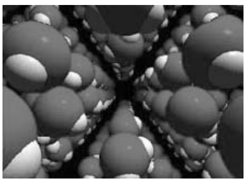
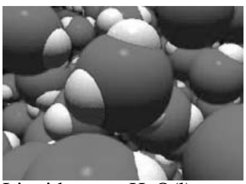
Selected Frame	Description	Misconceptions Targeted
Metal Solid		
 Solid copper, Cu(s)	Close packed copper atoms vibrate in an ordered lattice. Each atom is represented as a yellow copper(II) ion with its two electrons delocalised in a cloud.	Students have difficulty in conceiving of matter as multi-particulate. Ben-Zvi, Silberstein and Mamlok (1990) Matter is conceived as static. Novick and Nussbaum (1981)
Ionic Solids		
 Solid sodium chloride, NaCl(s)	Close packed sodium and chloride ions vibrate as electrostatic forces hold them together.	There is a tendency to believe that there are molecules or discrete ion groups in ionic solids Taber (1994) Students believe it is not possible to point to where the ionic bonds are unless you know which chloride ions have accepted electrons from which sodium ions Taber (1997)
Molecular Substances		
 Gaseous water, $H_2O(g)$	The average distance between molecules in a gas is much larger than in the liquid and solid states.	Students have difficulty imagining empty space. Matter is conceived as continuous. There is no vacuum. Andersson (1990a,b)
 Solid water (ice), $H_2O(s)$	We move into one of the hexagonal channels in the ice structure, look around at the vibrating molecules attracted together by hydrogen bonds, and then move back out of the channel.	Students confuse (1) intra-molecular bonds and intermolecular bonds and (2) van der Waals forces and hydrogen bonds. Levy Nahum, Hofstein, Mamlok-Naaman, and Bar-Dov (2004)
 Liquid water, $H_2O(l)$	Water molecules move around, closely packed and attracted together by hydrogen bonds, with some molecules in clusters.	There is a tendency to suggest that ice is more densely packed than liquid water Griffiths and Preston (1992) Students conceive of molecules in a liquid as being reasonably spaced such that it could be compressible Hill (1988)

Table 6.1 (*Continued*)

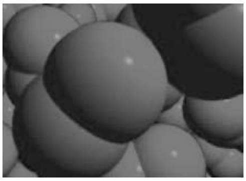
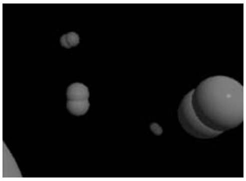
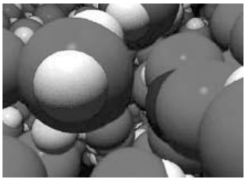
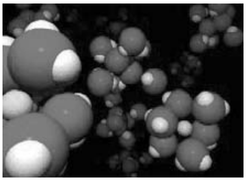
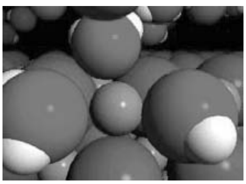
Selected Frame	Description	Misconceptions Targeted
 Liquid oxygen, $O_2(l)$	Oxygen molecules in the liquid state move *almost* randomly with respect to one another.	Students conceive of molecules in a liquid as being reasonably spaced such that it could be compressible Hill (1988)
 Gaseous oxygen, $O_2(g)$	Oxygen molecules moving quickly in space, occasionally colliding.	Students believe that there is little reduction in density when a liquid changes to a gas Pereira and Pestana (1991)
Aqueous Solutions		
 Aqueous copper(II) nitrate (~1M), $Cu^{2+}(aq)$ + $2NO_3^-(aq)$ 	Hydrated copper and nitrate ions, and water molecules, in a 1:3:55 ratio, roam amongst the water molecules, with the occasional formation of a transient ion pair, followed by its dissociation. Solvent water molecules omitted in version below to show proximity of hydrated ions Other VisChem animations show ~1M solutions of iron(III) nitrate, sodium nitrate, potassium thiocyanate, sodium chloride, and potassium fluoride.	Some students do not dissociate any ionic species in their representations of aqueous solutions Butts and Smith (1987) Particles in aqueous solutions are not generally drawn touching Butts and Smith (1987) Some students think that dissolved particles go into empty spaces inside water molecules Sequeira and Leite (1990)
Dissolving		
 Solid sodium chloride dissolves $NaCl(s) \rightarrow Na^+(aq)$ + $Cl^-(aq)$	Skating over the surface of the NaCl solid the camera pauses to see the vibrating ions in the lattice. Then water molecules come tumbling down, hydrating the ions in a competitive 'tug o' war' with electrostatic forces attracting the ions to the lattice.	There is a common inability to discriminate between dissolving and melting Haidar and Abraham (1991) Students rarely acknowledge the role of the polar nature of the water molecule in the process of dissolution Butts and Smith (1987) Students generally do not see dissolving as an interactive process but rather the automatic separation, then dispersal of solute molecules throughout the solvent Haidar and Abraham (1991)

Table 6.1 (*Continued*)

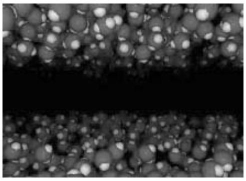
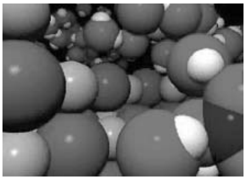
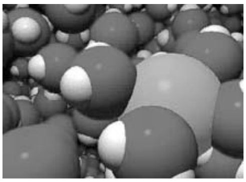
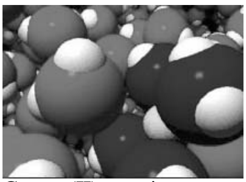
Selected Frame	Description	Misconceptions Targeted
Precipitation		
 Mixed aqueous solutions $Na^{+}(aq)$ + $Cl^{-}(aq)$ + $Ag^{+}(aq)$ + $NO_3^{-}(aq)$	At the molecular surface of the silver nitrate solution just prior to mixing with sodium chloride solution being added from above. The mixing of solutions at the molecular level enables new combinations of ionic collision to occur.	Students cannot explain why the precipitate can form immediately when the solutions are mixed.
 Silver chloride precipitation $Ag^{+}(aq) + Cl^{-}(aq)$ –> AgCl(s)	In a solution containing silver, sodium, nitrate and chloride ions a silver ion and a chloride ion collide, and form a stable ion pair. Another ion pair joins, and the resulting cluster joins a growing crystal of silver chloride, with spectator ions in the background.	Students imagine that a precipitate is composed of 'molecules', each containing a neutral ion pair or group of ions.
Complexation		
 Water exchange on hydrated iron(III) $Fe\text{–}OH_2(aq) + \mathit{H_2O} \rightleftharpoons Fe\text{–}\mathit{OH_2}(aq) + H_2O$	Exchange of a bonded water molecule with a nearby water molecule. Fe(III) ion represented by its van de Waals radius.	Students do not realize that water molecules in the first coordination sphere exchange with surrounding water molecules. This is a necessary first step in many complexation reactions.
 Copper(II) ammine complexation $Cu^{2+}(aq) + 4NH_3(aq) \rightleftharpoons [Cu(NH_3)_4]^{2+}(aq)$	Successive substitution of water molecules with ammonia molecules, with Jahn Teller lengthening of axial bonds to coordinated water. Cu(II) represented by its ionic radius.	Students have difficulty imagining how a square planar complex can form in solution.

Table 6.1 (*Continued*)

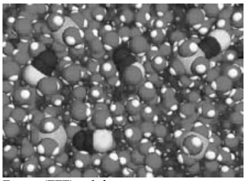
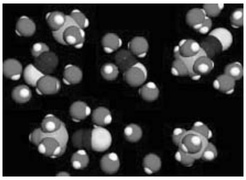
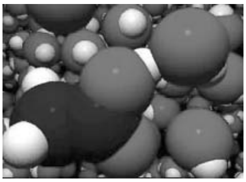
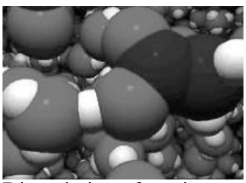
Selected Frame	Description	Misconceptions Targeted
Equilibrium		
 Iron(III) thiocyanate complexation equilibrium $Fe^{3+}(aq) + SCN^{-}(aq) \rightleftharpoons [Fe(H_2O)_5\ NCS]^{2+}$ 	Formation and dissociation of the isothiocyanatoiron(III) complex (each available as a separate animation) occurs at the same rate at equilibrium. Potassium and nitrate spectator ions are also present. The version below leaves out solvent water molecules and spectator ions to focus attention on the two reactions.	The use of everyday terms, ‘shift’, ‘equal’, ‘stress’, ‘balance’ when referring to equilibria can conjure up different visual ideas to students from those intended by the teacher. ‘Equilibrium’ is seen as a static two-sided picture, and this can be unintentionally reinforced by misleading metaphors and analogies. Equilibrium is seen as oscillating like a pendulum, and Le Chatelier’s stress-then-shift logic reinforces this misconception Bergquist and Heikkinen (1990) Lack of awareness of the dynamic nature of the chemically equilibrated state Gorodetsky & Gussarsky (1986)
Acid/Base Hydrolysis		
 Acetate hydrolysis $CH_3COO^{-}\ (aq) + H_2O \rightarrow CH_3COOH(aq) + OH^{-}(aq)$	An acetate ion removes a proton from a water molecule, with some difficulty, to form an acetic acid molecule and a hydroxide ion.	A base is something which makes up an acid Hand and Treagust (1988)
 Dissociation of acetic acid $CH_3COOH(aq) + H_2O \rightarrow CH_3COO^{-}\ (aq) + H_3O^{+}(aq)$	An acetic acid molecule donates a proton to a water molecule, with some difficulty, to form an acetate ion and a hydronium ion.	An acid is something which eats material away or which can burn you Hand and Treagust (1988)

Table 6.1 (*Continued*)

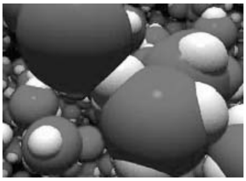
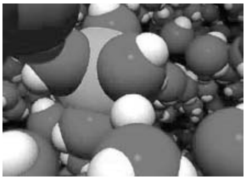
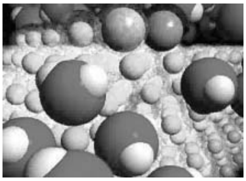
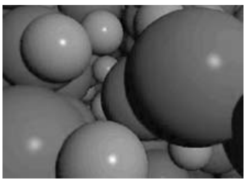
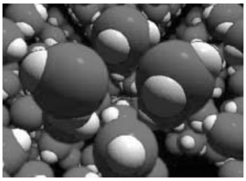
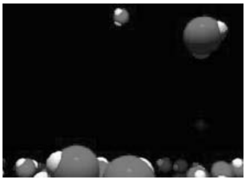
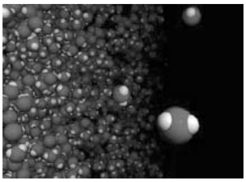
Selected Frame	Description	Misconceptions Targeted
 Autoionisation of water $H_2O + H_2O \rightleftharpoons HO^- + H_3O^+$	Amongst the bustle of water molecules two come together and exchange a proton, forming a hydronium ion and a hydroxide ion.	Students have difficulty imagining how pure water can contain any hydronium ions and hydroxide ions.
 Iron(III) hydrolysis $Fe\text{-}OH_2^{3+} + H_2O \rightarrow Fe\text{-}OH^{2+} + H_3O^+$	One of the coordinated water molecules on iron(III) loses a proton to a solvent water molecule. The charge density of the metal ion increases the acidity of the coordinated water molecule through polarisation.	Students have difficulty understanding how metal ions (without hydrogen atoms) can produce hydronium ions
Redox Reaction		
 Reduction of silver(I) by copper $Cu(s) + 2Ag^+(aq) \rightarrow Cu^{2+}(aq) + 2Ag(s)$	Hydrated silver ions migrate towards the copper surface. Electron cloud moves onto the silver ions to form atoms, with concomitant release of copper ions from the metal lattice. Both anodic and cathodic sites are represented.	Students have a 'reluctance' to perceive or represent chemical reactions as multi-particulate Ben-Zvi, Eylon and Silberstein (1987) Students 'cannot grasp the interactive nature of a chemical reaction' Ben-Zvi, Eylon and Silberstein (1987)
Physical Changes		
 Sodium chloride melting $NaCl(s) \rightleftharpoons NaCl(l)$	To show the difference between dissolving and melting we see the total energy of the ions in solid NaCl rise until the structure collapses to the liquid state.	Students believe that there is a significant reduction in density when a solid melts Hill (1988)

Table 6.1 (*Continued*)

Selected Frame	Description	Misconceptions Targeted
 Ice melting $H_2O(s) \rightleftharpoons H_2O(l)$	Starting within the ice structure the camera moves down to the molecules on the lower surface prior to melting. The total energy rises until the structure collapses to the liquid state.	There is a tendency to suggest that ice is more densely packed than liquid water Griffiths and Preston (1992)
 Evaporation of water $H_2O(l)$ –> $H_2O(g)$	Starting within the liquid water the camera moves up to the surface. Molecules break away, with some difficulty, and some return. More leave than return.	Students believe that there is little reduction in density when a liquid changes to a gas Pereira and Pestana (1991) Students believe that molecules increase in size when moving from solid to liquid to gas Gabel and Samuel (1987) Students believe that intramolecular forces are broken in phase changes Ben-Zvi, Silberstein and Mamlok (1990)
 Inside a boiling water bubble $H_2O(l) \rightleftharpoons H_2O(g)$	Moving through the water molecules in the liquid bubble wall, we suddenly break into the gaseous interior of the bubble. Some of the bubble wall can be seen in the background.	Bubbles in boiling water are made up of 'heat' or 'air' or 'oxygen and hydrogen' Osborne and Cosgrove (1983) and Bodner (1991) Melting and boiling of molecular compounds are processes in which covalent bonds within molecules are broken. Sleet (1993)

of the *VisChem* animations, and their targeted misconceptions from the educational literature. These misconceptions have been identified among students, from various age groups, regarding the nature of matter, molecular and ionic substances, aqueous solutions, and chemical reactions at the molecular level.

For instance, only *VisChem* animations portray the vibrational movement in solid substances (e.g., copper, sodium chloride in Table 6.1). This is important because this movement is correlated with temperature, and students need to understand this to interpret the significance of melting and boiling points in molecular-level terms.

Many diagrams in textbooks depicting particles in the solid, liquid and gaseous states are misleading because the relative spacing between particles is inaccurate (e.g., Fig. 1.7, p. 7, in Brown, LeMay, & Bursten, 2006). Little wonder that students develop poor mental models of states of matter. The *VisChem* animations are more accurate in this respect.

Few students have a 'feel' for the average distance between ions in a solution of a given concentration. *VisChem* animations portray ionic solutions at a concentration of about 1 mol/L, with ions separated from each other by, on average, about three water molecules (Table 6.1). This brings meaning to the magnitude of the number expressing molarity, in much the same way that people have a 'feel' for a length of one metre. Students are also encouraged to imagine dilution of a solution in terms of separation of ions by more water molecules.

The animations were produced using the three-dimensional drawing software program, *Infini D* (*Specular International*), and output assembled using the program *Director* (*Macromedia*). Compressed as *QuickTime* movies, they range from 200 to 300 frames running at 10 frames per second, with file sizes of 3 to 15 Mb (Tasker et al., 1996). These animations are available in analogue format on videotape, and in digitally compressed format on CD, DVD and downloadable from the Web (see http://bcs.whfreeman.com/chemicalprinciples3e and Tasker et al. (2002)–http://www.learningdesigns.uow.edu.au/exemplars/info/LD9/index.html, and go to the molecular construction tool and animations 'Crosslink'). They have also been incorporated into a range of multimedia programs associated with university-level chemistry textbooks (Jones & Tasker, 2002; Tasker, 1999, 2001, 2004; Tasker, Bell, & Cooper, 2003).

The animations portray substances, some in different states of matter, some undergoing physical changes, and some involved in common chemical reactions, as summarised in Fig. 6.3. All the building blocks – individual atoms, molecules, ions, and hydrated ions – are available as separate animations for use as 'keys'.

The animations were designed to be useful models of substances and processes at the molecular level. The challenge was to balance the often-competing demands of:

- scientific accuracy – such as very little space between adjacent molecules in the liquid state; complicated internal molecular bond vibrations; and the diffuse nature of electron cloud surfaces of atoms
- 'artistic license' required for clear communication – such as depicting slightly less than realistic crowding in the liquid state to enable visibility beyond the nearest molecules; the absence of internal molecular bond vibrations to reduce the degree of movement; use of reflective boundary surfaces on atoms at their van de Waals radii; and greatly reduced speed of molecules in the gaseous state
- technical computing constraints on rendering times and file size – such as the close-up view to limit the number of moving objects to be rendered; and the depiction of non-trivial events in minimum time to reduce the number of animation frames.

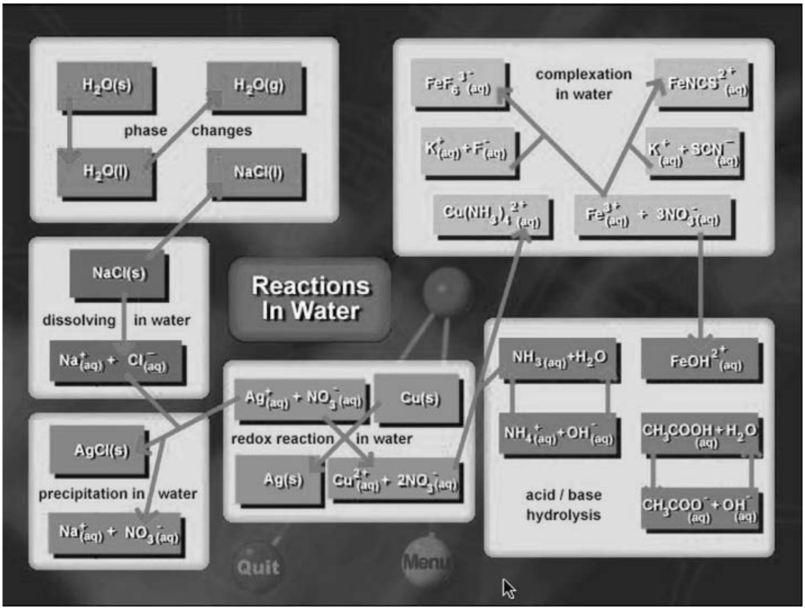


Fig. 6.3 Each substance and solution shown above is depicted in a *VisChem* animation. The physical and chemical changes shown with arrows are also animated

What Kinds of Messages can be Communicated in Molecular-level Animations?

The molecular world is multi-particulate, dynamic and, in the liquid state, crowded; and the interactions between particles are often subtle (e.g., hydrogen bonding). Our hypothesis has always been that animations should be effective for conveying these ideas and helping students to construct accurate mental models to make sense of observations in the laboratory.

For example, the redox reaction that occurs when aqueous silver nitrate is added to copper metal (Fig. 6.1) can be shown with an animation (Fig. 6.4) depicting the following key features of the substances and processes involved:

- *Frame 1*: vibrating, close-packed copper(II) ions (yellow) arranged in an orderly lattice, held together by the electron cloud
- *Frame 2*: water molecules and hydrated ions in silver nitrate solution come in contact with the copper lattice
- *Frame 3*: after a tug-of-war with hydrating water molecules a silver ion finally accepts electron cloud to become an atom, now with little attraction to the water molecules, embedded on the copper lattice
- *Frame 4*: a copper(II) ion is removed from the lattice as a hydrated ion
- *Frame 5*: a hydrated nitrate ion moves past as an uninvolved spectator ion
- *Frame 6*: another silver ion accepts an electron cloud to become an atom

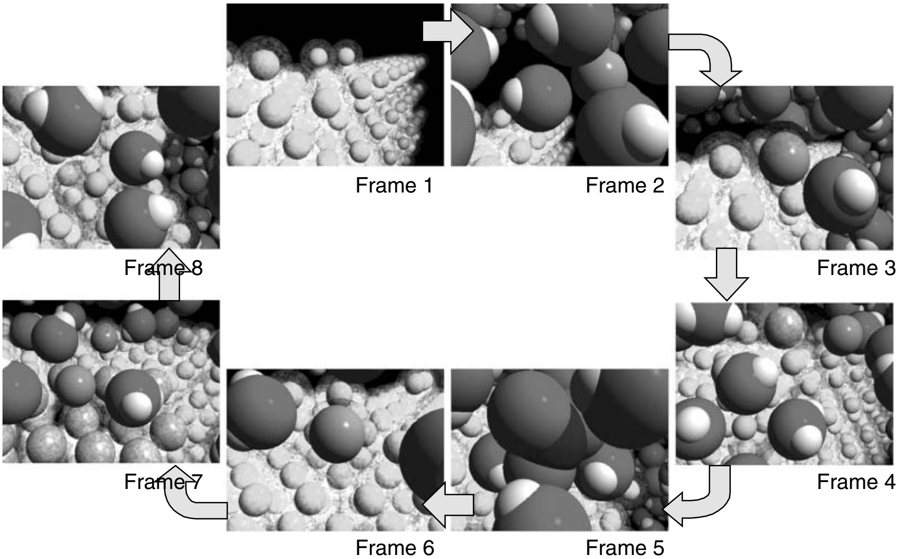


Fig. 6.4 Frames from the *VisChem* animation portraying copper metal, consisting of copper(II) ions (yellow spheres) embedded within a delocalised cloud of electrons, and silver ions (reflective grey spheres) reduced to atoms (grey spheres, each covered in a cloud layer)

- *Frame 7*: silver ions form atoms preferentially on silver atoms already accumulated on the lattice – the beginnings of a dentritic crystal
- *Frame 8*: another copper(II) ion is removed from the lattice as a hydrated ion

The animation depicts the reduction of many silver ions on both the copper surface and silver crystals, with concomitant release of half as many copper(II) ions, at anodic sites remote from the cathodic sites on the metal lattice. This separate site model is consistent with the observations (silver crystal formation, remote pockets of corrosion of copper), and is a more scientifically-accurate explanation for the 2:1 stoichiometric ratio than the misleading diagram, often drawn on a whiteboard, of each copper atom directly donating an electron to each of two silver ions that collide with it. *The point is to encourage students to reconcile their real observations with their mental model of what is happening at the molecular level, and to realise that the chemical equation is only a symbolic summary of the reaction.*

Animations of the molecular world can stimulate the imagination, bringing a new dimension to learning chemistry. One can imagine being inside a bubble of boiling water, or at the surface of silver chloride as it precipitates, as depicted in Figs. 6.5 and 6.6 respectively.

Most molecular-level processes involve competition between conflicting processes. Atkins (1999) has recommended that this is one of the most important 'big ideas' that we should communicate to students. Examples of this theme in *VisChem* animations include the competition for a proton between a base, like ammonia, and

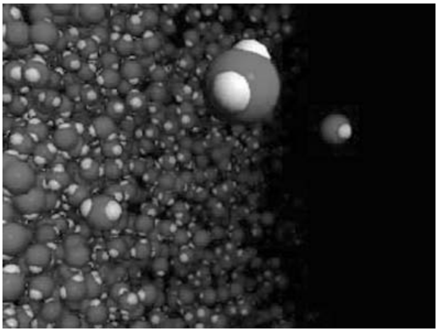


Fig. 6.5 A frame of the *VisChem* animation that attempts to visualise gaseous water molecules 'pushing back' the walls of a bubble in boiling water

a water molecule (Fig. 6.7); and between lattice forces and ion-dipole interactions when sodium chloride dissolves in water (Fig. 6.8).

Like all molecular-level animations, *VisChem* animations can also communicate misconceptions about processes at this level. They all convey the clear perception of 'directed intent' in molecular-level processes, instead of a more scientifically-accurate, probabilistic behaviour, governed by thermodynamics and kinetics.

We discovered this flaw during interviews with students. For example, one student thoughtfully drew this to our attention in the animation portraying silver chloride precipitation:

> This animation . . . shows water molecules . . . sort of carrying this structure [AgCl ion pair] along . . . like a bunch of little robots . . . The animation depicts something that . . . I think really happens by chance, as a very deliberate and deterministic sort of process and I think that's slightly misleading . . . Surely it must be possible to make it look less deliberate, less mechanical, maybe by showing . . . the odd one or two going into the structure but not all of them.

The reasons that animation frames are not usually 'wasted' on depicting *unsuccessful* encounters (the majority) are related to the technical imperative to reduce rendering times, and to minimise file size to enable rapid delivery over the web. However, we need to explicitly point out to students that this is a form of 'artistic license', and can be likened to the conventional use of a chemical equation to describe a reaction, rather than to list all the steps in the reaction mechanism.

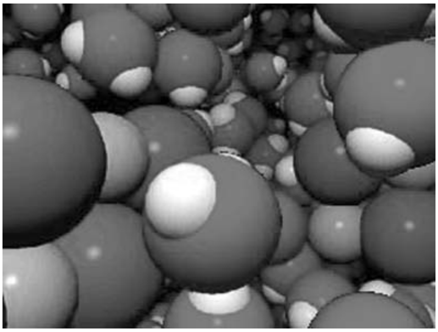


Fig. 6.6 A frame from another *VisChem* animation that depicts the precipitation of silver chloride at the molecular level

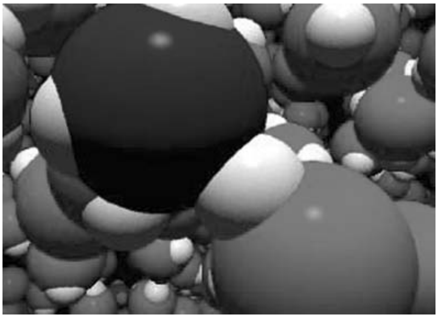


Fig. 6.7 Frame from a *VisChem* animation showing the 'tug-of-war' between an ammonia molecule and a water molecule for one of its protons

In contrast to choreographed animations, theory-driven simulations (e.g., *Odyssey* by Wavefunction, Inc.; see wavefun.com) offer a more accurate depiction of structures and processes at the molecular level. However, a limitation of simulations is that they often do not show key features of molecular events *clearly* because they occur only rarely (sometimes taking years in the slowed-down timescale used), at random, and usually with intervening solvent molecules blocking the view! Clearly simulations and animations should be used to complement one another.

Can we Direct Student Attention to Specific Key Features in an Animation?

As part of a research project to develop design principles for effective molecular-level animations, Dalton and Tasker (2006) have shown that different people with different prior knowledge perceive different features in an animation, affecting the animation's effectiveness as a learning resource. They compared novice and expert interpretations of the animation depicting the copper/silver ion reaction (see Fig. 6.4). Experts (N = 17) and novices (N = 18) first observed the reaction, then storyboarded their attempts to visualise the reaction at the molecular level, before being shown the *VisChem* animation without explanation. Participants were then

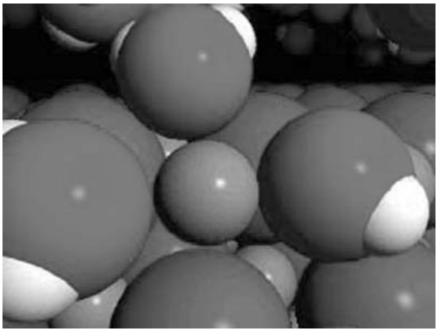


Fig. 6.8 Frame from a *VisChem* animation showing the hydration of a sodium ion on the surface of sodium chloride, despite strong attractive forces from the rest of the lattice

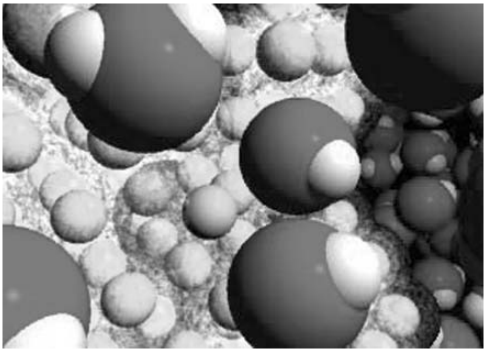


Fig. 6.9 Water molecules surround and hydrate a copper(II) ion (in the middle of the graphic) and, in so doing, remove it from the lattice. Novices and experts tend to focus their attention on different features

asked to provide a narration for the animation, with experts advised to tailor their narration for first-year university chemistry students.

Novices (94%), much more commonly than experts (47%), directed the viewer's attention to water molecules removing the copper ions from the lattice (See Fig. 6.9). This seemingly obvious feature in the animation was glossed over, or ignored by most experts.

We found that in general, experts tend to comment on features consistent with their prior knowledge of the oxidation process, or consistent with features they deem relevant for this level of teaching. They may ignore, or even fail to perceive, a visual feature they consider less relevant, for example, the role of the water molecules in this process. Novices, however, may rely more on the visual representation (because they have fewer expectations due to a lack of prior knowledge), noticing the visually-obvious hydration of the copper ion removal, or may search for ideas that confirm or contradict their initial conceptions (e.g., the possibility of an active role for the nitrate ions).

When seeing a process with more than one key feature viewers focussed on different features. In this case perception or feature selection appeared to be influenced, in varying degrees by novices and experts, by:

- visual acuity –the clarity of the feature
- prior knowledge – looking for what one expects to see
- pedagogical bias – deciding what aspects should be focused on for students at a first-year university level

Graphic devices (e.g., arrows), narration, and interface actions can be used to direct attention to a particular place on a particular frame in an animation. For example, in an animation of sodium chloride dissolving, students were asked to click on a sodium ion at the moment the water molecules win the tug-of-war to remove it from the solid lattice (Fig. 6.10). By this means we could direct student attention to the difficulty of removing an ion due to the competing forces exerted by the lattice and the water molecules for the ion.

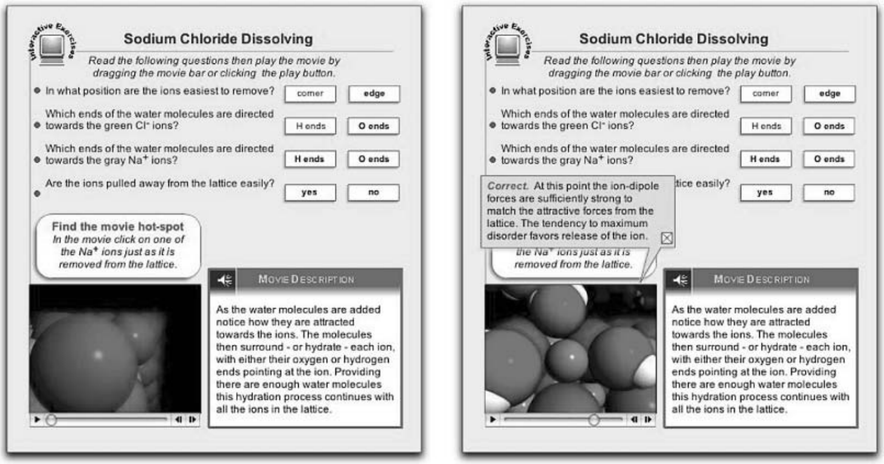


Fig. 6.10 Screens from an interactive animation in an ***ACS GenChem Web Companion*** module (Tasker, Bell, & Cooper, 2003). Preview questions focus attention on identifying certain features. 'Hotspots' are embedded on specified places on animation frames at certain times in the animation. When asked to identify when a specific event is happening the student clicks on the animation, and feedback is provided. In this instance the student response was correct

Research on the Effectiveness of VisChem Animations for Constructing Mental Models

Dalton (2003) conducted research into factors that affect a student's ability to form scientifically acceptable mental models of chemical substances and processes at the molecular level after exposure to *VisChem* animations. The study examined the changes in mental models of first-year chemistry students (N = 48) following a semester of teaching that emphasized molecular visualisation using the animations. The protocol involved a pre-test/post-test design with follow-up interviews. A transfer-test was also administered after the post-test, and prior to interviews. The animations were presented on the basis of recommendations in the literature (Milheim, 1993) and practical experience over five years of using the animations in lectures (see vischem.cadre.com.au, and go to Educational Support/Resources).

This study demonstrated that showing animations to students, with opportunities for them to practise drawing representations of the molecular world, significantly increased the number of scientifically acceptable 'key features' in students' representations of chemical phenomena at the end of the semester. Students developed more vivid mental imagery of these phenomena and had greater confidence in their images.

Evidence from interviews with fourteen students revealed, without prompting, that changes were largely attributed to having viewed *VisChem* animations. There was also an indication that some students had been able to transfer their ideas from animations to new situations, as evidenced by a statistically-significant correlation between the post-test and transfer test ($n = 35$, $r = 0.69$, $p = 0.01$), and comments in interviews.

However, in order to further improve perception of key features and ability to transfer these to new situations, we hypothesised that we needed to embed the animations into an engaging learning context so that students would be motivated to look for the key features, and rewarded for demonstrating deeper understanding at the molecular level.

Development of the VisChem Learning Design

In the growing field of interactive multimedia, a 'learning design' is a research-based sequence of 'learning activities', each involving one or more 'learning objects'. Learning objects are digital assets (e.g., an animation, photograph) in a context (provided by a narration, caption), designed usually with interactivity.

The *VisChem Learning Design* (Tasker et al., 2002) was developed on the basis of the above work, and guided by an audiovisual information-processing model (Tasker & Dalton, 2006). The design is described below, and more details can be found on the web site for the design (Tasker, 2002). This is one of a collection of exemplary ICT-based learning designs selected by a panel of Australian university educators to facilitate the uptake of innovative teaching and learning approaches in Australian universities (Harper et al., 2001).

The *VisChem Learning Design* can be used for any chemistry topic that requires a scientifically acceptable mental model of the molecular world. A typical learning experience in a face-to-face lecture context would involve students:

- *observing* a chemical phenomenon (chemical reaction or property of a substance) as a lecture demonstration, lab activity, or audiovisual presentation; and documenting their observations in words and/or diagrams
- *describing* in words, and drawing a representation of what is occurring at the molecular level to account for the observations; with the lecturer explaining the need for drawing conventions (e.g. to indicate relative size, movement, number, and crowding of molecules)
- *discussing* their representation with a peer, with the aid of the lecturer's advice to focus on the key features of the representation that explain the observations
- *viewing* an animation portraying the phenomenon at the molecular level, first without, then with narration by the lecturer, and looking for key features that might explain the observations
- *reflecting* with the peer on any similarities and discrepancies between their own representations and the animation, and then discussing these with the lecturer
- *relating* the molecular-level perspective to the symbolic (e.g. equations, formulas) and mathematical language used to represent the phenomenon
- *adapting* their mental model to explain a similar phenomenon with an analogous substance or reaction

The key criteria for the success of this design to promote visualisation as a learning strategy are the:

- constructivist approach that encourages the student to articulate prior understanding, and focus attention on key features of the prior mental model at the molecular level, before seeing the animations
- opportunity to discuss ideas and difficulties with peers
- practice and application of the visualisation skills developed, with the explicit expectation that these skills are valued, and would be assessed for grading purposes.

The learning outcomes are to assist students to:

- construct scientifically acceptable mental models of substances and reactions at the molecular level
- relate these models to the laboratory and symbolic levels in chemistry
- apply their models to new substances and reactions
- use their models to understand new chemistry concepts that require a molecular-level perspective
- address common misconceptions identified in the research literature
- improve their confidence in explaining phenomena at the molecular level
- enhance their *enjoyment of chemistry by empowering them to use their imagination to explain phenomena*, instead of just rote-learning terms and concepts, and solving problems algorithmically.

An Example of the VisChem Learning Design: Visualisation of a Redox Reaction

The learning design is an attempt to make each stage of the audiovisual information-processing model—perceiving, selecting, processing and encoding—as efficient as possible (Tasker & Dalton, 2006).

In the following example, we will assume that students have had previous experience with visualising simple substances—ionic solutions and copper metal—using *VisChem* animations, and are familiar with graphic conventions for representing molecules and ions. The learning outcomes of this activity are that a student should visualise a redox reaction as:

- a competition between conflicting influences—electron transfer and solvation—as recommended by Atkins (1999)
- involving many molecular events occurring at once, where the ratio of copper(II) ions produced, and silver atoms formed, are in the ratio of 1:2
- electron gain and release at different places

The learning design starts with observation of the reaction.

Step 1. Observing a Phenomenon

In the first step of the design students write observations for a laboratory-level chemical phenomenon. One can present this as a live demonstration, or with video, but one must ensure that *all relevant observations* are contributed by students.

Ideally, the phenomenon should be unusual, or counter-intuitive. In this case the colour change in the solution is from colourless to blue, with the growth of beautiful dendritic crystals (Fig. 6.1), and pitting of the copper. The question is – can these observations be explained in molecular-level terms?

At this point the instructor should allow students to think about and discuss this observation before rushing in with an explanation. The aim of this step in the design is to capture attention with an engaging context, and to generate a 'need to know'.

Step 2. Describing and Drawing a Molecular-level Representation

In this step students attempt to explain their observations by drawing *labelled molecular-level representations* of the substance or reaction, and also describe their ideas in words (Fig. 6.11). One needs to develop the 'drawing literacy' of the students by discussing conventions (e.g., representing relative sizes of atoms and ions, using space-filling or ball & stick models), and point out that they will have to do such drawings as part of formal assessment. This is a signal that communicating the details of one's model of the molecular level is a skill worth developing.

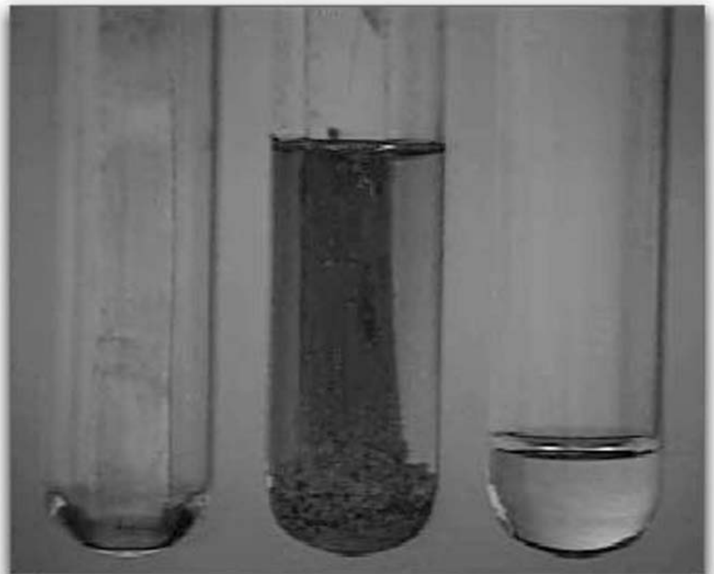


Fig. 6.11 An example of an observation with an apparently simple explanation

For some students this reaction occurs ‘in solution’ with copper atoms donating one electron to one silver ion, and another electron to another silver ion (see Fig. 6.12a). For many students the nitrate ions play an active in the reaction.

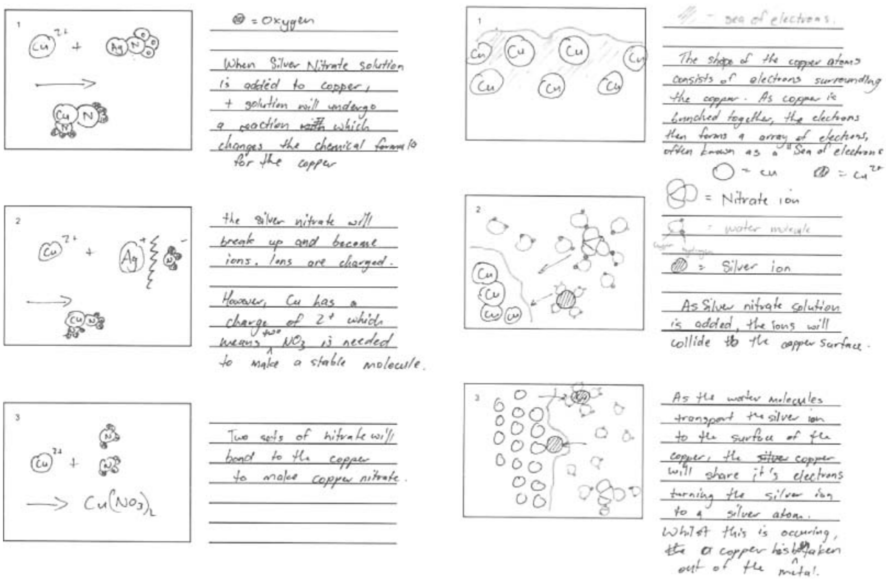
A *Molecular Construction Tool* (a free, downloadable program from the *VisChem Learning Design* web site – Tasker, 2002) can be used as an alternative to drawing a representation of their ideas on paper. The advantage of the tool is the progressive feedback available on the student’s representation of an ionic solution at any stage of the construction process (Fig. 6.13).

Step 3. Discussing with Peers

Following the advice to students to identify *key features* that explain the observations, they should receive initial feedback on their representations by discussion with peers (or from the *Molecular Construction Tool*). One should not identify correct or incorrect key features at this stage.

Step 4. Viewing Animations and Simulations

Animations and simulations can depict the dynamic molecular world more effectively than static pictures and words because students are spared the cognitive load



(a) (b)

Fig. 6.12 (a) A student’s storyboard of the reaction prior to seeing the *VisChem* animation in Step 2, and (b) then redrawn in Step 5 below after seeing the animation with a narration

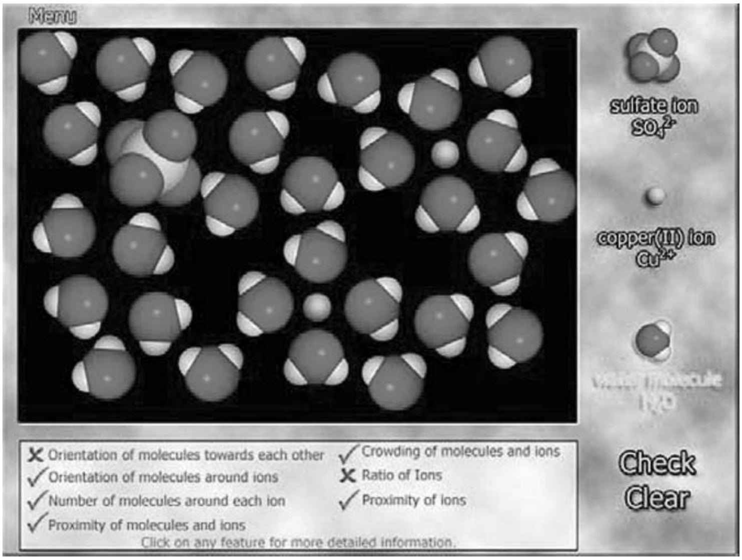


Fig. 6.13 A sample screen from the *VisChem Molecular-Level Construction Tool* (Tasker, 2002) showing feedback on seven key features. In this student's construction the feedback generated shows the ion ratio is incorrect, and too many water molecules are oriented incorrectly for optimum H-bonding

of having to 'mentally animate' the content. However, animations are *only effective if they are presented in a way that takes account of the limitations and processing constraints of the working memory.*

In a lecture setting, with time permitting, we recommend that each animation should be presented three times:

- First, without commentary, with students encouraged to look for key features they had, or did not have, in their own representations.
- Second, in short animation sequences ('chunks' to reduce the load on working memory), each with narration by the lecturer drawing attention to the important key features, and with responses to any questions from students.
- Third, in its entirety again, with repeated, simultaneous narration.

In this example, the animation (depicted in Fig. 6.4) involves a series of key features. Ideally the student should have complete control over the pace and view by dragging the movie bar. Use of the 'Play' button plays the movie at too fast a frame rate to perceive all the key features.

Step 5. Reflecting on any Differences with Prior Conceptions

In this step students reflect on differences between key features in the animations and in their own representations; *amending their drawings accordingly, if necessary.* Student drawings and descriptions of their conceptions of structures and processes at the molecular level often reveal misconceptions not detectable in conventional equation-writing questions. Fig. 6.12(b) illustrates the difference in storyboard after viewing the *VisChem* animation.

This activity in the learning design provides the opportunity for students to identify these misconceptions in their own representations, or those of their peers. *Experience shows this is more effective than having the lecturer simply listing common misconceptions.*

Step 6. Relating to Other Thinking Levels

In this step one should encourage student discussion to link the key features of the molecular-level animations to the other two thinking levels. In this example, the following questions would be useful:

Observational Level

- Can you explain the three observations — blue colour, copper pitting, and dendritic crystal growth? The latter is not obvious and requires students to explain how silver atoms deposit on silver metal rather than on the copper metal surface.

Symbolic Level

- Watch the animation and calculate the ratio of Cu^{2+} ions to silver atoms produced?
- Should the nitrate ions be included in the net ionic equation for this reaction?

Step 7. Adapting to New Situations

This step indicates if the student can transfer their ideas to a new situation. Can they draw a molecular-level representation for an analogous redox reaction shown at the laboratory level?

We have found that if visualisation is to be taken seriously by students as a learning strategy, it is essential that they are encouraged to practise their new skills with new situations, and assess their visualisation skills in one's formal assessment. In addition to questions that probe qualitative and quantitative understanding of concepts at the symbolic level, we need to design questions that require students to articulate their mental models of molecular-level structures and processes.

Conclusion

The need for a chemistry student to move seamlessly between Johnstone's three 'thinking-levels' is a challenge, particularly for the novice. Our work in the *VisChem* project indicates that animations and simulations can communicate many key features about the molecular level effectively, and these ideas can link the laboratory level to the symbolic level. However, we have also shown that new misconceptions can be generated.

To use animations effectively, we need to direct our students' attention to their key features, avoid overloading working memory, and promote meaningful integration with prior knowledge. We can do this by using constructivist learning designs that exploit our knowledge of how students learn.

'Scarring' misconceptions are those that inhibit further conceptual growth. To identify these misconceptions we need a strategic approach to assist our students to visualise the molecular level, and assess their deep understanding of structures and processes at this level.

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References

Andersson, B. (1990a). Pupils conceptions of matter and its transformations (age 12–16). In P. L. Lijnse, H. M. C. Eijkelhof, P. Licht, W. de Vos, & A. J. Waarlo (Eds.), *Relating macroscopic phenomenon to microscopic particles* (pp. 12–35). University of Utrecht.

Andersson, B. (1990b). Pupil's conceptions of matter and its transformations (age 12–16). *Studies in Science Education, 18*, 53–85.

Atkins, P. (1999) Chemistry: the great ideas. *Pure Applied Chemistry, 71*(6), 927–929.

Ben-Zvi, R., Eylon, B., & Silberstein, J. (1987). Students' visualisation of a chemical reaction. *Education in Chemistry, 24*(4), 117–120.

Ben-Zvi, R., Silberstein, J., & Mamlok, R. (1990). Macro-micro relationships: a key to the world of chemistry. In P. L. Lijnse, H. M. C. Eijkelhof, P. Licht, W. de Vos, & A. J. Waarlo (Eds.), *Relating macroscopic phenomenon to microscopic particles* (pp. 183–197). University of Utrecht.

Bergquist, W. and Heikkinen, H. (1990). Student ideas regarding chemical equilibrium. *Journal of chemical Education, 67(12)*, 1000–1003.

Bodner, G. M. (1991). I have found you an argument: the conceptual knowledge of beginning chemistry graduate students. *Journal of Chemical Education*, 68(5), 385–388.

Brown, T. L., LeMay, H. E., & Bursten, B. E. (2006). *Chemistry: The central science*. 10th Ed. Pearson Education, Inc., NJ.

Burke, K. A., Greenbowe, T. J., & Windschitl, M. A. (1998). Developing and using conceptual computer animations for chemistry instruction. *Journal of Chemical Education, 75*(12), 1658–1661.

Butts, B., & Smith, R. (1987). HSC Chemistry students' understanding of the structure and properties of molecular and ionic compounds. *Research in Science Education, 17*, 192–201.

Dalton, R. M. (2003). *The development of students' mental models of chemical substances and processes at the molecular level.* PhD Thesis, University of Western Sydney.

Dalton, R. M., & Tasker, R. F. (2006). Expert and novice interpretations of a Redox reaction: Comparison of participant narrations. *Journal of Research in Science Teaching,* Submitted for publication.

Gabel, D. L., Samuel, K. V. (1987). Understanding the particulate nature of matter. *Journal of chemical Education, 64(8)*, 695–697.

Gabel, D. (1999). Improving teaching and learning through chemistry education research. *Journal of Chemical Education, 76*(4), 548–553.

Garnett, P. J., & Hackling, M. W. (2000). Improving introductory chemistry students' ability to visualise the particulate basis of chemical reactions. *Chemeda: Australian Journal of Chemical Education, 51, 52, 53*, 45–56.

Gorodetsky, M., & Gussarsky, E. (1986). On the concept 'Chemical Equilibrium': The associative framework. *Journal of Research in Science Teaching, 27*(3), 197–204.

Greenbowe, T. J. (1994). An interactive multimedia software program for exploring electrochemical cells. *Journal of Chemical Education, 71*(7), 555–557.

Griffiths, A. K., & Preston, K. R. (1992). Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching, 29*(6), 611–628.

Haidar, A. H., & Abraham, M. R. (1991). A comparison of applied and theoretical knowledge of concepts based on the particulate nature of matter. *Journal of Research in Science Teaching, 28*(10), 919–938.

Hand B., Treagust D. F. (1997). Monitoring teacher's referents for classroom practice using metaphors. *International Journal of Science Education, 19(2)*, 183–192.

Harper, B., O'Donoghue, J., Oliver, R., & Lockyer, L., (2001). New designs for Web-based learning environments. In C. Montgomerie, & J. Viteli (Eds.), *Proceedings of ED-MEDIA 2001, World conference on educational multimedia, hypermedia & telecommunications* (pp. 674–675), Association for the Advancement of Computing in Education, Tampere, Finland.

Hill, D. (1988). Misleading Illustrations. *Research in Science Education, 18*, 290–297.

Hinton, M. E., & Nakhleh, M. B. (1999). Students' microscopic, macroscopic, and symbolic representations of chemical reactions, *The Chemical Educator, 4*, 1–29.

Johnstone, A. H. (1982). Macro and microchemistry. *School Science Review, 64*, 377–379.

Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer-Assisted Learning, 7*, 701–703

Jones, L., Jordon, K., & Stillings, N. (2001). Molecular visualisation in science education. *Report Prepared for the 2001 Gordon Research Conference on Science Education and Visualisation,* Arlington.

Jones, L., & Tasker, R. (2002), CD, workbook, and web site. *Bridging to the lab: media connecting chemistry concepts with practice*. WH Freeman & Co., New York.See http://bcs.whfreeman.com/bridgingtothelab/ and view the free sample, last accessed on December 18, 2005.

Kleinman, R. W., Griffin, H. C., & Kerner, N. K. (1987). Images in chemistry. *Journal of Chemical Education, 64*, 766–770.

Kozma, R. B., & Russell, J. (1997). Multimedia and understanding: expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching, 34*, 949–968.

Kozma, R. B., Russell, J., Jones, T., Marx, N., & Davis, J. (1996). The use of multiple, linked representations to facilitate science understanding, In S. Vosniadou, E. De Corte, R. Glaser, & H. Mandl. (Eds.), *International perspectives on the design of technology-supported learning environments* (pp. 41–60). New Jersey: Lawrence Erlbaum Associates.

Levy Nahum, T., Hofstein, A., Mamlok-Naaman, R., & Bar-Dov, Z. (2004). Can final examinations amplify students' misconceptions in chemistry? *Chemistry Education: Research and Practice, 5*(3), 301–325.

Lijnse, P. L., Licht, P., Waarlo, A. J., & de Vos, W. (Eds.). (1990). Relating macroscopic phenomena to microscopic particles. *Proceedings of Conference at Utrecht centre for science and mathematics education*. University of Utrecht, and references therein.*

Lowe, R. (2001). Beyond 'Eye-candy': Improving learning with animations. *Paper Presented at the Apple University Consortium Conference*, Townsville.

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

Nakhleh, M. B. (1992). Why some students don't learn chemistry. *Journal of Chemical Education, 69*, 191–196.

Nakhleh, M. B. (1993). Are our students conceptual thinkers or algorithmic problem solvers? *Journal of Chemical Education, 70*, 52–55.

Nakhleh, M. B., & Mitchell, R. C. (1993). Conceptual learning vs. problem solving. *Journal of Chemical Education, 70*, 190–192.

Niaz, M. (1995). Relationship between student performance on conceptual and computational problems of chemical equilibrium. *International Journal of Science Education, 17*, 343–355.

Novick, S., & Nussbaum, J. (1981). Pupils' understanding of the particulate nature of matter: A cross-age study. *Science Education, 65*(2), 187–196.

Nurrenbern, S. C., & Pickering, M. (1987). Concept learning versus problem solving: is there a difference? *Journal of Chemical Education, 64*, 508–510.

Osborne, R. J., & Cosgrove, M. M. (1983). Children's conceptions of the changes of state of water. *Journal of Research in Science Teaching*, 20(9), 825–838.

Pereira, M. P., & Pestana, M. E. M. (1991). Pupils' representations of models of water. *International Journal of Science Education, 13*(3), 313–319.

Russell, J. W., Kozma, R. B., Jones, T., Wykoff, J., Marx, N. & Davis, J. (1997). Use of simultaneous-synchronised macroscopic, microscopic, and symbolic representations to enhance the teaching and learning of chemical concepts. *Journal of Chemical Education, 74*, 330–334.

Sanger, M. J., & Greenbowe, T. J. (1997). Students' misconceptions in electrochemistry: Current flow in electrolyte solutions and the salt bridge. *Journal of Chemical Education, 74*(7), 819–823.

Sanger, M. J., Phelps, A. J., & Fienhold, J. (2000). Using a computer animation to improve students' conceptual understanding of a can-crushing demonstration. *Journal of Chemical Education, 77*(11), 1517–1520.

Sequeira, M., & Leite, L. (1990). On relating macroscopic phenomena to microscopic particles at the junior high school level. In P. L. Lijnse, H. M. C. Eijkelhof, P. Licht, W. de Vos, & A. J. Waarlo (Eds.), *Relating macroscopic phenomenon to microscopic particles* (pp. 220–232). University of Utrecht.

Sleet, R. J. (1993). Attitudes and images in chemistry. In C. Fogliani (ed.), *Australian chemistry resource book* (pp. 53–63). Charles Sturt University-Mitchell.

Taber, K. S. (1994). Misunderstanding the ionic bond. *Education in Chemistry, 31*, 100–102.

Taber, K. S. (1997). Student understanding of ionic bonding: Molecular versus electrostatic framework? *School Science Review, 78*(285), 85–95.

Tasker, R. (1992). Presenting a chemistry youth lecture. *Chemistry in Australia, 59*, 108–110.

Tasker, R., Bucat, R., Sleet, R., & Chia, W. (1996). The VisChem project: Visualising chemistry with multimedia. *Chemistry in Australia, 63*, 395–397; and *Chemistry in New Zealand, 60*, 42–45.

Tasker, R. (1999). CD for *Chemistry: molecules, matter and change*. In L. Jones & P. Atkins (4th ed.). New York: WH Freeman & Co.

Tasker, R. (2001). CD and Web Site for *ChemCom — Chemistry in the community*. An American Chemical Society Project. In H. Heikkinen (4th ed.), New York: W. H. Freeman & Co. See http://www.whfreeman.com/chemcom and go to 'Interactive ChemCom Media for Instructors and Students', Last accessed on December 18, 2005.

Tasker, R., Dalton, R., Sleet, R., Bucat, B., Chia, W., & Corrigan, D. (2002). VisChem: visualising chemical structures and reactions at the molecular level to develop a deep understanding of chemistry concepts, Last accessed on December 18, 2005, from the Learning Designs Web site: http://www.learningdesigns.uow.edu.au/exemplars/info/LD9/index.html.

Tasker, R., Bell, J., & Cooper, M. (2003). Web Site for *General Chemistry - an American Chemical Society Project*. In J. Bell (ed.), New York: WH Freeman & Co. See http://www.whfreeman.com/acsgenchemhome/, click on 'Web Companion', last accessed on December 18, 2005.

Tasker, R. (2004). Web Site for *Chemical principles, the quest for insight.* In P. Atkins & L. Jones (3rd ed.), New York: WH Freeman & Co. See http://www.whfreeman.com/chemicalprinciples/ and go to 'Animations', last accessed on December 18, 2005.

Tasker, R., & Dalton, R. (2006). Research into practice: visualisation of the molecular world using animations. *Chemistry Education Research and Practice, 7*, 141–159.

Velazquez-Marcano, A., Williamson, V. M., Ashkenazi, G., Tasker, R. F., & Williamson, K. C. (2004). The use of video demonstrations and particulate animation in general chemistry. *Journal of Science Education and Technology, 13*, 315–323.

Williamson, V. M., & Abraham, M. R. (1995). The effects of computer animation on the particulate mental models of college chemistry students. *Journal of Research in Science Teaching, 32*(5), 521–534.

Chapter 7
Engineering Instructional Metaphors Within Virtual Environments to Enhance Visualization

Debbie Denise Reese

Abstract Digital games worlds are systems of objects, their properties, behaviors, and the relations between them. They are immensely popular with people of all ages, currently especially the young. The educational community has begun to notice that game worlds present an attractive possibility for enhancing conventional educational achievement. The greatest potential of instructional games actually derives from the structural isomorphism between game worlds and conceptual worlds. This chapter describes how that isomorphism can be achieved through the use of structure mapping theory. A game world designed through applied structure mapping provides a way to introduce novices to expert thinking by making that thinking *visible* and *embodied* through a concrete metaphor.

Preface

It has been known for many years that learners can hold persistent, non-normative preconceptions of the ideas that are central to the sciences (e.g. Bransford, Brown, & Cocking, 2000; Chi & Roscoe, 2002). Thus, Hestenes, Wells, and Swackhamer (1992) noted that

> every student begins physics with a well-established system of commonsense beliefs about the how the physical world works derived from years of personal experience—commonsense beliefs about motion and force (that) are incompatible with Newtonian concepts in most respects—(these) commonsense alternatives to the Newtonian concepts are commonly labeled as misconceptions. They should nevertheless be accorded the same respect as we give scientific concepts (pp. 141–2)

To increase learner success in respect of the concepts of science, any learning environment should provide just-in-time instruction that scaffolds the formation of robust, normative, coherent understanding (Linn, Eylon, & Davis, 2004). Educators often turn to "instructional metaphors", otherwise known as "teaching models"

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(Gilbert & Boulter, 2000), to provide scaffolding for learning because many of the concepts studied in domains, for example chemistry, "are abstract, and are inexplicable without the use of analogies or models" (Gabel, 1999, p. 548). But because analogical reasoning is so powerful, misunderstanding can reinforce or cause non-normative knowledge (Gentner & Markman, 1997). To guard against the generation of misconceptions, instructional metaphors should be selected and constructed through the application of an empirically validated cognitive theory. Today's 3D game systems hold promise as metaphor-enhanced virtual worlds, but designing them requires the application of cognitive theory, instructional design theory, and game design theory. This chapter describes how to engineer metaphor-enhanced virtual worlds so that the learning objects involved can introduce learners to complex concepts through transactions supporting a coherent knowledge of natural phenomena.

Chapter Overview

The chapter is organized into eight main sections. The first introduces analogical reasoning as a ubiquitous cognitive process that has long been identified as a key for preparing novices to construct meaningful knowledge about complex concepts. The second advocates the educational desirability of instructional metaphors. The relationship between models and metaphors is then discussed. In the fourth section, an illustrated outline algorithm for the production of metaphor-enhanced learning objects is given. In the fifth section, the relationship of these ideas to visualization –the focus of this book –is discussed. An advocacy of computer-based games in science education is then presented, followed by an agenda for future research. Final, recommendations for action are put forward.

Analogical Thinking

Humans use the structure of what they know (a source domain) to think about what they don't know (a target domain). This is analogical thinking, the inferring of the relational properties of a targeted domain by thinking about the relational properties of a second domain, and it is ubiquitous within human cognition (Hummel & Holyoak, 1997). Often, analogical reasoning is a form of embodied cognition (Lakoff & Johnson, 1999): learning based upon what can be experienced by the body. The major processes underlying analogical reasoning were specified by Dedre Gentner 25 years ago in her structure mapping theory (Gentner, 1983). Empirical validation of models derived from the theory has brought principal cognitive scientists in the field to agreement that humans construct their metaphors[1]

[1] Throughout this chapter, *analogy* or *analogical reasoning* refers to the cognitive process of mapping between two domains and *metaphor* is used to refer to a particular instantiation of that process as the relational mapping between two specific domains.

according to the relational structure of the source and target domains (see Gentner & Holyoak, 1997, p. 2).

During analogical reasoning, the relational structure of the source domain is used to make *candidate* inferences about the relational structure of the target domain. Candidate inferences provide the power of analogical reasoning. They are hypotheses about unknown aspects of the target domain, derived from what is known about the source domain. Unfortunately, miss-specified analogies can foster candidate inferences that lead to or reinforce misconceptions or naïve mental models.

The issue is the accuracy of the correspondence (the mapping) between the source and target domain. Structure mapping requires a strict specification system such as propositional networks or concept maps (Gentner, 1980). This is because research has shown that the mapping between a source and a target is constrained by *isomorphism* – the need for a one-to-one correspondence of the structural relations between domain concepts (Gentner, 1983; Gentner & Markman, 1997). Structure mapping is based upon the systematicity principle:

> a predicate [a concept-concept relation] that belongs to a map-able system of mutually interconnecting relationships is more likely to be imported into the target than an isolated predicate (Gentner, 1983, p. 163).

A "deep relational structure" means that a domain (i.e. a system of relations) contains many levels and strands of interconnecting relationships. According to the systematicity principle, people prefer to map systems that have deep relational structure (Gentner, 1993).

The necessity for isomorphism and the desirability of systematicity require an expert in metaphor to be involved in the specification of instructional metaphors. Such a person will represent domains and the mappings between them graphically by the use of labeled nodes (ovals) and labeled directional arcs. Two aspects will show that apt, well-specified metaphors have been produced. First, the graphical representations of the concepts and the relations between them will look alike in both the source and the target domains except that the labels that name concepts in the two domains will differ. Second, the graphical representations will both have a deep relational structure. This will be shown in the levels of concepts and number of concept linkages within a domain.

Traditionally, educators, scholars, and researchers have selected their source analogies by intuition or in the light of established patterns of the discourse used in a domain (e.g., Baker & Lawson, 2001; Meyer, Chalon, David, & Bessiere, 2001). However the selection is made, it is vital that the drawing of the analogy is done with expertise. When domain specifications and the mapping between source and target domains have not been carefully done, when the specification of isomorphism and systematicity are left to chance, it is highly probable that any mis-alignment between the two will tend to produce superficial metaphors which lead to misconceptions and naïve mental models (Gentner & Markman, 1997). The avoidance of this pitfall is of central importance to effective learning.

Virtual Metaphor-enhanced Learning Objects

In order to ensure that instructional metaphors are properly designed, I have extended the concept of just-in-time instruction (that which is available when students are both prepared to and need to learn from it) to include the use of metaphor-enhanced learning objects that are available to students when they require prior knowledge to prepare them for learning a complex concept (Reese, 2003a, 2003b; Reese & Coffield, 2005). A metaphor-enhanced learning object is an advance organizer (Merrill, 2002). Such advance organizers appear to be most helpful for students who lack prior knowledge within a domain and when concrete models of the to-be-learned are difficult to construct (Smith & Ragan, 1990). They assist in learners in concretizing, structuring, and assimilating concepts (Simons, 1961, as cited in Smith & Ragan, 1990, p. 61). When instructional metaphors are used as advance organizers, visual representation of them enhances a learner's ability to visualize the underlying metaphor that is being used (Smith & Ragan, 1990). Indeed, instructional metaphors are more effective when accompanied by visual representations.

A 2004 United States Department of Education analysis of 8000 K-12 student responses to a questionnaire showed that today's learners want online technologies, 24/7, that will prepare them to succeed at their studies (U.S. Department of Commerce, U.S. Department of Education, & NetDay, n.d.). A repository of metaphor-enhanced learning objects designed in the form of digital games would help to address this need. Gee (2005) proposed principles for learning based upon his analysis of good video games. Whether contained within a game or within other contexts, the learning object is, of course, but one component of a well-designed learning environment.

The effective implementation of instructional metaphors may require more than a written or oral description: they need to be presented in a useable, accessible, form. Both the theory of conceptual metaphor (Lakoff & Johnson, 1980, 1999) and transactional analysis (Cantril, 1960) suggest that analogs would be most effective if placed within concrete (material) environments with which learners could interact. To afford the construction of a viable mental model, concrete analogs must be engineered to highlight just the right relationships. Because of this, it is highly unlikely that real-world objects could be easily harnessed to become a just-in-time learning object. Rather, the learning object could more readily be engineered within a virtual environment (Reese, 2003a; Reese & Coffield, 2005). Just as people build their understandings of the concrete world through sensory interaction with that world, learners could interact with the virtual world engineered to replicate the relational structure of the to-be-learned target. Today, as gaming and computer science have expanded capability to engineer immersive, virtual worlds, technologies are readily available with which to produce virtual metaphor-enhanced learning objects. Individually or as a class, students and their teachers can share the exploration of a virtual environment that empowers them with the prior knowledge necessary for success.

Models and Metaphors

As has already been said, models represent the relational structure of a targeted domain. Most models are of the *first-degree*: the work of the model is to reduce a phenomenon to its salient characteristics. That is, the model is a simplification of the system that highlights the targeted relational structure so that the learner can interact with it and recognize how it functions. The first-degree model provides a concrete representation of the phenomenon and is helpful to learners' building mental models of unfamiliar, *concrete* domains. When a targeted concept is highly *abstract* it may be difficult to represent it as a first-degree model. This occurs when a domain's salient relational characteristics are unfamiliar *and* its salient relational structure does not lend itself to embodied instantiation; that is, in a form that can be experienced with the senses. An *instructional metaphor* is a *second-degree* model designed to embody the targeted relational structure of the to-be-learned and represent it within a concrete source domain. The first-degree model representation of the source domain is also the second-degree model of the target domain. If a target's domain's subordinate concepts are concrete, a first-degree model can probably adequately represent it. Models map target domain sub-concepts on to the concrete characteristics of the model representation. Metaphors map target domain sub-concepts to the sub-concepts of a concrete source domain.

Basic level objects are those with which people interact with their senses (Rosch, 1978). People's cognitive organization of information into categories and prototypical category membership derives from real-world interactions at the basic level (Lakoff, 1987; Rosch, 1978, 1983): for example, non-specialists typically categorize trees and furniture at the basic level. Oak, elm, willow, and apple are examples of basic level tree nouns. Chair, table, bed, and couch are examples of basic level furniture nouns. People can form images of objects at the basic level. One cannot form an image of a piece of "furniture," but one can form an image of a chair or table or bed or couch. The former is too abstract to be imaged without additional information. People learn easiest those real-world objects and relations that are body syntonic (Papert, 1980, p. 63); that is, related to their senses and knowledge about their own bodies. However, many natural phenomena studied by scientists such as chemists are complex and lack body syntonicity (even when the human senses are amplified by tools). While people interact with the world at the macro level (akin to Rosch's, 1983, basic level), chemists study phenomena that occur at the submicro (particulate) level (Gabel, 1999). These chemistry concepts are theoretical because there are no observable exemplars (Lawson, Alkhoury, Benford, Clark, & Falconer, 2000). Chemistry adds another level of challenge for novices, because it requires students to think at the symbolic level (Gabel, 1999). Challenging introductory chemistry concepts, such as the mole, appear to be apt domains for instantiation as second-order models (metaphors).

Whether developed as a first- or second-order representation, models must be adequately and viably specified and mapped. Pragmatic considerations lead specification by determining the goal of specification. In the case of instructional environments, the goals are learning outcomes. In the case study below, I illustrate how I did this by collaboration with a high qualified university chemistry educator.

Developing a Suitable Instructional Metaphor

This section is a summary of the procedures followed to develop the instructional metaphor "A balanced chemical equation is a ceramic tile grid". Fuller details are available elsewhere (Reese, 2003b, 2005; Reese & Coffield, 2005). It consists of six steps or elements

1. **Specifying the target domain**
   The specification procedure is recursive. The first step is to identify and represent the targeted, to-be-learned, domain concepts and the relationships between them. Although my partner and I used concept mapping to specify a domain, Gentner (1980) used propositional networks. She advised that any representational system is appropriate as long as it: treats concepts as a whole; distinguishes between attributes and relations; presents domain structure as hierarchical (higher-order concepts subsume lower-order concepts). Our work to date suggests that specifications that are too large are unwieldy. Limiting the stoichiometry specification to mass-mass and mass-mole relations permitted specification of a 13-concept domain. This is a manageable size.

   The specification team allowed the structure mapping isomorphism principle to constrain the target domain specification. These proactive constraints during the target domain specification and source-target mapping directed the process and avoided the need for re-specification. The target domain specification required two constraining procedures—isomorphic straightening and metaphor cleansing:

   - *Isomorphic straightening.* Some domains use more than one label for a concept. Inclusion of multiple nodes that represent the same concept would result in one concept from the source domain mapping on to multiple target domain concepts. This would be a transgression of the principle of isomorphism. The design team resolved the issue by selecting one label as a replacement for the two original terms and used this label within the target domain specification. The team incorporated explanation of the subtle inflections represented by the original terminology into later instruction.
   - *Metaphor Cleansing.* Metaphors are such an integral component of science practice (e.g., Gilbert & Boulter, 2000) that metaphor analogs from the source domain can slip into target domain specifications. They can appear in two ways: (a) concrete concepts from the source domain are found in the target domain, and (b) concepts from some external source domain are found in the targeted domain specification. Design teams must be vigilant and select appropriate terminology to replace these terms.

2. **Selecting and specifying the source domain**
   While specifying the target domain, the design team began to identifying candidates for the source domain. Scientific theory is often derived through analogy

as scientists posit candidate inferences from a known domain to an unknown domain (Boyd, 1993; Hawking, 1992; Kuhn, 1993), forming theory constitutive metaphors (Petrie & Oshlag, 1993, p. 591). The designers analyzed domain discourse to identify possibly useful candidate theory constitutive metaphors which were then evaluated. Early candidates required modification guided by the constraint of basic leveling. As a basic level concept must be image-able, it would have been easy to specify a source domain at too abstract a level. Therefore, the design team scrutinized candidate source domains and their sub-concepts and reduced any that were too abstract to serve as a suitable basic level concept. Their use within metaphor-enhanced environments requires that all source domain nodes can be developed as objects with properties and behaviors. The design team needed to conduct "basic leveling" during the iterative rounds of source and target mappings and specifications. It scrutinized source domain concepts and sub-concepts and removed any that were too abstract to serve as a suitable basic level concept.

Theoretically, the design team could have specified the source domain using a template of the target domain, with the node (concept) labels erased. Source domain specification would simply have entailed filling in the blanks. In practice, source domain specification seemed to become an iterative procedure during which the target domain specification was refined. Experts from both target and source domain are always required during the iterative cycles to insure that specification modifications do not compromise the integrity of the target specification.

3. **Identifying the fundamental element**
During specification of the domains and cross-domain mapping, the design team had to identify the key relational primitive. This is the domain sub-concept that comprises the most fundamental element – the smallest sub-division – of the specified domain. Within the stoichiometry target domain under analysis, it is the atom (see node 5 in Fig. 7.1). The source domain will contain an isomorphic atomistic element (the tile, see node 5 in Figs. 7.2 and 7.3). Care was taken to specify the relational properties of the relational primitive, and to map those relations as properties within the source domain primitive (see Table 7.1). These relational characteristics were subsumed within other domain sub-concepts (see Table 7.2). Because of this, the relational properties of the atomistic element constrained possibilities for the source domain. This constraint aided in the selection of a source domain from source domain candidates. Notice in Fig. 7.3 how the tiles fit together to form the modular patterns.

4. **The Higher-order domain**
It is helpful if the design team can identify an overarching higher-order domain that generalized the relational structure of the target domain. The labels on the relational arcs remained constant from target to higher-order domain (see Figs. 7.1 and 7.4). Each higher-order domain sub-concept was generalized to a more abstract concept. Fig. 7.4 illustrates a higher-order domain isomorphic to the target domain in Fig. 7.1. Table 7.3 displays the correspondences between the target (Fig. 7.1), source (Figs. 7.2 and 7.3), and higher-order domains (Fig. 7.4) for the Balanced Equation-Tile Grid metaphor. For example, in the row for node number 1: A rule is a higher-order correlate of the targeted sub-concept

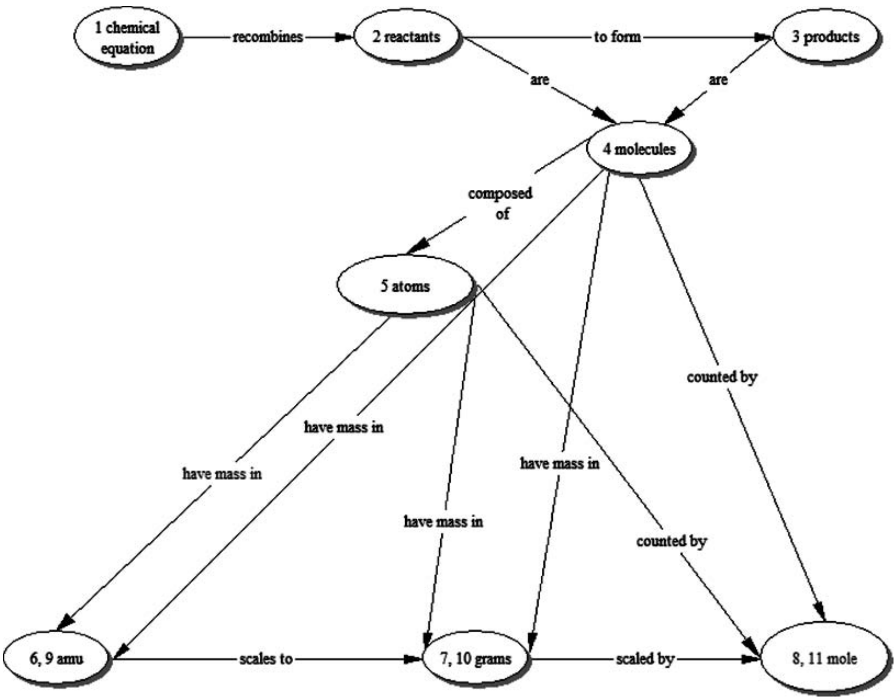

Fig. 7.1 Target domain concept map specification for stoichiometry mass-mass and mass-mole relationships. Relations between concepts are represented by labeled arcs. Domain subconcepts are represented by labeled ovals. Nodes are numbered. Isomorphic nodes are numbered the same way across chapter Figs. 7.1–7.4

chemical equation; a resource is a higher-order correlate of the targeted subconcept reactant, etc.

5. **Evaluating analog for aptness**
   When a higher-order domain can identified and specified, the design team can use it to identify candidates for use as source domain analogs and to evaluate their aptness for use in metaphor-enhanced learning environments. Aptness is evaluated in two dimensions: systematicity and abstractness (see Fig. 7.5). First, an apt source domain should be relationally isomorphic to the target domain, locating it at the high end of the systematicity dimension. Second, an apt source domain will be concrete, locating it on the far left of the concrete-abstract continuum. Thus, an apt source domain candidate will be located at the top left-hand side of the aptness dimensions graph.
6. **Specifying the source domain**
   Source and higher-order domain specification directed the design team back again and again to the target domain, resulting in what we were convinced was a lean and elegant specification. Once specification was complete, the source domain was relationally isomorphic to the target domain. Relational structure,

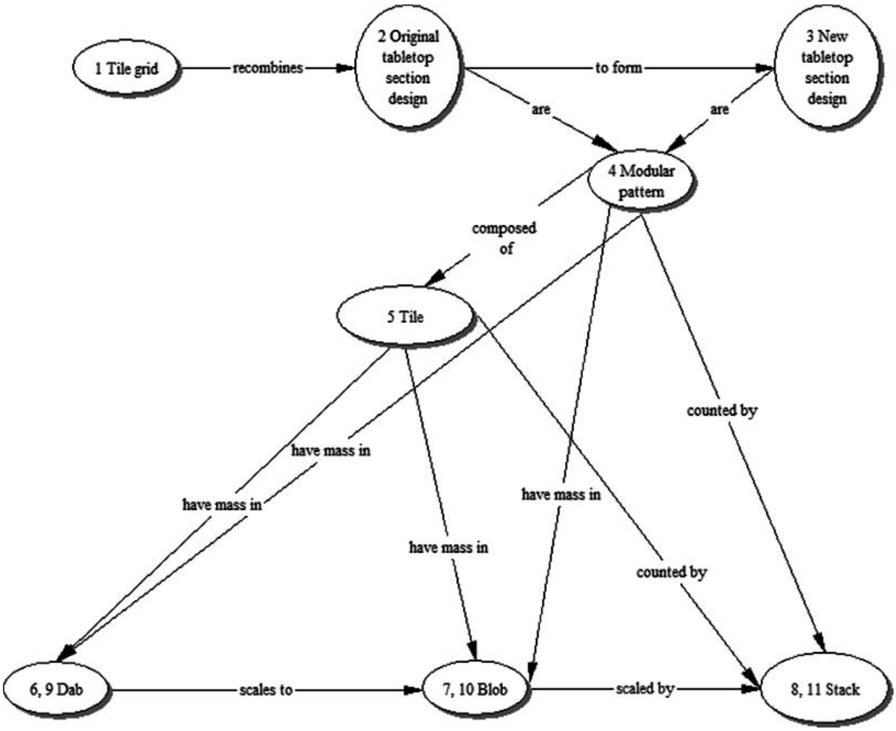

Fig. 7.2 Source domain concept map specification for stoichiometry mass-mass and mass-mole relationships. Relations between concepts are represented by labeled arcs. Domain subconcepts are represented by labeled ovals. Nodes are numbered. Isomorphic nodes are numbered the same way across chapter Figs. 7.1–7.4

represented by the arcs, was identical in the source, target, and higher-order domain representation (if specified). The labels on the arcs were identical. The nodes occupied identical locations within each of the three specification maps. The only difference in the source, target, and higher-order concept maps is the labels within the concept modes.

Whilst it is easy to specify a source domain sub-concept at too abstract a level, inclusion within metaphor-enhanced environments requires that all source domain nodes can be developed as objects with properties. Reiterating, the design team must scrutinize source domain concepts and reduce any that are too abstract to act as a suitable basic level concept.

Visualization and Embodied Cognition

Gilbert, Boulter, and Elmer (2000) defined scientific models as those employed within a contemporary or historical scientific community to make predictions (p. 42).

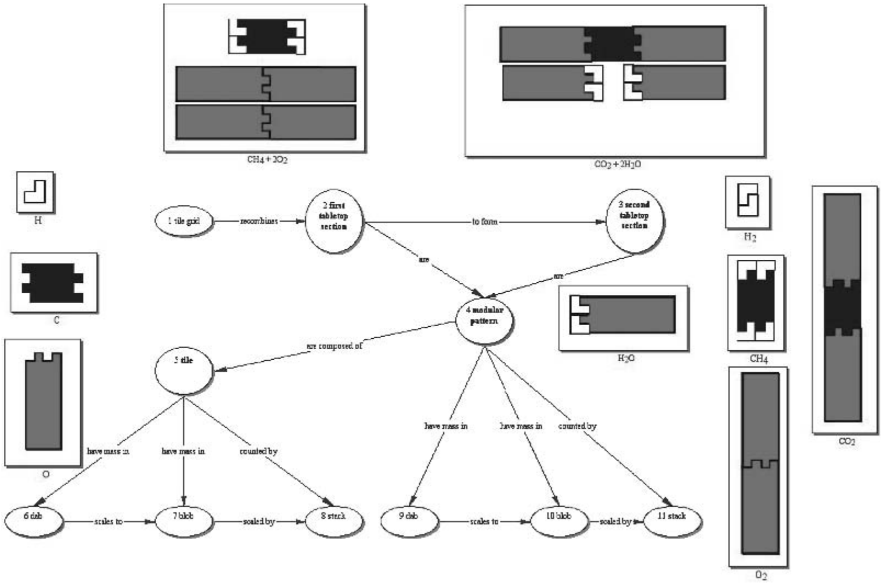

Fig. 7.3 Source domain concept map specification for stoichiometry mass-mass and mass-mole relationships, with concepts approached through two paths (from the modular pattern, the molecule analog, and the tile, the atom analog) printed twice. Relations between concepts are represented by labeled arcs. Domain subconcepts are represented by labeled ovals. Nodes are numbered. Isomorphic nodes are numbered the same way across Figs. 7.1–7.4. The illustrations surrounding the concept map are drafts of the object primitives used to represent the relational characteristics of the most atomistic level of the map, the modular pattern level (molecule analog) and the tabletop section design (reactant/products level)

Instructional metaphors are pedagogical versions of scientific models, adapted for use within a curriculum. Boulter and Buckley, (2000, pp. 46–47) classified models within a typology by crossing *modality of representation* with *representational attributes*. There are four modalities of representation: verbal, visual, mathematical, concrete. A verbal model is heard or read: metaphors and analogies are verbal models. Visual models are seen Mathematical models use quantitative representations or formulations. Concrete models are 3D material representations. Gestural models involve movement of the body or its parts. Within their typology, models that employ one or more of these modes are mixed models. There are three pairs of representational attributes within the Boulter and Buckley topology : quantitative versus qualitative, static versus dynamic, and deterministic versus stochastic.

Computer-mediated virtual environments blur the distinction between physically concrete models (3D) and their 2D correlates. Metaphor-enhanced learning objects are mixed models. As used within a virtual world, a metaphor-enhanced learning object may involve all of the modalities and are all are dynamic because they respond to learner input. The inclusion of the other two pairs of representative attributes is determined by the relational structure of the to-be-learned.

Table 7.1 Target Domain Atomistic Element and Source Domain Primitive Relational Properties for the Balanced Equation-Tile Grid Metaphor

Target Domain – Atom	Source Domain – Tile
Atoms cannot be divided (are not divided) during normal chemical reactions like the one we were studying.	Only whole tiles in designs used. Tiles cannot be divided when a modular pattern or a table top section is designed. Tiles are never chipped, cut, or split in any way.
The basic unit for constructing molecules is the atom.	The basic element in constructing the modular pattern is the tile.
Two properties considered about the atoms that make up molecules are: 1. The mass of the atoms. 2. The number of connections (bonds) the atoms can form with other atoms.	Two properties considered about the tiles that make up modular patterns were: 1. The overall size of the tile. 2. The number of connection nubs.
Atoms have many other properties that distinguish them from each other, but these additional properties did not concern us at this time.	Tiles have different colors, but this superficial characteristic did not affect the way the tiles fit together.

Table 7.2 Superordinate concepts relational characteristics build on atomistic relational characteristics

Target Domain–Balanced Chemical Equation	Source Domain–Tile Grid
A balanced chemical equation uses all atoms from reactants: The number and identity of the atoms is the same for both sides of the equation.	Must use all tiles from original pattern: The number and identify of the tiles is the same for both sides of the grid.
In a balanced chemical equation, molecules in the reactants can not be used in the products.	Must not repeat any modular patterns: No modular patterns in the original design can be used in the new design.
In a balanced chemical equation [and for the types of atoms we are looking at] all the [unpaired] valance electrons must connected [be paired by forming bonds].	All nubs must be used: All nubs on a given tile must be connected to the nubs on other tiles
All available bonding sites [unpaired electrons] are used. All molecules must be valid: When all available bonding sites [unpaired electrons] are used, a molecule is valid.	All modular patterns must be valid: A modular pattern is valid when all of its tile nubs are connected.
The number of particular atom type in the reactants is always equal to the number of that particular atom type in the products.	The number of particular tile type in the original tabletop design is always equal to the number of that particular tile type in the second tabletop design.
The number of moles of a particular atom type in the reactants is always equal to the number of moles of that particular atom type in the products.	The number of stacks of a particular tile type in the original tabletop design is always equal to the number of stacks of that particular tile type in the second tabletop design.

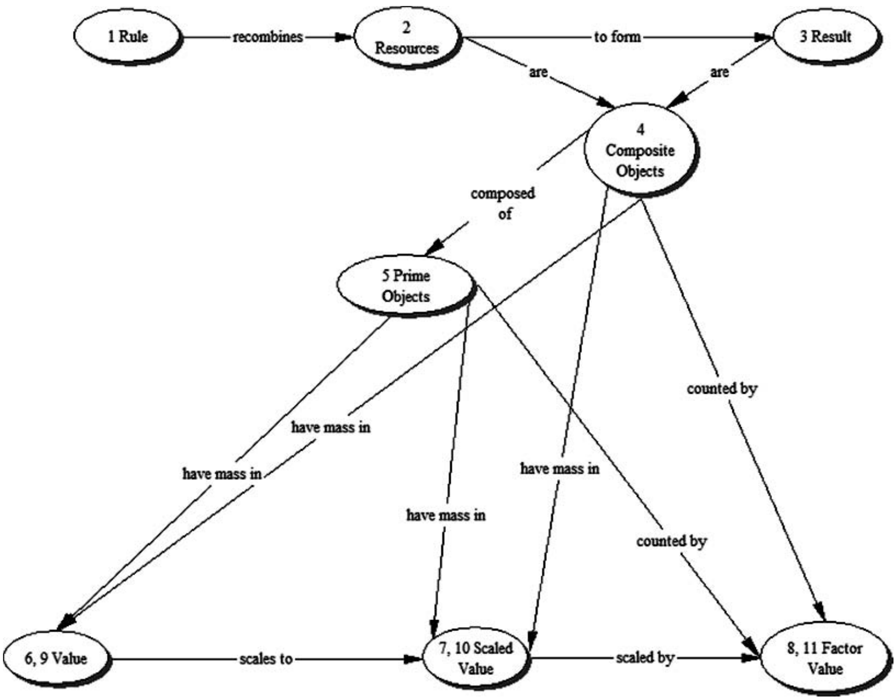

Fig. 7.4 Specification of the Higher-Order Abstract Domain for Stoichiometry Mass-Mass and Mass-Mole Relations. Relations between concepts are represented by labeled arcs. Domain sub-concepts are represented by labeled ovals. Nodes are numbered. Isomorphic nodes are numbered the same way across chapter Figs. 7.1– 7.4

Transformations between concrete or visual objects to a mental model require a set of visual literacy skills. Gilbert (2005) defined visualization as a metacognitive skill, requiring sub-skills that support metavisual capacity: Spatial visualization[2]:

Table 7.3 Target, source, and higher-order domain sub-concepts for the balanced equation-tile grid metaphor

Node Number	Target	Source	Higher-order
1	Chemical Equation	Tile Grid	Rule
2	Reactants	Original Tabletop Section Design	Resources
3	Products	New Tabletop Section Design	Result
4	Molecules	Modular Pattern	Composite Objects
5	Atoms	Tile	Prime Objects
6, 9	AMUs	Dab	Value
7, 10	Grams	Blob	Scaled Value
8, 11	Mole	Stack	Factor Value

[2] Gilbert (2005) suggested spatial interpretation as a more apt terminology for spatial visualization (p. 21).

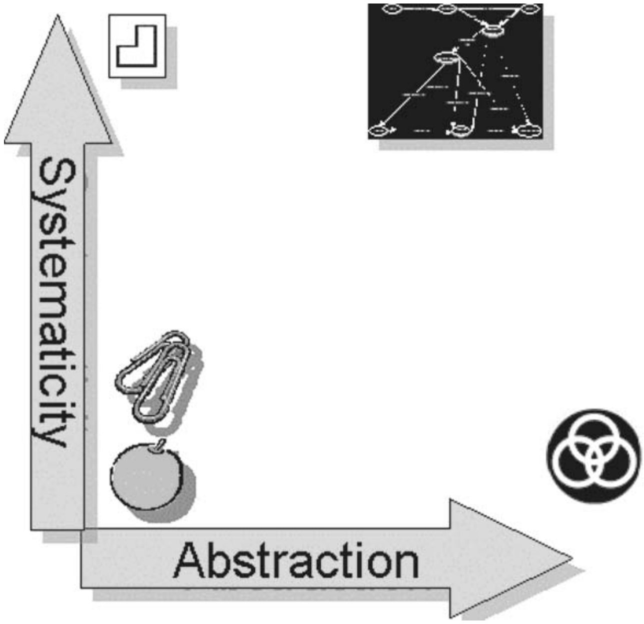

Fig. 7.5 Systematicity and Abstraction Dimensions of Aptness: Illustrated Using Stoichiometry Mass-Mass/Mass-Mole Domain Illustrations. Systematicity runs from 0–100% relationally isomorphic mapping between analog and targeted domain. The concrete to abstraction dimension is determined by how well the source domain concepts and sub-concepts can be represented as concrete objects and relationships. The black square in the upper right-hand corner is the higher-order abstract domain specification (see Fig. 7.4). The lower left-hand side picture of the orange represents a very concrete analog with very little systematicity. The paper clip image represents an analog with a bit more systematicity. The ceramic tile metaphor represented by the white tile image in the upper left is 100% isomorphic to the target domain. The black circle in the lower right represents the trinity, an analog that scores low in systematicity and high in abstraction. A good candidate for specification as a source domain will score high in systematicity and low in abstraction

the ability to understand three-dimensional objects from two-dimensional representations of then (and vice versa); Spatial orientation: the ability to imagine what a three-dimensional representation will look like from a different perspective (rotation); Spatial relations: the ability to visualize the effects of the operations of reflection and inversion (p. 21).These models can be manipulated and *acted upon*. Learners' visual literacy could be initiated by introducing them to "regular, geometrically simple forms" (p. 22) of models and the building sophisticated literacy skills take place through progressive differentiated instruction (e.g., the inclusion of cues, such as how diagrams represent three-dimensionality).

Metaphor-enhanced learning objects are virtual concrete environments. They are each designed to provide an *experience* relationally isomorphic to the targeted concept. They provide transactions, *transactions with* the human sensory apparatus. These metaphor environments model the human cognitive and physical activity that is analogous to a targeted concept. Of themselves, metaphors do not necessarily require metavisualization skills, and they do not necessarily privilege visualization. Any degree of visual primacy is due to the human body and the manner in which it interacts with itself and the external world. When metaphors are provided within learning objects, visual hegemony is the result of current technologies, the interface between them and the human body, and the analogous interface between the human body and the natural environment. Although a specific instantiation of a metaphor might require metavisual capacity, interpretation of a metaphor-enhanced learning object does not usually mandate spatial visualization, orientation, or relations skills. Instead, it requires the learner to match the relational properties of the concrete source domain with the target domain. This is a syntactical procedure of the meaningfully matching of structural correspondences according to *mutual alignment* (Kurtz, Miao, & Gentner, 2001).

While a first-order model and a metaphor might both derive from the same domain specification, they represent different types of "visualization" processes. Metaphor-enhanced learning objects are scaffolding that makes *thinking* concrete. A metaphor provides the learner with concrete transactions with objects and concrete objects that interact with each other. And all interaction is analogous to the scientific model of the targeted domain's relational structure. In the case of a metaphor-enhanced virtual world, the representation is an analog to the real world environment with similar visualization requirements.[3] A good deal of that concreteness derives from and instantiates in visual imagery.

Cognitive scientists and instructional designers identify two types of knowledge (Anderson, 2002). Declarative knowledge is an individual's system of conceptual knowledge. Within the brain, neural networks representing well integrated, coherent domains have deep relational structure composed of conceptual nodes and the relations among them. Procedural knowledge is the knowledge of relational rules (e.g., if-then rules) and procedures (e.g., step 1, step 2, step 3, etc.). The two types of knowledge interact in response to goal structures. One of the major differences between novices and experts within any particular domain is that experts have developed deep, hierarchical, highly organized declarative knowledge (Bransford et al., 2000). This affords them sensitivity to "patterns of meaningful information" (p. 21) and allows them to "chunk information" for easy analysis, retrieval and application (p. 21). This deep knowledge structure guides expert thinking about a domain through core concepts, big ideas, and major principles and laws (p. 24). As I have defined them, instructional metaphors are scaffolds for the development of deep, hierarchical, highly organized, domain-specific declarative knowledge.

Instructional metaphors scaffold the construction of declarative knowledge by creating conditions that motivate analogical reasoning: the human cognitive process of interpreting new experience based upon previously encountered concrete (or relatively familiar) experiences. Metaphor-enhanced learning objects involve visualization in two ways:

[3] Thus, any metavisual literacy requirement would derive from the relational structure of the targeted analog.

1. Perceiving through the sense of sight
   Metaphor-enhanced learning objects are visual by virtue of (a) the characteristics of the human sensory and cognitive apparatus and (b) those characteristics of the physical environment after which they are modeled and the manner in which human senses perceive those physical environments.
2. Making thinking visible
   The science education literature has recognized the importance of *making thinking visible* (Linn, Davis, & Eylon, 2004). While the focus is often the representation of learners' mental models, learner scaffolding and prior knowledge is facilitated when learners possess relevant prior knowledge that prepares them to learn (Schwartz & Martin, 2004). Metaphor-enhanced learning objects instantiate the scientific model within a concrete analog and thus *make thinking visible*.

Metaphor-enhanced learning objects are designed to make the targeted expert model visible and embodied through basic level objects. Instructional metaphors are designed to make the abstract concrete and the implicit explicit. A metaphor-enhanced virtual environment is thinking made visible. Any learning environment that is created is a visual instantiation of the experts' mental model of the targeted domain. By watching the concrete objects and their responses during learner-controlled transactions, the sighted learner constructs a visual analog of the relational structure of the targeted abstract concept. This becomes a chunked (Bransford et al., 2000) knowledge structure of visual, embodied experience upon to which the learner can meaningfully map the to-be-learned concept. The metaphor serves as prior knowledge.

Concept maps were designed to make relational structure (concepts and the relations between them) visible (Ausubel, 2000; Novak & Musonda, 1991). When concept maps are successful at this, they enhance meaningful learning by helping the learner see relational structure. Concept maps are visualizations of conceptual models. The instructional metaphor is built by mapping the concept map of the targeted domain on to an analogous concrete domain. The virtual world is built from the concrete domain. The metaphor-enhanced virtual world is a visualizable conceptual model.

However, metaphor-enhanced virtual worlds are more than visualizations of conceptual models. They provide lived, embodied, experiences analogous to the deep relational structure of the conceptual model representing the targeted domain. The encoded visualization is an embodied memory, a virtual prior experience within a compelling possibility space contrived to support learner engagement with a "reality" that foreshadows a to-be-learned relational structure.

Deep play within the metaphor-enhanced virtual world engages the player within a defined relational structure. Deep play provides visual and other sensory transactions with a targeted domain's relational structure to support deep understanding. Yes, the player will perceive the analog with the player's own eyes, but metaphor-enhanced virtual worlds offer more for they scaffold deep understanding that prepares a learner to visualize the to-be-learned as a correlate of lived experience.

Game-based Science Education: An Opportunity Awaiting Development

There is a contemporary community of scholarship supporting the position that games provide the type of embodied experiences necessary to situate learning (Gee, 2003), and that educational environments should apply the principles inherent in good game design. There is also evidence from a United States Department of Education study of 55,000 K-12 students that, at least in the United States, adolescents have a preferred vision of education that would support the affordances of metaphor-enhanced game worlds. The researchers asked the students:

> Today, you and your fellow students are important users of technology. In the future, you will be the inventors of new technologies. What would you like to see invented that you think will help kids learn in the future? (U.S. Department of Commerce et al., n.d., p. 5).

The researchers analyzed 8,000 of the answers to probe for common themes and interests. There were four overarching themes: Digital devices; Access to computers and the Internet; Intelligent tutor/helper; Ways to learn and complete school work using technology. Overall, those students would like 24/7 access to technology tools that scaffold their understanding.

While any learning object may be placed within an online repository, available 24/7, virtual worlds add the capacity for embodied experience. Learners can actually navigate within a virtual world and engage in transactions that introduce and reinforce the relational structure of a targeted conceptual domain. When the to-be-learned concept is too abstract to be understood by a novice if modeled directly, it can be realized as a virtual world that is a concrete analog of the to-be-learned. Today's game developers have the techniques, hardware, and sophistication to further contextualize a virtual world within a game. Game developers are good at designing games that motivate people to play. Compelling metaphor-enhanced game worlds will engage learners in exploring and manipulating concrete analogs of targeted relational structure. It is hoped that these experiences will motivate novice learners to focus their attention on the critical relational attributes of targeted concepts and assist the learners in visualizing how they function together as a system (Smith & Ragan, 1990). Furthermore, the well-designed metaphor-enhanced game world will encourage "active and critical, not passive, learning" (Gee, 2003). According to Gee, active learners "experience the world in a new way" as they "develop resources to future learning and problem-solving" (p. 45). Critical learners innovate by producing meanings for themselves. Enhanced ability to visualize the relational structure of targeted content will help novices construct a viable and "new way of experiencing the world" (p. 26).

The Research Agenda

Once a set of metaphor-enhanced learning objects has been developed, learning scientists can begin a four-pronged research agenda.

Mutual Alignment

Cognitive scientists have found that learners must engage in effortful and conscious activity in which they bring the source and target domain sub-concepts into alignment (Kurtz et al., 2001). Learners do this by actually constructing the mapping between target and source domain sub-concepts and then by consciously describing the relationship shared by each sub-concept dyad in a process termed *mutual alignment*. Mutual alignment is similar to process of elicited self-explanations studied by Michelene Chi and her colleagues (Chi, 2000; Chi, Bassok, Lewis, Reiman, & Glaser, 1989; Chi, de Leeuw, Chiu, & LaVancher, 1994). Chi and her colleagues found that elicited self-explanations increased understanding. Experts in the operation of metaphor must validate an effective methodology for engaging learners in a process of self-explanation for how the targeted domain sub-concepts align with the source domain sub-concepts.

Target Domain Episodes

Is it more effective to present an entire set of source domain episodes followed by the entire set of target domain episodes, or is to more effective to present the source-target dyads in sequence, or to present them in dyad sets? Previously developed metaphor-enhanced learning objects (Reese, 2003a, 2003b) and learning object specifications (Reese, 2005; Reese & Coffield, 2005) have immediately followed each source domain episode with its dyad partner, the target domain analog episode. Each episode was followed by a mutual alignment task. It is possible that other presentation organizations might be more effective.

Metaphor-enabled Learning Communities

As with any meme, metaphor-enhanced learning objects are designed to be a resource shared by a community (in this case, a learning community) to enhance communication and shared understanding. What is the best way to incorporate metaphor-enhanced learning objects within face-to-face and virtual learning communities? As included within virtual environments, vetted and approved by communities of stakeholders, metaphor-enhanced learning objects should serve as educative tools (Davis & Krajcik, 2005) that prepare each participating educator with a virtual shared experience of just the right mental model to scaffold learner construction of a normative, robust, and coherent mental model of a targeted domain concept. Will educators require training in how best to integrate metaphors into shared domain discourse and practice within the learning community? Will integration be seamless, or will it require techniques developed through design experiments conducted in collaboration with teacher practitioners? Will face-to-face cases require a separate set of practices than distance education learning communities?

Situated Learning: The Learning Context

The metaphor-enhanced learning object does not carry the teaching load. It is but a component of an integrated instructional unit. It serves as an advance organizer (Ausubel, 1963; Merrill, 2002). Recent scholarship suggests that concept knowledge is constructed when people build and reorganize personal theories through conceptual change (Jonassen, 2006). A metaphor object provides 24/7 access to viable prior knowledge that can serve as an anchor for learning complex concepts. A well-constructed set of metaphor-enhanced virtual worlds will allow learning scientists to use design experiments (Brown, 1992; Collins ,1991; Kelly ,2003) to uncover principles for best practice in incorporating metaphor-enhanced learning objects within instructional units.

Recommendations

In the light of this chapter, the following recommendations are made for the design of instructional games to enhance the quality of the representations made and the visualization achieved:

- The instructional content (the targeted domain) of the game must be completely analyzed before its design begins.
- The embedded assessment of in-game learning is desirable and requires use of analogous scenarios to those that have served as a basis of the instruction.
- Structure mapping theory should be applied for the development of *game* scenarios that are analogous to *conceptual* scenarios.
- The methodology for metaphor-enhanced instructional design in general and the Systematicity and Abstraction Dimensions Model in particular should be applied to the design of instructional games.
- Whilst the quality of the play experience is a primary goal in instructional game design, it should be fully constrained by the relational structure of the conceptual structure of that which is to be learned.
- As the design of instructional game worlds requires the input of skilled game design professionals, highly proficient subject-matter experts, and instructional experts, it requires considerable financial investment.
- The design of metaphor-enhanced instructional game worlds requires the input of experts in the operations of analogy and metaphor, who must oversee domain specification and analog mapping.

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References

Anderson, J. R. (2002). Spanning seven orders of magnitude: A challenge for cognitive modeling. *Cognitive Science, 26*, 85–112.

Ausubel, D. P. (1963). *The psychology of meaningful verbal learning*. New York: Grune and Stratton.

Ausubel, D. P. (2000). *The acquisition and retention of knowledge: A cognitive view*. Boston: Kluwer Academic Publishers.

Baker, W., & Lawson, A. E. (2001). Complex instructional analogies and theoretical concept acquisition in college genetics. *Science Education, 85*(6), 665–683.

Boulter, C. J., & Buckley, B. C. (2000). Constructing a typology of models for science education. In J. K. Gilbert & C. J. Boulter (Eds.), (pp. 41–57). Boston: Kluwer Academic publishers.

Boyd, R. (1993). Metaphor and theory change. In A. Ortony (Ed.), *Metaphor and thought* (2nd ed., pp. 481–532). New York: Cambridge University Press.

Bransford, J. D., Brown, A. L., & Cocking, R. R. (Eds.). (2000). *How people learn: Brain, mind, experience, and school*. Washington, DC: National Academy Press.

Brown, A. L. (1992). Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings. *Journal of the Learning Sciences, 2*(2), 141–178.

Cantril, H. (Ed.). (1960). *The morning notes of Adelbert Ames, Jr.: Including a correspondence with John Dewey*. New Brunswick, NJ: Rutgers University Press.

Chi, M. T. H. (2000). Self-explaining expository texts: The dual processes of generating inferences and repairing mental models. In R. Glaser (Ed.), *Advances in instructional psychology* (pp. 161–238): Lawrence Erlbaum Associates.

Chi, M. T. H., Bassok, M., Lewis, M. W., Reiman, P., & Glaser, R. (1989). Self-explanations: How students study and use examples in learning to solve problems. *Cognitive Science, 13*, 145–182.

Chi, M. T. H., de Leeuw, N., Chiu, M.-H., & LaVancher, C. (1994). Eliciting self-explanations improves understanding. *Cognitive Science, 18*, 439–477.

Chi, M. T. H., & Roscoe, R. D. (2002). The processes and challenges of conceptual change. In M. Limón & L. Mason (Eds.), *Reconsidering conceptual change. Issues in theory and practice* (pp. 3–27). The Netherlands: Kluwer Academic Publishers.

Collins, A. (1991). Toward a design science of education. In E. Scanlon & T. O'Shea (Eds.), *New directions in educational technology* (pp. 15–22). New York: Springer-Verlag.

Davis, E. A., & Krajcik, J. S. (2005). Designing educative curriculum materials to promote teacher learning. *Educational Researcher, 34*(3), 3–14.

Gabel, D. (1999). Improving teaching and learning through chemistry education research: A look to the future. *Journal of Chemical Education, 76*(4), 548–554.

Gee, J. P. (2003). *What do video games have to teach us about learning and literacy*. New York: Palgrave Macmillan.

Gee, J. P. (2005). What would a state of the art instructional video game look like? Retrieved from http://www.innovateonline.info/index.php?view=article& id=80.

Gentner, D. (1980). *The Structure of Analogical Models in Science (report No. 4451, NTIS No. AD-A087–625)*. Springfield, VA: National Technical Information Service, U. S. Department of Commerce.

Gentner, D. (1983). Structure mapping: A theoretical framework for analogy. *Cognitive Science, 7*, 155–170.
Gentner, D. (1993). From metaphor to analogy in science. In A. Ortony (Ed.), *Metaphor and thought* (2nd ed., pp. 447–480). New York: Cambridge University Press.
Gentner, D., & Holyoak, K. J. (1997). Reasoning and Learning by Analogy: Introduction. *American Psychologist, 52*(1), 32–34.
Gentner, D., & Markman, A. B. (1997). Structure mapping in analogy and similarity. *American Psychologist, 52*(1), 45–56.
Gilbert, J. K. (2005). Visualization: A metacognitive skill in science and science education. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 9–28). Boston: Kluwer Academic publishers.
Gilbert, J. K., & Boulter, C. J. (2000). *Developing models in science education*. Boston: Kluwer Academic publishers.
Gilbert, J. K., Boulter, C. J., & Elmer, R. (2000). Positioning models in science education and in design and technology education. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education*. Boston: Kluwer Academic publishers.
Hawking, S. (Ed.). (1992). *Stephen Hawking's a brief history of time: A reader's companion (prepared by Gene Stone)*. New York: Bantam Books.
Hestenes, D., Wells, M., & Swackhamer, G. (1992). Force concept inventory. *The Physics Teacher, 30*, 141–158.
Hummel, J. E., & Holyoak, K. J. (1997). Distributed representations of structure: A theory of analogical access and mapping. *Psychological Review, 104*(3), 427–466.
Jonassen, D. H. (2006). On the role of concepts in learning and instructional design. *Educational Technology, Research, & Development, 54*(2), 177–196.
Kelly, A. E. (Ed.). (2003). Theme issue: The role of design in educational research. *Educational Researcher, 32*(1), 3–4.
Kuhn, T. (1993). Metaphor in science. In A. Ortony (Ed.), *Metaphor and thought* (2nd ed., pp. 533–541). New York: Cambridge University Press.
Kurtz, K. J., Miao, C.-H., & Gentner, D. (2001). Learning by analogical bootstrapping. *The Journal of the Learning Sciences, 10*(4), 417–446.
Lakoff, G. (1987). *Women, fire, and dangerous things: What categories reveal about the mind*. Chicago: The University of Chicago Press.
Lakoff, G., & Johnson, M. (1980). *Metaphors we live by*. Chicago, IL: The University of Chicago Press.
Lakoff, G., & Johnson, M. (1999). *Philosophy in the flesh: The embodied mind and its challenge to western thought*. New York: Basic Books, A Member of the Perseus Books Group.
Lawson, A. E., Alkhoury, S., Benford, R., Clark, B. R., & Falconer, K. A. (2000). What kinds of scientific concepts exist? Concept construction and intellectual development in college biology. *Journal of Research in Science Teaching, 37*(9), 996–1018.
Linn, M. C., Davis, E. A., & Eylon, B.-S. (2004). The Scaffolded knowledge integration framework for instruction. In M. C. Linn, E. A. Davis, & P. Bell (Eds.), *Internet environments for science education* (pp. 47–72). Mahwah, NJ: Lawrence Erlbaum Associates.
Linn, M. C., Eylon, B.-S., & Davis, E. A. (2004). Knowledge integration perspective on learning. In M. C. Linn, E. A. Davis, & P. Bell (Eds.), *Internet environments for science education* (pp. 29–46). Mahwah, NJ: Lawrence Erlbaum Associates.
Merrill, M. D. (2002). First principles of instruction. *ETR&D, 50*(3), 43–59.
Meyer, C., Chalon, R., David, B., & Bessiere, C. (2001). *A learning environment based on metaphors, concept maps and hypermedia: Application to computer networks' training*. Paper presented at the ED-MEDIA 2001, World Conference on Educational Multimedia, Hypermedia, & Telecommunications, Tempere, Finland.
Novak, J. D., & Musonda, D. (1991). A twelve-year longitudinal study of science concept learning. *American Educational Research Journal, 28*(1), 117–153.
Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. New York: Basic Books, Inc., Publishers.

Petrie, H. G., & Oshlag, R. S. (1993). Metaphor and learning. In A. Ortony (Ed.), *Metaphor and thought* (2nd ed., pp. 579–609). New York: Cambridge University Press.

Reese, D. D. (2003a). *Metaphor and content: An embodied paradigm for learning*. Unpublished doctoral dissertation, Virginia Polytechnic Institute and State University.

Reese, D. D. (2003b). Trees of knowledge: Changing mental models through metaphorical episodes and concept maps. In R. E. Griffin, V. S. Williams, & J. Lee (Eds.), *Turning trees: Selected readings*. International Visual Literacy Association.

Reese, D. D. (2005). *The analogical designs model.* Paper presented at the Association for Educational Communications and Technology, Orlando, FL.

Reese, D. D., & Coffield, J. (2005). Just-in-time conceptual scaffolding: Engineering sound instructional metaphors. *International Journal of Technology, Knowledge, and Society, 1*(4), 183–198.

Rosch, E. (1978). Principles of categorization. In E. Rosch & B. B. Lloyd (Eds.), *Cognition and categorization* (pp. 27–48). New York: Lawrence Erlbaum Associates, Publishers.

Rosch, E. (1983). Prototype classification and logistical classification: The two systems. In E. K. Scholnick (Ed.), *New trends in conceptual representation: Challenges to Piaget's theory?* (pp. 73–86). Hillsdale: New Jersey: Lawrence Erlbaum Associates.

Schwartz, D. L., & Martin, T. (2004). Inventing to prepare for future learning: The hidden efficiency of encouraging original student production in statistics instruction. *Cognition and Instruction, 22*(2), 129–184.

Smith, P. L., Ragan, T. J. (1990). Designing visual analogies for instruction. *Journal of Visual Language,* 10(2), 60–83.

U.S. Department of Commerce, U.S. Department of Education, & Netday. (n.d.). *Visions 2020.2: Student views on transforming education and training through advanced technologies*. Retrieved. from http://www.ed.gov/about/offices/list/os/technology/plan/2004/site/documents/visions_20202.pdf.

Chapter 8
Teaching Chemistry with and Without External Representations in Professional Environments with Limited Resources

Liliana Mammino

Introduction

External representation is a fundamental instrument in science teaching and learning:

- It enables effective explanations of concepts and descriptions that can be complementary to those provided by the text and make them clearer by attracting the students' attention on the key issues of each discourse. In this way, it can help overcome (at least partially) the well known difficulties (Mallinson, Sturm, & Mallinson, 1952; Lahore, 1993) at reading science texts.
- It provides additional routes for communication and interactions that have the great advantages of immediateness.
- It facilitates the familiarisation with invisible entities and phenomena. In the case of chemistry (Gabel, Samuel, & Hunn, 1987; Gabel 1993; Smith & Metz, 1996), this includes the whole world of atoms and molecules, i.e., the entire interpretation framework.
- It is essential for the generation of mental images (internal representations) of objects and phenomena. Mental images are an essential component of human mental processes in general and scientific elaboration in particular (Kwadl & Smit, 2001) and are consequently essential also for science learning:
  Students who operate with few or no mental images are not really learning (Harre, 1970).

In the case of chemistry, learning and understanding depend largely on the level of acquired familiarity with the two main issues of the microscopic description: *how molecules are made* and *what molecules do*. This microscopic world is unrelated to everyday experience, and external representations are the only way of trying and overcoming the barrier between what can be related to direct experience and what is far from it, or between what can be somehow perceived as concrete, and what is often perceived as abstract. The systematic use of carefully designed external

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representations can make the microscopic world familiar enough for students to be able to imagine and discuss what molecules do (Mammino, 1998a, 2002a).

On the other hand, the benefits of these representations depend extensively on students' visual literacy, i.e., on their ability to identify and understand all the information conveyed by an image. Images are meant (and need to be) a communication tool. Their communication ability depends on the two ends of the communication: the design (that needs to take into account all the details of the concept/s concerned, but also all possible aspects of students' receptivity and possible responses) and the reception, i.e. the way in which students are ready to approach an image and interpret it. Once these routes function with sufficient efficiency, the representations become also an excellent tool for interactions - classroom interactions as well as interactions in informal set-ups (Mammino, 1999a).

Difficulties in reading external representations have been identified in several contexts. The representations related to chemistry may imply more difficulties than others, because of being related to unfamiliar objects and events. The difficulties identified in a context (Italy) where students' visual literacy is nurtured since the early years of schooling, were considered indications of two main aspects: the difficulties inherent to the chemistry discourse (as perceived by students, above all in relation to the diffuse ways of introducing it as a new subject) and the difficulties that might arise from modes of representation design that are more designer-centred (how the person who designs the images perceives them or feels about them) than student-centred (investigation and prediction of how students will perceive and interpret the representations). An investigation of students' interpretations of external representations in secondary school chemistry books and other materials (selecting images from a broad variety of topics), showed that both the interpretation of their meaning, and their relationships with the discourse developed in the text, often posed difficulties. In addition, some representations appeared insufficiently rigorous and others appeared misleading, above all when one single representation was overcrowded with information. This investigation highlighted aspects of students' difficulties in interpreting external representations, and prompted us to design representations trying to convey one or very few important messages at a time. We also accompanied these representations with careful and systematic guidance in their reading, also worded to highlight the relationships of the representations to the text (Mammino, 1994, 2003). The response (known from teachers' comments) proves the option to be effective. Search for continuous refinement of the option (also in view of the need to respond to changing students' attitudes) is still in progress.

The difficulties diagnosed in disadvantaged contexts include all the aspects identified in "more advantaged" contexts plus a number of other factors. The more of these negative factors, the heavier the impact, because these negative factors combine to exacerbate each other's undesirable effects. Removing all the factors inherent in a disadvantaged context is beyond the possibilities of individual teachers or even individual teaching/learning institutions. Interventions within the teaching/learning activities in individual courses can only aim at reducing the impact of these factors, trying to minimise them as far as circumstances allow.

This chapter discusses some options designed to minimize these factors in a specific context, the University of Venda (UNIVEN) in South Africa. It attempts to outline a comprehensive picture in order to highlight how the types of design/interventions relate to the characteristics of the context:

- with particular attention to those aspects that make it "disadvantaged". The "disadvantaged" concept, as used in the current discussion, does not refer only to limited resources, but includes an ensemble of factors and aspects that hamper students' possibility to fully benefit from the courses. The recognition and analysis of these factors, and of their implications, constitute the motivations for (and provide the guidelines in) the design and implementation of approaches aimed at decreasing their impact.
- The need to provide diagnostic information which highlighting the effects of inadequate exposure to (or familiarization with) external representations through the consideration of some crucial aspects. The information is documented through a number of examples from students' works. In the perspective of the design of strategies, this diagnostic information constitutes the essential basis for the design to be linked to the real needs of the students concerned.
- the need for strategies designed so far in relation to the diagnosed aspects. The main features of their implementation are also outlined, as well as the main students' responses (the analysis of to latter providing guidelines for continuous optimisation as well as for the search of new routes).

The diagnoses, explorations of strategies and recommendations presented here are based on nine years of research and observations at UNIVEN, while teaching chemistry courses. Diagnoses and explorations are still in progress, as inherent components of the teaching activity (i.e., of the attempt to continuous improvement of the quality of teaching and of the tuning of the pedagogical options to the students' needs). The difficulties discussed here are still present and, therefore, observations and design are continuing within the courses being taught currently. Most of the mistakes diagnosed are recurrent - they have not been observed only once, they keep on being encountered. In other words, the problems, the investigation and the strategies presented here are part of the present as well as the past. Their relevance for the present is dominant, because all the experience gained through the past contributes to the construction of the options for the present, at classroom level and in all the other forms of interactions with the students. To better underline this, the current discussion utilises present tenses rather than description-styles more typical of already closed (or completed) projects.

The discussion makes concrete references to chemistry courses, because they are the ones for which the options that will be presented were designed, and in which they were implemented. This does not limit the validity range of the methodological considerations or the pedagogical approaches, since chemistry comprises all the fundamental features typical of the sciences (Mammino, 1999b): broad experimental foundations, an interpretation framework based on the objects and events of the invisible microscopic world of atoms and molecules and on how they determine behaviours and phenomena of the macroscopic world, the extensive presence of mathematics as a tool of description and prediction – all aspects that, in different ways, require external representations for a full communication.

Learning/understanding about the microscopic/molecular level, and the way its events generate macroscopic phenomena, is crucial in the study of chemistry and largely determines learning results (Lijnse, Licht, Vos, & Waarlo, 1990). However, this poses particular difficulties to students worldwide, as documented by extensive research (Nussbaum & Novick, 1982; Mitchell & Kellington, 1982; Ben-Zvi, Eylon, & Silberstein, 1986; Anderson, 1990; Sawrey, 1990; Nakhleh, 1992; Lee, Eichinger, Anderson, Berkhaimer, & Blakeslee, 1993; Harrison & Treagust, 1996; Ebenezer & Erickson, 1996; Maskill, Cachapuz, & Koulaidis, 1997; De Posada, 1997; Mammino, 1997; Dominguez, De Pro, & Garcia-Rodeja, 1998; Mammino & Cardellini, 2005). The types of difficulties towards understanding or of misconceptions in this regard, diagnosed among the population of disadvantaged students considered in this study, are often similar to those documented in other contexts. The benefits that students can receive from the use of external representations are, however, more difficult to attain when the familiarity with these representations is inadequate or poor. The current study thus highlights both the fact that the difficulties diagnosed in disadvantaged contexts include (1) all the factors identified in "more advantaged" ones and (2) the presence of additional negative factors stemming from the disadvantaged context.

The Context

"Historical" Disadvantage

The University of Venda (in the Limpopo Province in South Africa) is chosen as reference for the "disadvantage" concept, because of its comparatively extreme situation, since it combines the "normal" disadvantages of under-resourced (even severely under-resourced) contexts with the still-existing consequences of a policy that aimed at excluding a group (the majority group) from science education. In this way, it constitutes a reference that includes what is probably one of the broadest and most diversified ensembles of factors aggravating students' difficulties towards learning and, above all, towards learning science.

The term "historically disadvantaged" has officially been used in South Africa with reference to learning institutions that were "for blacks only" during the *apartheid* regime. The education for blacks, whose terms and objectives were defined by the *Bantu Education Act* (1953) and, later, by the *Education and Training Act* (1976), were aimed at preparing them for the roles of dependent workers and, therefore, excluded broad-vision aspects. In particular, the regime did not envisage science careers for blacks, and the access to science knowledge was very limited even at school level. Schools for blacks were heavily under-resourced and the teachers' qualifications were mostly inadequate. All this made the disadvantages related to science education so extensive that some of them might even be un-matched in other contexts. The laws have changed since 1994 (when *apartheid* ended), but changing the reality requires enormous interventions. Huge efforts are in progress in many directions, like:

- upgrading of infrastructures;
- renovation of the pedagogical approaches by shifting to practices favouring central roles for the learners;
- enhancement of teachers' preparation (e.g., in 2005 the Limpopo Province Government initiated a project sponsoring some secondary school teachers to attend university and attain science degrees, so that they can have pilot roles in the upgrading of science teaching in the Province);
- particular emphasis on science education.

However, changing the teachers' pedagogical approaches on a large scale, upgrading their subject knowledge, and preparing new teachers to address the dire shortage of secondary school science teachers, is an enormous task that cannot be accomplished in a short time; but it is also pre-requisite to a real improvement of the situation. That is why heavy disadvantages are still present, and their consequences easily diagnosable.

Challenges of a University in a Prevalently Poor Rural Set-up

The University of Venda is situated in a rural area, with still a high poverty rate (the association of "being rural" and "being poor" is unfortunately a condition found in many parts of the world, and poverty is a heaviest source of disadvantage).

All the students are black. This is no more the result of politically-based restrictions – as in the *apartheid* period – but a spontaneous outcome of socio-economic as well as attitude factors. Students from well-to-do black families prefer to register at universities that were formerly "for whites only" (where facilities are historically much better, and that are also more renowned), while students who cannot afford the higher fees of those universities, and the additional expenses of living in big towns, register at UNIVEN. In this way, most students come from economically disadvantaged or straightforward poor families. They have attended secondary school in the area – where the combination of having formerly been "for blacks" and of belonging to a rural set-up means that the schools are seriously under-resourced both in terms of facilities and in terms of teaching staff.

This situation poses great challenges to the university, and actually UNIVEN is undertaking the mission of addressing disadvantages and attempting to set a model for higher education in rural set-ups, with close links with the surrounding communities and a promoting role for sustainable development. The extent to which this mission can be realistically pursued largely depends on the design of options that can enable students to overcome their initial under-preparedness and attain levels of knowledge and expertise *au pair* with those attained by students having more advantaged backgrounds and attending more advantaged institutions.

As already mentioned, the context is highly informative for the investigation and diagnosis of the impacts of the factors causing the disadvantage and aggravating students' difficulties. On the other hand, redressing past inequalities and addressing the existing problems is a matter of urgency and, therefore, diagnoses need to constitute the foundation for the design of effective interventions to be implemented without delays. In mathematical terms, diagnostic work alone is *necessary, but not sufficient*: the design, implementation, testing and continuous optimisation of options is the necessary active and constructive component of a teacher's work. At the tertiary level, this has the task of addressing incoming students' under-preparedness so that, at the end of the undergraduate course, the students' qualification (B.Sc.) reaches reasonable (and marketable) standards. The nature and role of this task determines many aspects of the design of pedagogical options.

Difficulties with Learning

Of the ensemble of factors aggravating students' difficulties, three have dominant impacts as far as the learning/understanding of science is concerned:

- the use of a second language as medium of instruction;
- the inadequate familiarity with science and its approaches;
- the inadequate visual literacy.

The use of a second language as medium of instruction is related to colonial heritage. The difficulties stemming from it have been extensively documented (Case, 1968; Brodie, 1989; Nangu, 1994; Mammino, 1998b, 2005a) and will not be discussed here, except for their impact on the efficiency of the use of representation. The other two factors are more closely related to features of pre-university instruction.

The inadequate familiarity with science and its approaches is due to several causes, including the already-mentioned scarcity of teachers in general (resulting in overcrowded classes), the scarcity of adequately prepared science teachers (affecting the quality of teaching/learning) and a teaching approach favouring (or even requesting) memorisation, while largely neglecting (or even excluding) interactions and discussions. The last cause is obviously connected to the previous ones, because only teachers that are sufficiently confident of their specific knowledge are mentally and emotionally available to interactions and discussions (this has also been confirmed through personal interviews, highlighting a sort of invincible uneasiness at the thought that some students might ask questions that the teacher will not be able to answer).

On the other hand, passive memorisation is unable to generate a perception of what science is. Even when not openly favoured or requested, passive memorisation is the option to which students resort in front of their own communication difficulties (*communication* in the broadest sense of the term: reading, listening, interpreting, expressing) and also in front of teachers' attitudes discouraging interactions. As a result, passive memorisation is highly generalised. It determines many aspects of students' attitude, clearly highlighted by the fact that the only expectation of incoming first year students, in a classroom, is that the lecturer provides material that they can memorise and reproduce (when the lecturer explains verbally, most students look passive; when the lecturer starts writing something on the board, they immediately "mobilize" and start copying with a very keen outlook, the outlook of someone who is now doing "the important thing": storing something that can later be memorised). Random interviews with students, asking to demonstrate how they do their study work, visualize two operations: reading a certain number of lines in the source (textbook, course handouts) and then trying to repeat it without looking at the text. The passivity of this way of learning is further documented by the scarcity of questions (from the students' side) asking for explanations of texts.

The inadequate visual literacy results from poor or null use of external representations in previous instruction, and the impact is more serious because the insufficient use of representations for the sciences concerns an age-range (from childhood to 18) in which imagery has a fundamental role as a communication tool, capable of reaching deeper internalisations than other communication forms. As an outcome, students have poor ability both at reading representations and at drawing images to express or represent something.

Diagnoses and Documentation

Sources of Information and Presentation Criteria

The diagnoses presented in this section are the outcomes of observations during nine years direct experience at UNIVEN. They refer mainly to first year general chemistry courses, as those that more immediately interface with pre-university instruction and its outcomes, but also (though with less frequency) to physical chemistry courses in subsequent years (these being selected not because of any assumed peculiarities of physical chemistry, but because they are the courses taught by the author).

The main sources of information are students' works and classroom interactions. These are considered the most reliable sources, because they correspond to situations in which students put all efforts to try and produce best responses. Therefore, mistakes, as well as skipped answers, genuinely correspond to inadequacies and preparation gaps.

In the current discussion, the diagnoses made at the tertiary level are presented with the role of illustration of the outcomes of teaching sciences without, or with direly inadequate, use of representations. The major aspects of chemistry (and science) learning that are affected by the absence of external representations are analysed under specific subsections. Appropriate documentation would require the reproduction of a considerable number of drawings from students' works, since such drawings are the best source of information about the level of visual literacy and the presence or absence of mental images. However, this would be unrealistic because of the space it would require and, therefore, short descriptions of selected significant images from students' works will be outlined, highlighting the aspects that are more important for diagnostic purposes.

General Remarks on how the Benefits of Representation are Missed

Representations have all the potentials to help decrease the impact of the other difficulty-generating factors, by:

- being and additional communication tool, to a considerable extent independent of the level of mastering of a specific language, and capable of clarifying the contents and meaning of texts and of classroom explanations;
- decreasing the risk of misinterpretations of the information provided by a text – a risk that is dramatically enlarged by inadequate mastering of the language that is the medium of instruction.

However, inadequate visual literacy drastically decreases the benefits of external representations by affecting both communication routes:

- The lack of familiarity with reading and interpreting images decreases the communication efficacy of images utilised as explanation tools.
- The lack of the habit to mentally anticipate/design images, and the inadequate drawing mastering – that is a frequent complementary component of inadequate visual literacy – decrease students' ability to communicate their conceptions and perceptions through images of their own production, up to the point that they rarely think of images as a possible communication tool.

The observations carried out at first university year level are testimonials (through assumed cause/effect relationships and confirmed by random personal interviews with students) of scarce or null use of representation in prior instruction. This can be ascribed to a variety of factors:

- general limited resources;
- inadequate or ineffective utilisation of representation in teaching material;
- inability of non-adequately prepared teachers to resort to creative options, such as creating their own images during the classroom activities;
- and presumably other factors that would be identified by additional specific investigations.

All this is directly responsible of the inadequate development of students' visual literacy. As a consequence, students are deprived:

- of the clarifications that can be provided through images;
- of the possibility of acquiring/building mental images in relation to the sciences;
- of the greater familiarity with concepts and descriptions that results from the communication immediateness of imagery.

In addition, the difficulties associated with the use of a second language decrease the efficacy of verbal or written communication, including when this communication is meant to provide guidance to the reading and interpretation of images. This constitutes an additional difficulty to the development of visual literacy that is difficult to address even at the tertiary level.

The combination of all these factors is responsible for the nearly absence of science-related mental images by students entering the first university year, as well as for their difficulties at benefiting from the use of imagery during the teaching/learning activities. The consequences on conceptual understanding in chemistry are documented in the next sections, through detailed consideration of some crucial aspects.

The Impact of the Absence of Mental Images About the World of Molecules

Students entering the first year chemistry courses show scarcity or total absence of abilities to use or create mental "chemical" representations, with the only exception of few – often not adequately rigorous – representations that they have memorised and reproduce in whatever situation. This shows that, in the rare instances when representations have been presented, they have just been incorporated into the passive memorisation option that is so widely spread in pre-university instruction. A typical example are the obsolete models of molecules built from planetary-modelled atoms, that often constitute the only chemical images incoming students possess and that are particularly inappropriate, because they suggest – as consistent inferences – a number of misconceptions, first of all the perception/conviction that molecules are planar (Mammino, 2002a).

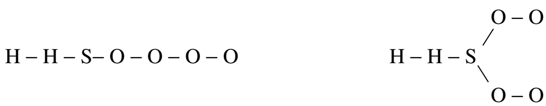
It can be noted that the frequency of non-rigorous representations provided in pre-university instruction appears to be higher in disadvantaged contexts. The causes would require further investigation, but the replacement of obsolete representations (or of any type of obsolete information) would require teachers' in-service upgrading. This in-service would need to contain adequate debates on the content and conceptual aspects of the courses and would also need to be capable of overcoming the common inertia to changes of perspectives. This, in turn, would require the availability of a sufficient number of instructors to realise the upgrading activities.

Given the situation, it becomes necessary to diagnose both the absence of mental representations and the possible presence of incorrect or obsolete ones, on working with incoming students. Experience shows that, for addressing measures to have some efficacy, the diagnosis needs to be made as early as possible, and needs to be shared with the students. This means that even the diagnostic part is integrated into the classroom interactions, with the objective of fostering students' awareness of their own inadequacies and initialising their engagement as early as possible. In this way, interactions aim at awakening students' attention and mental engagement, so that they recognise the need for critical revisions of the information they might have already acquired and become ready to respond actively to explanations and clarifications, or to personally seek for them. Furthermore, this mode of operating is in line with transparency criteria and with the conviction that students need to be involved in all the aspects of their education, so that they can also know (and evaluate) the motivations of the teacher's interventions or options-selection. Diagnosis and explanations can integrate within the same exercises at classroom level, in sequences whose main framework can be pre-designed, but needs to remain sufficiently flexible to make allowance for all the new features that may stem from the spontaneity inherent to interactions.

The absence of representations of molecules is a typical example of the nearly total absence of chemical mental representations. It is also the most serious because chemistry is the science of molecules. Therefore, it is an aspect that needs addressing since the beginning of the course. One of the first diagnostic exercises proposed to students entering the first year general chemistry course (already in the second or third week of the course) is to ask them to draw their representation of a water molecule. Some students (a rather small minority) start with the planetary model of the O atom and the two H atoms, with shared electron pairs on the circles, while the other students simply wait. When the former are asked to explain the meaning of their drawings, they are usually unable to do so. In particular, they appear not to be aware that each planetary system represents an atom – what is in line with the frequent inadequate awareness that molecules are objects made of atoms, or that these atoms build a structure and that this structure is three-dimensional. Those drawings appear thus to be solely the result of passive memorisation (a sort of regurgitation), without any reflection on their meaning or implications (reflections that have probably never been stimulated).

Immediately afterwards, a hint on how to draw the models is provided, by inviting students to try and represent the atoms with spheres (with the element symbols inside each sphere) and the bonds with segments, and providing the additional information that the H atom is capable to form only one bond. At this stage, most students draw the spheres in a straight line, in the same sequence as they appear in the formula, i.e., in the H−H−O sequence.

Similar responses are observed when students are asked to draw models of other molecules on the basis of purely geometrical information – exercises that are considered relevant for the familiarisation with molecules (Mammino, 1994, 1999a, 2003). For instance, in the case of the H_2SO_4 molecule, the following geometric information is provided: no H atom is bonded to the S atom; no H atom is bonded to another H atom; no O atom is bonded to another O atom; the H atom can make only one bond. However, models corresponding to the same sequence as in the formula appear frequently in students' answers, with the two following most frequent frames:



The responsibility for answers of this type can be traced to the absence of mental representations of molecules as well as to poor visual literacy in general. Exercises of this type could be viewed as sort of puzzles: putting some pieces together, knowing certain constraints. But such an operation requires enough visual literacy to mentally view the pieces (the atoms) and the constraints (the geometrical information), anticipating the mutual organisation of the pieces, and this literacy is largely absent.

Understanding what molecules do is essential to the understanding of the chemical reaction phenomenon. The topic is generally introduced within the first month of the first year general chemistry course. The main inadequacies or mistakes in students' pre-conceptions, as well as in their understanding of classroom explanations, are clearly highlighted by very simple representation exercises focusing directly on the meaning of "reaction" (on what a chemical reaction is). For instance, after balancing the chemical equation for the formation of HCl or water, students are asked to represent the initial and the final situations in separate drawings. The initial situation is usually represented correctly, i.e., with molecules in proper proportions under the corresponding formulas in the left hand side of the chemical equation. For the final situation, they re-write the chemical equation (since a separate image is required), but they maintain the models of the molecules of the reactants under their formulas on the left side of the arrow, and they often assemble all the initial atoms into one structure under the formulas of the products on the right side of the arrow. These drawings have a high diagnostic role, highlighting the conceptual misunderstandings about the nature of the process and its major aspects:

- The permanence of the models of the reactants molecules in the representation of the final situation shows inadequate understanding/internalisation of the fact that the molecules of the reactants are destroyed during the chemical reaction and, therefore, they are not present at the end (the introduction of the chemical reaction concept in the initial part of the first year course does not yet include chemical equilibrium, for obvious gradualist reasons in "building up" the conceptual content of the course).
- The fact that one all-including structure is drawn on the products side for the final situation shows inadequate understanding/internalisation of:
    - the fact that new molecules are formed, and that they are not juxtapositions of the initial molecules, but have their own (different) structures;
    - the role of stoichiometric coefficients, as providing information about the number of molecules of each substance involved. These coefficients are present even in the simplest examples considered, like the formation of the water molecule or the hydrogen halogenides molecules. For instance, the model representing a 4-atom structure (two H atoms and two I atoms, alternating in a square cyclic structure), often drawn under the "2 HI" in the right side of the reaction for the formation of HI, shows unclear understanding that it means "two HI molecules" (besides highlighting the lack of transfer of the information acquired under a different "chapter", since, at this stage, students have already repeatedly encountered the information that the H atom makes only one bond).

Many errors encountered in the writing and balancing of chemical equations can also be ascribed to the absence of mental representations of molecules. Equations like $S + O_3 \rightarrow SO_3$, and many others containing similar mistakes, arise from the lack of internalization of the meaning of the indexes in chemical formulas – an internalization that is possible only through adequate presentation and discussion of models of molecules (Mammino, 1994, 2003).

Another theme for which the absence of mental representations of molecules, and the lack of familiarity with the use of such representations, heavily hampers conceptual understanding, is the broad issue of chemical bonding. At exercise level, students find it difficult to extend, to analogous cases, the information and description discussed for a given case. For example, the formation of the bond in the HCl molecule is often discussed in detail at classroom level, with representation (on the board) as an integral part of the explanation (visualising the separate atoms, with their half-occupied 1s and $3p_z$ orbitals respectively and the caption “separate atoms” underneath and, on a subsequent image, the overlap of the two orbitals with the caption “HCl molecule” underneath). But when the students are asked to describe the formation of the bond in the HBr or HI molecule, they find it difficult to follow a similar description pattern, and the images with which they accompany their description are often absurd. In particular, they find it difficult to clearly identify the “isolated atoms” and “molecule” concepts and to recognise the analogies between the $4p_z$ or $5p_z$ orbitals of the halogen atoms, involved in the formation of the HBr and HI molecules respectively, and the $3p_z$ orbital of Cl, involved in the formation of the HCl molecule. Though, at first glance, these exercises would appear to imply nearly mechanical reproductions of an already given pattern, this is not the case when the pattern itself is not recognised. The difficulties encountered by students show the combined impact of inadequate background preparation, inadequate visual literacy and inadequate language mastering, made more evident by not being shadowed by the regurgitation of memorised material. The exercises are typical examples of cases in which passive memorisation cannot be of any use, because it is necessary to identify and understand all the details of the information presented (including all the details of external representations) in order to be able to discuss an analogous case. The outcomes also suggest that inadequate visual literacy is less apt to be shadowed by regurgitation of passively memorised material than inadequacies at text-understanding because, in images, the number of details is reduced with respect to a text, but the details that are needed are those corresponding to the key aspects of conceptual understanding (by its nature, an image implies a selection of the key aspects with respect to a text).

Inadequate visual literacy and inadequate drawing mastering often prevent even senior students from incorporating finer details into their drawings, like using spheres of different sizes for different atoms (e.g., making the hydrogen atom smaller than the other). It also affects purely copying operations. For instance, some B.Sc. Hons students taking the quantum chemistry course, on copying molecular geometries from simple stick-and-balls software-constructed models, drew all the bond angles as 90° angles, what can only be due to inadequate ability at reading the information conveyed by the image (on the computer screen) that they are trying to reproduce, or to inadequate drawing mastering, or to both.

The Interpretation of Symbolic Visual Representations

Reading symbolic external representations requires the awareness of their symbolic nature as well as the awareness of their roles and usefulness. Inadequate visual literacy, combined with inadequate familiarity with the scientific approach (e.g., the role of mathematics as a tool for description and prediction) results in failure to recognise the symbolic character of many representations, in realistic (literal) interpretations of symbolic representations and in consequent generation of misconceptions. Typical examples are the literal interpretations of the symbolic representations of:

- entities of the microscopic world, like electrons (e.g., the conviction that *electrons have the shape of small arrows*, expressed by many first year students);
- non-visualisable physical quantities, like the spin (also often identified as an arrow, or as the direction of the arrow-shaped electron, or even replacing the role of the electron altogether, as indicated by statements like "*each orbital contains two spins, one opposite the other*");
- mathematically-generated entities, like orbitals.

The difficulties at distinguishing between reality and symbolic representations are aggravated in second-language contexts, because the use of a second language, with the inadequate (not sufficiently sophisticated) level of mastering common among science students, enables solely the understanding of simple sentences and simply-expressed concepts. Explanations of method-relates aspects, like the meaning and role of symbolic representations, often require a higher level of language mastering to be understood sufficiently enough as to be at least partially internalised. This constitutes a clear example of mutual aggravation of language-related difficulties and difficulties arising from poor visual literacy.

A more detailed consideration of the case of atomic orbitals and electron configurations may better highlight the complexity of representing certain aspects of our description of the microscopic world and the difficulty of designing representations that do not indirectly suggest misconceptions. The complexity is probably maximum in this case (at least, among the material commonly presented at first and second year levels) because the images need to simultaneously represent non-visible, and even non well-definable, objects (electrons), non-visualisable physical quantities (spin) and mathematical functions (orbitals).

The selection of the symbols for this representation is the most delicate issue, because of the perceptions that the symbols might generate. For instance, the use of boxes to represent atomic orbitals favours the misconception that orbi*tal are some sort of boxes located inside the atoms* (a conviction expressed in these very terms by a number of students). In addition, the use of contiguous boxes for degenerate orbitals

2p 3d

generates the misconception that they consist of a single orbital divided into compartments, as expressed in students' works by sentences like:

The p orbital consists of three connected squares, and each square can receive two electrons.

The sentence also highlights the inference that the orbitals (and, consequently, the atom) are two-dimensional (an inference that is also strongly suggested by the planetary models of the atom utilised in the explanation of chemical bonding (Mammino, 2002a)). Other students, on recalling the boxes, express uncertainty as to whether orbitals and atoms are 2- or 3- dimensional:

An orbital is a region/area in an atom where there is a probability of finding an electron.

Other misleading representations of electronic configurations are encountered in the description of the formation of chemical bonds. Some teaching materials utilised at pre-university level illustrate the attainment of the octet by showing completely occupied boxes for individual atoms. E.g., for the chlorine molecule (Cl_2), the provided representations have the following appearance:

↑↓	↑↓	↑↓

3p orbitals of the first Cl atom

↑↓	↑↓	↑↓

3p orbitals of the second Cl atom

This type of representation would be correct only for negative monoatomic ions in ionic compounds. It is not correct for the other cases. Most students infer that these molecules consist of ions. When they write sentences like

The Cl_2 molecule consists of two Cl^- ions

they justify the statement through those images. In this way, students develop misconceptions by deriving consistent inferences from non-rigorous (or straightforward erroneous) images provided to them. The example shows that students may be able to derive consistent inferences from the images provided, but they are not able to criticise an image, or to realise that the inference, though consistent with the image, is absurd (two negative ions do not bond to each other) and, therefore, to go back to the image and question it. Such ability to critical thinking is probably not very common in any context, but it is unavoidably much rarer in a context where students have been deprived of the reflection abilities fostered by interactions and by the full utilisation of the resources of the language (what is initially possible only through the mother tongue, and becomes possible in a second language only after it has been acquired through the mother tongue).

Diagrams – the Representation of Abstract Thinking

Diagrams represent those features of phenomena that can be described mathematically. Their interpretation requires abilities depending on the ability to relate concepts, their language expression, their mathematical translation and images, i.e., the ability to read symbolic representations and the ability to mutually relate mathematical descriptions and physical descriptions.

Inadequate awareness of the nature of symbolic representations often results in literal reading or interpretations of diagrams. For instance, students taking the second year chemical thermodynamics (physical chemistry) course, and recalling only the image representing a cyclic process, define a cycle in the following terms:

> A cycle is a process that occurs in the shape of a circle: the movements of the process occur in states that are encountered in a circle.

Insufficient abilities at mutually relating graphical representations and physical meanings result in the drawing of incorrect diagrams or even in incorrect interpretations of correct (often memorised) diagrams. Examples of the former type are the diagrams of the concentration of products versus time in a chemical reaction, often drawn by students of the third year physical chemistry course (chemical kinetics component). Many students draw a continuously increasing curve, what highlights inadequate understanding of the meaning of concentration and of the meaning of a continuously increasing diagram (it would mean that the concentration would become infinite). On the other hand, some students of the same course draw a correct diagram for the trend of the reaction rate versus time (a decreasing diagram, when autocatalysis is excluded) and then comment:

> The diagram shows that the reaction rate increases with time

what suggests that the diagram has been somehow memorised, but not understood, or that the concept-image association ability is not adequate even for concepts that are expected to be immediate, like the increasing or decreasing concepts (on the other hand, an influence of the inadequate word-concept association in a second language (Mammino, 2000a) cannot be excluded, and its presence and extent would require independent checking).

Several inadequacies in basic aspects of visual literacy are highlighted by the drawing of diagrams, both in relation to laboratory experiments and in relation to theoretical components of the course. For examples, it happens frequently that students do not use a constant scale on the same axis. The ability to mentally associate the length of an interval on a straight line (the length of a segment) with a range of numerical values is part of basic visual literacy: relating a visual feature (length) to measurement-results and their magnitude. Similarly, the ability to select the coordinates of key points according to the physical meaning of what is represented depends on the ability to read and interpret diagrams. E.g., when students, on representing the adiabatic expansion in the Carnot cycle, draw an end point corresponding to a smaller volume than the starting point, they fail to relate the expansion concept (increase in volume) to its graphical representation.

The drawing and annotation of diagrams require familiarity with at least the bases of the scientific method. For examples, the inadequate awareness of the distinction between systems and processes (Mammino, 2002b) results in incorrect annotations on diagrams. This is, e.g., the case of second year students representing an adiabatic process and an isothermal process starting from the same initial situation by two different curves and annotating them as *isothermic system* and *adiabatic system* (a system cannot be represented by a curve; only the trend of variables and, therefore, aspects relative to processes, can be represented by curves on a Cartesian diagram).

Strategies

The Design and Implementation of Strategies

The design of strategies to effectively utilise representations as a teaching/learning tool, notwithstanding the difficulties arising from the under-preparedness and poor visual literacy of incoming students on one hand, and the constraints posed by limited resources on the other, requires accurate preparation and reflection. Such design needs to take into account and integrate general pedagogical knowledge and the aspects of the local context. It therefore needs to:

- be based on diagnosed students' difficulties - as the starting information identifying the needs that are typical of a given context - and take into account all the details of those difficulties, because each detail needs to be addressed in a specific way;
- integrate the presentation of images to illustrate and clarify concepts with the stimulation of a gradual development of students' abilities towards imagery, as the course proceeds;
- being implement able without sophisticated facilities, mostly (or, better, totally) by using a white board and coloured markers;
- provide for continuous checking through interactions with students, and utilise the outcomes of this same checking for continuous optimisations of the approaches.

The design of strategies also needs to take into account the requirements related to the nature and objectives of representation. Imagery is a form of communication. Like all communications in the sciences, it needs to respond to the requirements of the *language of science*: being rigorous, clear and simple (Mammino, 1995, 2006). The requirement of rigour is the most fundamental, since it relates to the correctness of what is communicated (including both the most evident/straightforward messages and the implications stemming from them). On using imagery within interactive approaches, pursuing rigour becomes an excellent tool for explanations and clarifications (Mammino, 2000b) and for the prevention of misconceptions. Systematic attention to rigour integrates well with all the practical options that can be designed, selected and adopted, and makes them more effective.

Particular context-related perceptions or responses also need to be taken into adequate account. For example, students entering the first year university have shown a sort of psychological refusal when first asked to draw images. An investigation about the reasons highlighted the perception that being asked to draw images was not in line with their novel status of university students, that it would be more appropriate for junior students. Perceptions like this, once identified, need timely addressing, if one wants to utilise external representations in an effective way (Mammino, 2002a). Experience shows that the difficulty can be overcome by informing students that external representation is an integral component of the study of molecules at research level, above all in advanced branches of chemistry like computational chemistry. This information, by establishing external representation as a tool for advanced science work, deprives the previous, uninformed perception of any ground, thus enabling students' acceptance of the use of representations within the course.

Other context-related reasons make the resort to poor materials (pebbles, coloured berries etc.) non-viable, not acceptable to university students, both because those materials would be perceived as apt for activities at primary or junior school levels and because they would be perceived as discriminatory (students will obviously know or assume that such activities would not be carried out in "advantaged" tertiary-level institutions). Drawing, on the board or in their notebooks, remains therefore the most viable resort, since it can be presented and perceived as a fully professional activity that integrates with the explanations and discussions. It is thus necessary to ensure maximum benefits from its use.

The maximisation of benefits is better pursued within interactive teaching/learning options, that enable the combination of the advantages of interactions and the advantages of external representations (Mammino, 1999a), not only as a pure sum, but with mutual enhancement of the benefits (more or less in the way in which the $2ab$ term adds to the pure $a^2 + b^2$ sum in the development of $(a + b)^2$). Classroom interactions (Brewer, 1985; Forman & Cazden, 1985) stimulate and maintain students' attention towards the material discussed, enable students to catch details that would otherwise remain unnoticed, prevent the insurgence of passive attitudes and provide an immediate-type feedback to the teacher, thus enabling immediate responses, both in terms of specific clarifications and in terms of more refined "tuning" of the overall explanation to the needs of the students. Representation is an optimal instrument to attract students' attention on all the relevant aspects of each issue, and to stimulate reflections on, and discussion of, each aspect. Representation-based discussions:

- expand the diversity of teaching/learning tools and of the prospectives from which concepts and descriptions are considered;
- favour the generation of mental images and ensure that mental representations are correct, thus establishing fundamental bases for further learning.

Considerable difficulties towards classroom interactions are diagnosed, above all at first year level, because incoming students are not used to them. Interviews highlight that, besides the lack of habit or familiarity with classroom interactions, other factors make it uncomfortable for students to answer questions and generally to intervene in the classroom set up. Language-related difficulties (inadequate mastering of English, the second language that is the medium of instruction) have major impacts in hampering the level of communication abilities that is needed for interactions. They also have major responsibility for the lack of interactions at previous-instruction level, as clearly expressed in the findings reported by Dube, (1992), diagnosing "breakdowns in communication between teachers and their pupils which in many cases lead to the formation of inaccurate concepts among learners" and suggesting that one cause of this was the "lack of opportunity for pupils to take an active role in the learning process" and the scarcity of "pupil-initiated exchanges during lessons". It is what Nyapfeme and Letseka (1995) call the "linguistically based inability to receive and communicate information". Besides the objective limitations in communication abilities, the awareness of their inadequate mastering of English causes uncomfort and shyness at expressing things without being sure of expressing them correctly.

Though it is not possible, within a chemistry course, to effectively address language-related difficulties, it becomes necessary to overcome at least the psychological and emotional difficulties towards interactions, to guide students to gradually develop the conviction that the interactive option is more interesting and that, if they accept it and take part in it, it is more beneficial for them. This attitude-shift also requires a particular struggle against the tendency to passive memorization. The tendency is so dominant that students memorize any type of material: the course handouts, the answers to tests, the solutions of any problem discussed during the course. Then, they tend to reproduce/regurgitate the memorized parts, often in such a passive way that they do not even check whether the material that they reproduce is related to the question they want to answer in a given moment (the extreme cases being the use of numerical values, memorized from some example-problem within a new similar problem having different data-values). Memorization is antithetical to interactions: passive memorization does not involve understanding, while interactions require understanding and aim at enhancing understanding. Therefore, the core of the desired attitude-shift is from passivity to understanding. This, in turn, can be viewed as an essential component of a general shift from lack of independence to independence. Students' "inadequate independence" is in general a major cause of the difficulties associated with the transition from secondary school to university (Chipere, 1993). Developing the ability to interactions necessarily requires the acquisition of a certain degree of independence, because only an independent piece of thought can result in "something to say" from the student's side.

A variety of strategies have been utilised to convince students (sometimes even to gently force them initially) to accept interactions, like:

- asking students to write their answers (and the lecturer checks a good number of them and proposes the most significant for discussion), until students themselves spontaneously grow tired of the practice and make attempts to answer verbally;
- simply informing students that the lecturer will continue waiting until one or more of them accept/attempt to give an answer;
- moving very close to those students who try to answer, but do so by barely whispering (then the lecturer repeats the inaudible answers loudly and proposes them for discussion).

A detailed discussion of the way these options facilitate the initiation of interactions would go beyond the scope of the current work; but the quick mention just made is important to better outline the overall situation and the pedagogical approach, as well as to the further discussion of the role of representation as an interaction tool.

Additional difficulties arise in large groups. The first year group consists of 370–385 students, all taking the lectures together, and comprising students from different faculties (mathematics and natural sciences, environmental sciences, agriculture, nursing sciences). Under these circumstances, intensive participation of each and every student in the interactions becomes unrealistic. However, it is important that students participate as much as the circumstances allow, so that, for each question or issue, a representative sampling of answers and opinions is gathered and utilised for discussions and clarifications. This also concerns the use of imagery. For example, the diagnostic utilisation of imagery can cover every student in the smaller 2nd year and 3rd year groups, while only representative samplings are possible in the large 1st year group. However, even in this large group, each student needs to be put in a position to perceive that he/she is engaged in the common work and is object of attention. This is possible only if the sampling (the drawings actually checked by the lecturer and made object of discussion, for each exercise proposed) is sufficiently representative to have high probability to cover all the most common interpretations, alternative conceptions, misconceptions or errors. The teacher's experience with previous groups (in previous academic years) provides guidelines to estimate the representativeness of the sampling and to enlarge it when needed.

The criteria outlined in the previous subsections constitute fundamental references and guidelines in the design of approaches. Concrete illustration of such roles requires the consideration of practical examples. A broad range of examples is already available, but the space of a chapter does not allow detailed consideration of all (or even only a considerable number) of them. The most viable option is therefore the consideration/selection of some crucial issues, and a brief presentation of how their main features are addressed. It was considered important to select issues that are representative of fundamental aspects in relation to the care for pedagogical efficiency, for the paramount role of the content (the conceptual/understanding component) in science courses, and for the attention to the basic features of the scientific method. The following issues are selected as crucial and are analyzed under individual sections:

- the use of external representations to engage students' attention and foster their active participation;
- the design of options for those aspects/themes where understanding and expertise depend on an adequate degree of the ability to abstract thinking;
- the difficult issue of analogies – an issue bordering/overlapping with representations and requiring an adequate dose of critical thinking.

Attracting and retaining students' attention is one of the most difficult tasks in a teaching activity. Ensuring their active participation throughout an activity (a lecture, a tutorial) is expected to correspond to maximum pedagogical efficiency. Two representation-based options are considered here in this regard: the construction of representations and the analysis of errors.

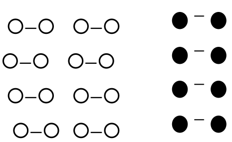
Representations-based exercises can have an initially diagnostic purpose (as described in Section 9.3), aiming at identifying the presence or absence of mental representations, their correctness when present, or how students respond on being asked to represent something through an representation – what, for many of them, implies having to think in terms of representations for the first time in their educational careers. Each diagnosis is immediately followed by addressing activities, like the ones outlined in the next paragraphs.

The diagnosis of absence of mental representations implies the need to generate some and, therefore, addressing approaches require both the selection of which ones are more important to generate (in terms of the information/messages they convey) and the selection of the actual representations to be proposed as integral part of the development of the course content.

The diagnosis of incorrect representations implies the need to replace them with correct ones. To increase the impact of the corrections, students need to be engaged as actively as possible in the correction itself. This is pursued through the collaborative construction of new representations, where the teacher provides guidance and – above all in large groups (like, e.g., the first year group) – does the actual drawing, on the basis of students' suggestions. It is important that the teacher implements students' suggestions also when they are not correct, because this offers the opportunity of clarifications utilising all the explanation power of the analysis of errors. Any incorrect suggestion, after being implemented, is immediately proposed for discussion. For example, in a collaborative construction of stick-and-balls models of molecules, the teacher attracts students' attention on the constraints (number of bonds for each atom and any structural information given), draws what students suggest and then highlights whether a given suggestion complies with the constraints or violates them.

The collaborative construction of representations representing the initial and final situation of a chemical reaction develops through several learning stages. A first stage is static, aimed at highlighting the reasons why it is necessary to balance chemical equations. Models of molecules are drawn under the corresponding formulas of the chemical equation, so that students can count the atoms of each type and ensure that no atom is created or destroyed. This, however, is still a static vision, it does not convey the perception of a process taking place; in particular, it is not adequate to correct the incorrect representations drawn by students as "final situation". A subsequent stage tries to focus on the process by visualising what happens and attempting to mimic the progress of the reaction, as much as enabled by the use of a pen and a board. For instance, for the formation reaction of water, a pre-selected initial situation, with molecules in stoichiometric proportions, is drawn on the board and proposed to students:

$$\mathbf{2\,H_2 \quad + \quad O_2 \quad \text{-------}> \quad 2\,H_2O}$$



Then students are asked to consider that one oxygen molecule reacts and to help draw the new situation. This implies drawing two water molecules on the right and erasing one oxygen molecule and two hydrogen molecules from the left. The physical (manual) action of erasing molecules from the left in order to draw new ones on the right is the best approximation to the *ongoing process* concept that can be achieved by using a pen and a piece of paper or a board. It is convincing for students, and the exercise continues until all the molecules of the reactants have been erased. In this way, the "final situation" is reached by mimicking the process, and the correct representation acquires the convincing power of something that has been built gradually, with all the motivations explained and, above all, with the lecturer following the students' indications (i.e., with students being the ones that actively decide each step).

Analogous exercises are proposed utilising different reactions, to prevent the risk that somebody might consider the process and the conclusions as valid only for one reaction. Analogous exercises are also utilised to illustrate the *limiting reactant* concept. E.g., by starting with the same 12 hydrogen molecules as in the previous example and 10 oxygen molecules and repeating the procedure, four oxygen molecules remain on the left when no hydrogen molecules are available. In spite of the drawing conveying a clear message, it requires also the assistance of the lecturer for students to conclude that those molecules cannot react for lack of the other reactant (several students appear inclined to combine them into a supermolecular structure, rather than leaving them unreacted).

Many topics offer opportunities for collaborative constructions of representations, with the attention focusing of those aspects that students find more difficult. For instance, phenomena concerning solutions can be clarified by counting the particles of solute (or solutes) and considering the volumes of solvent, while building the representations. These exercises are carried out along the lines depicted in (Mammino, 2003) and with the same type of representations. They consider dilution and all the various possibilities of mixing of solutions (mixing two solutions of the same solute, with different concentrations; mixing two solutions containing different solutes; mixing two electrolytic solutions with a common ion). For each case, students have to decide the number of small spheres representing the solute/s particles and the volume of resulting solutions. Students' suggestions about volumes are usually correct, but the suggestions about the number of solute particles are often incorrect, e.g., several students wish to maintain the same "crowding" of solute particles (number of particles per unit volume) rather to maintain the same total number of solute particles on dilution. This difference is in line with the greater difficulties at imagining/understanding the microscopic level (number of particles and how they are distributed) than the macroscopic one (what happens to volumes when the content of one container is poured into another container already containing a certain amount of liquid). Suggested incorrect options are immediately discussed against the conceptual or practical information or the definition to which they refer.

The analysis of errors is a powerful tool for explanation (Mammino, 1996; Love & Mammino, 1997). The use of representations enables two types of identification, discussion and correction of errors:

- The correction of errors highlighted by the representations drawn by students. This is carried out mainly through the collaborative construction of representations, outlined previously, when the group is large, but also through the discussion of interesting incorrect representations identified (by sampling) in students' individual works. When the size of the group enables it, all the drawings by individual students are discussed, and the collaborative construction follows the discussion (so that it can benefit from it).
- The use of representations to illustrate the meaning of incorrect statements in an immediately understandable way. This proves particularly useful for errors concerning the distinction between the microscopic world and the macroscopic world, for language-related errors and for errors stemming from the combination of these two aspects.

Representations drawn by students provide the broadest variety of diagnostic information and, therefore, of errors that require analysis. For this reason, it is important that students draw representations independently (not only during classroom activities) to prevent the risk that diffuse or serious misconceptions fail to surface and be discussed/addressed. During activities like the collaborative construction of representations, incorrect suggestions are visualised and discussed immediately, when the construction of the representation is still in progress, and, therefore, only some misconceptions are identified (e.g., the idea that, on dilution, the "crowding" of solute particles remains the same), while the timely correction prevents the surfacing of others. A more complete identification of alternative representations is linked to activities in which students first draw their own representations, and the representations are discussed in a second moment. Therefore, individual drawing of representations needs to be allowed enough space (as much as compatible with the group size), to enhance the probability of "picking up" as many errors as possible for analysis.

Errors in which it is particularly difficult to untangle language-related components and the unclear distinction between the microscopic and the macroscopic worlds are often encountered in the description of gases. Statements like

> Gases move along straight lines and collide with each other.

are very frequent. The illustration of the literal meaning, by drawing two gas cylinders moving towards each other and colliding makes students laugh (the world *gases* pertains to the macroscopic description and, therefore, the container is the only possible representation). The representation impresses some students deeply enough for them to afterwards remember that *gases* and *gas molecules* are different subjects and can do different things and, therefore, it is necessary to distinguish clearly between what *gases* (macroscopic entities) are doing and what their *molecules* (microscopic entities) are doing. The same approach is utilised for the discussion/correction of statements containing conceptually analogous errors, like:

> For a reaction to occur, the reactants must collide.

(the collisions concern the molecules of the reactants, and it is important to refer to molecules to understand the collision theory of chemical reactions).

Unfortunately, the improvement obtained through external representations is not always satisfactory when language-related issues are the main or sole causes of a given mistake. For example, representations illustrating that a bond *in* a molecule (e.g., the O-H bond in the water molecule) is inside the molecule itself, while a bond *between* molecules (e.g., the hydrogen bond between two water molecules) links two individual molecules, have increased the correct focus of the answers to questions of this type (by first year students) from 35–45 % to 45–55 %, but not more - the habit to a random (without distinction of meaning or functions) use of the *in* and *between* prepositions overcoming the impact of the explanations and the power of representation (Mammino, 2006a). This can be considered a further documentation of the extent of the impact of using a second language as medium of instruction (the word-concept and sound-concept association being much more deeply internalised in the mother tongue (Mammino, 2006b).

There are also some cases in which the representation of errors is better restricted to individual discussions with the students making them, to prevent the risk of spreading of absurd representations. Examples of this type are the following chaotic (and meaningless) descriptions of the outcomes of chemical bonding:

> In the HCl molecule, a partially positive ion attracts a partially negative ion from the other atom.
> In the Cl_2 molecule, the nucleus between the two atoms attracts electrons for each atom.
> In the Cl_2 molecule, the two C-Cl are set in the region between the nuclei.
> In the Cl_2 molecule, the two chlorine atoms will spend most of their time between the nucleus, in that way are sharing electron.

The statements clearly highlight the total absence of mental representations of atoms and molecules. The first sentence suggests the idea that ions are something on the atom, not the atom itself (that has simply acquired a charge). The other sentences highlight great confusion about where nuclei are located, or representations in which they are entities independent of the atoms. Students who write sentences of this type are usually unable to utilise drawings to explain what message/information they wished to convey. However, representations, in which the ideas expressed by these sentences are depicted, are better utilised for individual explanations, to prevent some of them from entering and undesirably remaining in the ensemble of mental representations that students are encouraged to develop during the course.

Visualizing Beyond the Representation of Objects

The cases considered in the previous sections refer to the description of objects (e.g., the three-dimension structure of molecules) and what they do (what happens to molecules in a chemical reactions, what happens to the solute particles on dilution, etc.). Representation can go beyond that, and provide representations of entities and aspects related to our models, or to our way of studying phenomena. Some options in this regard are considered in the following subsections.

There are items for which whichever representation might be utilised will not correspond to reality. In such cases, the main objective is that of preventing the generation of misconceptions, and this objective might be better pursued by the use of more abstract symbols, i.e., symbols that do not recall any type of concrete representation that would not correspond to reality. This is the case, e.g., of orbitals and electron configurations. As already mentioned, representing orbitals with boxes suggests actual two- or three-dimension boxes into which electrons take lodgings, and representing degenerate orbitals as consecutive boxes generates the additional misconception of a bigger box partitioned into three (or five, or seven) smaller ones. It was therefore decided to use more abstract symbols – short horizontal segments, clearly separated and only aligned (horizontally) when they represent degenerate orbitals – to represent the orbitals in order of increasing energy and to visualise electronic configurations (Mammino, 1994, 2003). Unlike boxes, segments do not correspond to any object that students can imagine as being "inside the atom" and, therefore, they are more compatible with the kind of abstract thinking that corresponds to the terms of the mathematical description of the microscopic world. So far, no student has interpreted these drawings in terms of orbitals being segments, or the atoms containing segments inside, or electrons lodging on top of segments, what confirms that the choice is viable. Moreover, the separation of the segments representing degenerate orbitals has prevented the idea that they might be compartments of a single entity.

The reasons for preferring segments are clearly discussed with students, in relation to the nature of the entities we want to represent. On the other hand, changing previously learnt and internalised representations is not easy, and the early internalisations often re-surface when students are under stress; e.g., when they write tests and exams, a number of students go back to the use of boxes in their symbolic representation and to answers repeating the misconceptions that the use of segments is trying to correct. Though a systematic study of the re-surfacing of initial representations/conceptions in conditions of higher stress is still to be carried out, the observation of its occurrence is considered an indication of the deeper internalisation level of the concepts and representations encountered in the first encounter with a given subject and, therefore, also an indication in support of the need of extreme rigour even for and within the simplified presentation of concepts that is unavoidable in pre-university instruction (Mammino, 1999c, 1999d).

Understanding sets of logical steps, and the connections between individual steps, is not easy for students. Doing it through a second language increases the difficulties enormously, since logic is the component that remains more difficult through a second language, if it has not previously been learnt through the mother tongue (Rubanza, 2002; Mammino, 2005a). On the other hand, there are courses in which it is unavoidable to introduce procedures with complex logic, like the Hartree procedure for the study of multi-electron atoms or the Hartree-Fock procedure for the study of molecules in quantum chemistry courses. Then, the collaborative construction of representations is applied to a collaborative construction of flow-charts, accurately based on the reading and interpretation of the textbook and extensively guided by the teacher (Mammino, 1998c, 2005b). In this way, the need to build subsequent entries in the flow chart prompts the identification of the logic of the text and the exercise becomes also a form of training to the reading of scientific literature.

Attempts to build flow charts to illustrate the logic behind certain inferences or conclusions have also been carried out, but not yet in a systematic way. An example is the illustration of the inference that electrolytic solutions contain ions, where two independent trends of interpretations of experimental observations combine to yield the inference (see Fig. 8.1). The resort to a flow chart was prompted by the observation of particular difficulties in identifying the presence of two separate "information + interpretation" sets and the additional interpretation stemming from their convergence.

Mathematics involves representation as an integral component: both Euclidean geometry and analytical geometry (study of functions) utilise representations (representations of geometrical entities, diagrams). When mathematics is utilised as a description tool in physical sciences, the representation becomes associated with physical meanings:

- it represents trends and enables predictions;
- it is fundamental for the identification of regularities (including laws).

In disadvantaged contexts, the familiarity with mathematics is often inadequate, the familiarity with its descriptive role in physical sciences is even lower and the inadequate visual literacy reduces or prevents the benefits of the communication

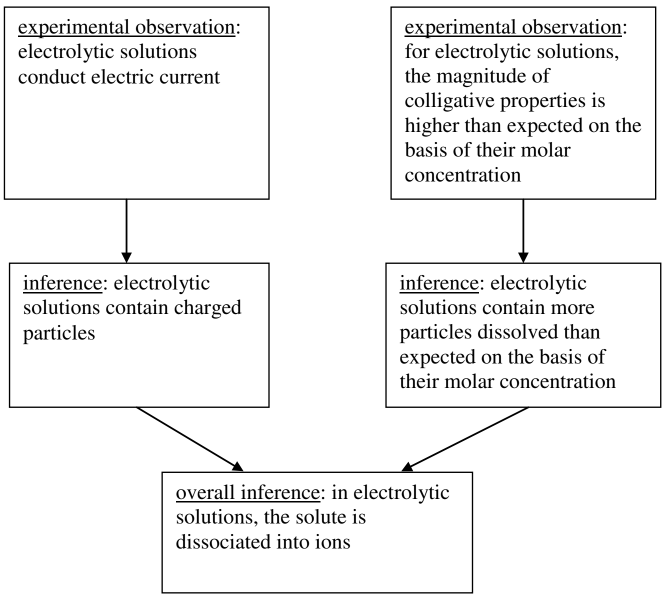


Fig. 8.1 Flow chart highlighting the logic of the reasoning that led to the conclusion that electrolytic solutions contain ions dissolved

immediateness of diagram representations. Addressing options focus mainly on the translation from one to the other modes of descriptions: description through words, through equations and through diagrams.

The first exercises of this type come rather early during the first year general chemistry course, with reference to the laws of ideal gases. Experience has shown widely spread presence of misconceptions for the *direct proportionality* and *inverse proportionality* concepts, with the respective incorrect definitions "two quantities, x and y, are directly proportional if y increases when x increases" and "two quantities, x and y, are inversely proportional if y decreases when x increases". Attempts to counteract these misconceptions simply by providing the correct statements or by providing and discussing the corresponding equations, did not have a great impact. The corrective option that has proved more effective utilises representation through diagrams. The lecturer draws several diagrams responding to the criterion "y increases as x increases" (or to the criterion "y decreases as x increases") and asks the students to choose which one represents direct proportionality (or inverse proportionality). The first effect on students is the realisation that there are several options corresponding to each of their definitions, and only one of them can be called *direct proportionality* (or *inverse proportionality*). This visual "shock" sets the ground for the acceptance of the correction. Then, the corresponding equations are written, and the description through words (definitions) comes last.

The translation from one form of description to another (language, equations and diagrams) is continued throughout the courses, either through exercises (within classroom interactions) or as a normal component of new explanations. However, in spite of improvements, some difficulties persist even in advanced courses, as highlighted by the diagrams and their interpretations provided by third year students during the chemical kinetic course. Moreover, resurfacing of the initially internalised conceptions appears in tests and exams. For instance, the impact of the initial definitions of direct and inverse proportionality that students had been provided in pre-university instruction resurfaces in statements considering quadratic or exponential dependences as "direct proportionality", what once more indicates that the most effective measure would be prevention, i.e., the provision of correct (strictly rigorous) definitions and representations since the students' first encounter with a concept.

Analogies are a form of representation that does not depict the object of attention, but something else, and requires to make comparisons and to focus on similarities, but also to be aware of differences. The use of analogies may be tricky, above all when the analogy refers to an object of the microscopic world. An illustrative example from the author's direct experience refers to the rather common comparison of Thomson's atom with a water melon. The students of a secondary school group (that the author was visiting, in Italy, several years ago) were happily answering a question about Thomson's atom by utilising the analogy: "Thomson's atom is like a water melon: the red pulp is both the mass and the positive charge, the seeds are the electrons imbedded in it". The dominance of the watermelon representation in the answers prompted the author to ask "and how big is the atom according to Thomson?" and the answer came immediately "Like a water melon".

Experiences of this type, and normal reflections, recommend the avoidance of analogies for objects. An object can be depicted through a representation representing it, even if it belongs to the microscopic world: there is no need for analogies. The situation may be different for concepts. Certain concepts benefit from analogies. The problem then becomes the appropriate selection of the analogy, both in terms of its effectiveness and in terms of conceptual rigour.

Analogies referring to familiar situations can prove the most effective. For example, it took a certain time to find an effective analogy for the *limiting reactant* concept. The old analogy of pairing people in a dance looses its meaning when a dance is a group issue and not a pairs issue; and even a "pairing" referred to marriage may not be so effective where polygamy is customarily accepted. The context itself offered the best analogy, once the realization of its efficacy came to the mind. As already mentioned, about 370–385 first year students attend the general chemistry lectures in a room with 150 seats, so that many students have to stand or sit on the floor or on the side-steps. Therefore, the "natural" analogy is between the number of seats and the number of students. And students find it easy to come to the conclusion that "the number of seats is the limiting factor" preventing the possibility that all the students sit on chairs, or that "the number of students is in excess with respect to the number of chairs" and "the students in excess cannot have a seat". Then, the terms of the analogy are extended to drawings using molecules of reactants in non-stoichiometric proportions, to conclude that part of the molecules of the reactant in excess cannot react.

The physical inadequacies of the context provided an effective analogy also for the *shielding* concept, a concept unfamiliar to many students, but needed in the discussion of the trend of the ionisation energy from top to bottom down a group. Representations showing increasing layers of internal shells in the atoms are obviously drawn on the board, but that by itself is not sufficient to explain the meaning of *shielding effect*. The overcrowding of lecturing facilities (and other factors) frequently cause a rather high level of external noise. This suggested the possibility of explaining the *shielding* concept through the way walls shield external noise (with suggestions like "if there were two walls, one after the other, would we hear more or less noise from the neighbouring room?"). The physical representations of the analogy facilitate the understanding of a general concept, after which that concept can be utilised for the theme under consideration.

The importance that analogies are referred to concepts and not to objects is further highlighted by the quantization concept. The common representation of a staircase results in a variety of incorrect ideas about what electrons might do (climbing upon something whose steps are the energy levels, etc.). If the analogy is totally separated from what electrons do, and focuses on the concept "a certain quantity is quantised", examples from everyday life can provide rigorous references. E.g., the distance from the ground of a person standing on a step of a stair (both feet on the same step in the drawings proposed to students) is quantised (Mammino, 1994, 2003). This analogy refers solely to the quantisation concept, without implying comparisons between objects of the microscopic world and objects of the macroscopic world, or suggestions on what the objects of the microscopic world might do. Therefore, it is conceptually and methodologically "clean".

Discussion and Conclusions

Representation plays essential roles in science and technology. It is an integral component of conceptual developments in mathematics (diagrams) and an essential design component in engineering. It is an enormously powerful tool for explanation in science education. In chemistry courses, it plays a fundamental role in the familiarization with the invisible world of atoms and molecules.

Teaching chemistry without external representations implies a terrible impoverishment in communication effectiveness, in understanding, in students' internalisation of concepts and in their perceptions of the subject. The situation of incoming students at UNIVEN, who have mostly been taught without (or nearly without) external representations in pre-university instruction, constitutes a clear illustration of the negative impact of the lack of visualization and the consequent lack of mental representations.

External representations can play important roles in addressing the factors that characterize disadvantaged contexts. However, the extent to which students can benefit from these representations is closely related to the extent of their visual literacy. Inadequate visual literacy, consequent to insufficient or null use of visualization in pre-university instruction, decreases the effectiveness of representation-based approaches that could be utilized to address the impacts of the factors affecting students' possibilities to acquire and master scientific knowledge - inadequate background familiarity with science and its approaches and poor language-mastering. It becomes necessary to design options for a guided use of representations, aimed at supporting the teaching and learning of the course content and, simultaneously, at enhancing students' visual literacy and their ability to read and interpret representations.

A professional situation with limited resources does not enable the access to sophisticated modes of external representations, like, e.g., students using representational software on computers in their personal work. On the other hand, many of the problems of a disadvantaged context would not be solved by standard representational tools, but require specific addressing and, therefore, specific design. Commercial representational software is not designed to address problems like inadequate visual literacy and the barriers associated with the use of a second language as medium of instruction (though they would undoubtedly be beneficial to students, once their visual literacy reaches an apt level). The options for the use of representations need to account for all the identified aspects of students' difficulties and respond to the changes from one group of students to another. At the same time – from a "material" point of view – the approaches need not to exceed the restrictions determined by inadequate availability of material resources.

The options designed and adopted within general and physical chemistry courses make use of classroom interaction as the best set-up to utilise visualization, and utilise drawings both for exercises directly engaging students and as an integral component of the presentation of new material. It is suggested that the usefulness of such options may extend beyond the context in which they were designed, and even beyond other disadvantaged contexts. For instance, an option like the collaborative construction of representations as an explanation, clarification and interaction tool was born and developed out of necessity, but has proved to have positive aspects that respond to sound pedagogical criteria. It makes representations a component of classroom interactions, thus turning them into an instrument to engage students actively and stimulate reflections and personal inquiries. By becoming an integral component of students-teacher contacts, representations acquire a linkage role in the overall teaching/learning process to an extent that is probably unequalled in contexts with more resources. This does not mean that being under-resourced is positive. It does, however, hint at the possibility that options developed to try and overcome part of the difficulties of being under-resourced, as well as the difficulties inherent to students' under-preparedness, may be worth applying within better resourced contexts, with the improvements made possible by greater resources availability, but maintaining the pedagogical aspects that make those options tools for interactions, explanations and stimulation of collective search and of individual enquiries.

Finally, there are a number of aspects that have not yet been investigated thoroughly, but whose investigation might stimulate new thoughts and provide new insight. Some of them have already been mentioned in the above discussion, like the deeper internalisation of the models and representations encountered first, and the impacts of such depth in the case of incorrect conceptions and representations, even after explanations and discussion attain the level of conscious acceptance of the corrections. Other issues interesting for investigation might be more closely related to the search for links between traditional ways of teaching/learning and the European-derived pedagogical approaches, e.g., in this region, the traditional transmission of information through generations was oral rather than visual. However, a visual culture is widely and rapidly spreading in common life, through the generalised diffusion of television. Searching for optimal encounters and convergences of the use of representation in science teaching and the use of culturally-inherited oral-learning resources (when still present) could constitute one of the challenging pathways for the overall enhancement of science literacy and acquisition of science knowledge in developing/emerging contexts.

References

Anderson, B. (1990). Pupil's conceptions of matter and its transformations (age 12–16). *Studies in Science Education, 18*, 53–85.

Ben-Zvi, R., Eylon, B., & Silberstein, J. (1986). Is an atom of copper malleable? *Journal of Chemical Education, 63*(1), 64–66.

Brewer, I. M. (1985). *Learning more and teaching less*. Guildford, Surrey: SRHE & NFER-Nelson.

Brodie, K. (1989). Learning mathematics in a second language. *Educational Review, 41*(1), 39–53.

Case, S. M. (1968). The language barrier in science teaching. *Teacher Education in New Countries, 9*(1), 15–26.

Chipere, N. (1993). Dependence and the transition from high school to university in Zimbabwe. *Society for Research in High Education International News, 19*, 4–7.

De Posada, J. M. (1997). Conceptions of high school students concerning the internal structure of metals and their electric conduction: structure and evolution. *Science Education*, 445–467.

Dominguez, J. M., De Pro, A., & Garcia-Rodeja, E. (1998). Las particulas de la materia y su utilizacion en el campo conceptual de *calor* y *temperatura*: un estudio transversal. *Enseñanza de las Ciencias, 16*(3), 461–475.

Dube, C. N. (1992). *Learning from the written word in a second language: Advantages and problems*. University of Zimbabwe, M.A. dissertation.

Ebenezer, J. V., & Erickson, G. (1996). Chemistry students' conceptions of solubility: A phenomenography. *Science Education, 80*(2), 181–201.

Forman, E. A., & Cazden, C. B. (1985). Exploring Vygotskian frameworks in education: the cognitive value of peer interaction. In J. V. Wertsch (Ed.), *Culture, communication and cognition: Vygotskian perspectives*. Cambridge: Cambridge University Press, 323–347.

Gabel, D. L., Samuel, K.V., & Hunn, D. (1987). Understanding the particulate nature of matter. *Journal of Chemical Education, 64*(8), 695–697.

Gabel, D. L. (1993). Use of the particle nature of matter in developing conceptual understanding. *Journal of Chemical Education, 70*(3), 193–194.

Harre, R. (1970). *The principles of scientific thinking*. University of Chicago Press.

Harrison, A. G., & Treagust, D. F. (1996). Secondary students' mental models of atoms and molecules: implications for teaching chemistry. *Science Education,* 80(5), 509–534.

Kwadl, N. D., & Smit, I. J. J. (2001). *Proceedings of the 9th SAARMSTE Conference.*

Lahore, A. A. (1993). Lenguaje literal y conotado en la enseñanza de las ciencias. *Enseñanza de las ciencias, 11*(1), 59–62.

Lee, O., Eichinger, D. C., Anderson, C. W., Berkhaimer, G. D., & Blakeslee, T. D. (1993). Changing middle school students' conceptions of matter and molecules. *Journal of Research in Science Teaching, 30*, 249–270.

Lijnse, P. L., Licht, P., Vos, W., & Waarlo, A. J. (1990). *Relating macroscopic phenomena to microscopic particles. A central problem in secondary science education*. Utrecht: CD-β Press.

Love, A., & Mammino, L. (1997). Using the analysis of errors to improve students' expression in the sciences. *Zimbabwe Journal of Educational Research, 9*(1), 1–17.

Mallinson, G. G., Sturm, H. E., Mallinson, L. M. (1952). The reading difficulty of textbooks for high school chemistry. *Journal of Chemical Education, 29*, 629–630.

Mammino, L. (1994). *Chimica Viva*. G. D'Anna, Firenze (Italy).

Mammino, L. (1995). *Il linguaggio e la scienza (guida all'espressione corretta nelle scienze).* Societá Editrice Internazionale, Torino (Italy).

Mammino, L. (1996). L'analisi degli errori come strumento didattico. *Nuova Secondaria, 10*, 75–76.

Mammino, L. (1997). Un estudio de la forma en que los alumnos perciben la distinción y las mutuas relaciones entre el mundo microscopico y el mundo macroscopico. *Anuario Latinoamericano De Educación Química, IX*(2), 178–189.

Mammino, L. (1998a). Explorando los empleos de las imagines en la enseñanza de la química. *Anuario Latinoamericano de Educación Química, X*, 54–59.

Mammino, L. (1998b). Science students and the language problem: Suggestions for a systematic approach. *Zimbabwe Journal of Educational Research, 10*(3), 189–209.

Mammino, L. (1998c). Evidenciación de estructuras lógicas en la enseñanza de la química teórica. *XXIV International Conference of Theoretical Chemists of Latin Expression*, Puebla (Mexico).

Mammino, L. (1999a). Explorando los empleos de las imagines como instrumiento de enseñanza interactiva. *Anuario Latinoamericano de Educación Química, XII*, 70–73.

Mammino, L. (1999b). La chimica come area ideale per l'educazione al linguaggio della scienza. *Edichem '99: Chemistry in the Perspective of the New Century*. Bari (Italy), 212–230.

Mammino, L. (1999c), Stimulating the awareness of the pitfalls of excess simplification. *International Education Conference: In-service Education for Teachers – Skilling and Re-skilling of the Teaching Force in the New Millennium*, University of Venda (South Africa), 25–27 October.

Mammino, L. (1999d). Semplificazione nella presentazione dei concetti: necessità ed esigenze. *Edichem '99: Chemistry in the Perspective of the New Century*. Bari (Italy), 341–356.

Mammino, L. (2000). Rigour as a pedagogical tool. In S. Seepe & D. Dowling (Eds.), *The language of science*. Vyvlia Publishers (South Africa), 52–71.
Mammino, L. (2000a). Studying the details of the transition from the mother tongue to the second language. In S. Seepe & D. Dowling (Eds.), *The language of science*. Vyvlia Publishers (South Africa), 94–101.
Mammino, L. (2002a). Imagery: a tool for the generation, expression and recognition of students' views about the world of molecules. *Proceedings of the 10th SAARMSTE Conference*, 237–243.
Mammino, L. (2002b). La percepción de la distinción entre sistemas y procesos por parte de los alumnos de química. *Anuario Latinoamericano de Educación Química, XV*, 125–129.
Mammino, L. (2003). *Chimica Aperta*. G. D'Anna, Firenze, (Italy).
Mammino, L. (2005a). Language-related difficulties in science learning. I. Motivations and approaches for a systematic study. *Journal of Educational Studies,* 4(1), 36–41.
Mammino, L. (2005b). Computational chemistry in chemistry and pharmacology research capacity building. An African perspective. 6*th Theoretical Chemistry Workshop in Africa & East and Southern Africa Environmental Chemistry Workshop*, Windhoek (Namibia).
Mammino, L. (2006a). *Terminology in science and technology – an overview through history and options*. Ditlou Publishers, Thohoyandou, South Africa.
Mammino, L. (2006b). Language-related difficulties in science learning. II. The sound-concept correspondence in a second language. *Journal of Educational Studies*. In press.
Mammino, L., & Cardellini, L. (2005). Studying students' understanding of the interplay between the microscopic and the macroscopic descriptions in chemistry. *Baltic Journal of Science Education, 1*(7), 51–62.
Maskill, R., Cachapuz, A. F. C., & Koulaidis, V. (1997). Young pupils' ideas about the microscopic nature of matter in three different European countries. *International Journal of Science Education, 19*(6), 631–645.
Mitchell, A. C., & Kellington, S. H. (1982). Learning difficulties associated with the particulate theory of matter in the Scottish integrated science course. *European Journal of Science Education, 4*(4), 429–440.
Nakhleh, M. B. (1992). Why some students don't learn chemistry. Chemical misconceptions. *Journal of Chemical Education, 69*(3), 191–196.
Nangu, N. C. (1994). How can we be expected to learn science in English? *Southern African Association for Research in Mathematics and Science Education Proceedings*.
Nussbaum, J., & Novick S. (1982). Alternative frameworks, conceptual conflict and accommodation: towards a principled teaching strategy. *Instructional Science, 11*, 183–200.
Nyapfeme, K., & Letseka, M. (1995). Problems of learning among first year students in South African Universities. *South African Journal of High Education, 9*(1), 159–167.
Rubanza, Y. I. (2002). Competition through English. The Failure of Tanzania's Language Policy. In K. K. Prah (Ed.), *Rehabilitating African Languages*, CASAS Book series No 18, 39–51.
Sawrey, B. A. (1990). Concept learning versus problem solving: revisited. *Journal of Chemical Education, 67*(3), 253–254.
Smith, K. J., & Metz, P. A. (1996). Evaluating student understanding of solution chemistry through microscopic representation. *Journal of Chemical Education, 73*(3), 233–235.

Section C
Learning with External Representations

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Following an attempt to integrate the notions of external representation, internal representation, and visualization, earlier Sections have addressed the vexed issue of the nature of visualization itself and of how science curricula and teaching materials can be designed in such a way as to recognise the great cognitive importance of visualization. This final Section is focused on learning, which we must remind ourselves is the central purpose of science education, and in particular on how visualizations – those meanings attributed to both external and internal representations – play their key role in shaping and guiding what is learnt, how it is learnt, and to what effect it is learnt.

It is possible to provide science education courses only in the audio mode i.e. by just talking at students, but this has been shown to be dysfunctional for the learning of many of them. A slight improvement, one that is widely found, is the use of the audio mode augmented by one visual mode, often the use of OHPs (over-head transparencies). However, with the progressive recognition of the educational value of external representations, helped by the advent of suitable computer software, the use of multiple external representations (MERs) is growing apace. The use of MERs implies not only the use of many external representations but also their presentation in a variety of ways e.g. by means of video, traditional 2D and 3D materials, computer modelling software, probeware . . .

In Chapter 9, Ainsworth presents an introduction to multiple representations and their contribution to learning. She points out that they can, taken together, provide complementary information about the phenomenon being studied, can be sequenced so that simpler representations lead the learner towards an appreciation of more complex forms, and that their use facilitates the formation of cognitive structures for and links between the varied ideas that they present. She goes on to review the problems that students have in using multiple representations, particularly their lack of both an understanding of the interpretative conventions attached to each and of the phenomena that they represent. She then summarises some points of 'good practice' for material designers/teachers in respect of representations: assess

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students' understanding of the interpretative conventions involved, use the minimum necessary number of MERs; sequence them to obtain maximum benefit, provide support (presumably by tutoring) and, most importantly, decide what educational function each MER is to serve. It becomes evident that much more detail of how students go about learning from MERs is needed if the educational significance of this 'good practice' is to be explained and justified.

Nakhleh and Postek provide one aspect of such a level of analysis. In Chapter 10, they review the research literature of the educational value of external representations *per se* and then of MERs. They then go on to present a case study of the responses of a small group of undergraduate chemistry students to a module of the SMVChem computer-based programme, in which phenomena are presented and explained in one or more modes of representation. 'Think aloud' protocols were used to deduce students' use and valuation of: real-time video of a phenomenon (the macro level); an animation (the sub-micro level); and a graph (the symbolic level), each of which could be accompanied by an audio commentary. The students found the video the most useful mode of representation and the animation the least useful (because it went too fast). Most interestingly, the audio inputs were perceived as being a distinct channel of information, whilst the sequence in which the representations were viewed governed their perceived educational value.

Michalchik et al take this analysis of the process of learning one stage further in Chapter 11. Their study of the use of the ChemSense computer programme by a small number of grade 11 high school students has three major components: the use of associated probeware so that the behaviour of the phenomenon (the dissolution of salt in water) could be directly studied at the same time as multiple representations of the its progress; the use of situative learning theory within which to represent the significance of what was said as students worked together in small groups; the use of a 'model for the development of representational competence' as a framework for evaluating the outcomes of the educational experience. The nature of the interactions taking place between the students was obtained by the analysis of videotapes, whilst progress towards representational competence was assessed using a pre-/post- test questionnaire strategy. The six classroom 'episodes' presented illustrate what happened as ChemSense was used, whilst the questionnaire showed that the students did learn not only about the dissolution of salt in water but also about the nature of representation. The chapter ends by pointing out the vital role the teacher has in supporting the use of such a resource but also, by implication, at how detailed and accurate must the teacher's understanding of the phenomenon be if, assuming the possession of good questioning technique, effective support is to be provided for students.

If one is trying to understand a complex state, skill, or process, a useful strategy is to represent a more familiar, contrasting, view and to compare the two. Thus, in medicine, the elusive state of 'being healthy' is best defined as the absence of the state of 'being ill'. In the philosophy of science, the elusive 'nature of science' can be more clearly perceived by contrasting it with the 'nature of pseudo-science' (e.g. clairvoyance). In a similar way, considerable insight (sic) into the nature of visualization can be obtained by examining the understanding of representations achieved by those with visual impairment or total blindness. In a most original contribution included as Chapter 12, Jones and Broadwell review the sparse but valuable literature of the evidence for the achievement of visualization in respect of 'images' (defined as 'representations that are spatial but not visual in origin') by these groups. They conclude with recommendations for 'good practice' by teachers: the extensive use of 3D external representations and of diagrams in Braille; the use of haptic feedback tools and of audio feedback from probeware; a full recognition of and sympathetic response to the problems that such students have in science classes.

The especial value of the haptic dimension to the formation and understanding of internal representations by the visually impaired and totally blind is echoed in the last chapter in the book. In Chapter 13, Reiner and Gilbert examine the role of internal representations, external representations, and visualization in the use of 'thought experiments' (TEs) in science education. Defined as 'devices of the imagination used to investigate the nature of things', the chapter points to the central role played by TEs in science and argues for a clear recognition of their, already existing, major role in science education. Having rehearsed a 'model for a TE', case studies of how both eminent scientists and school students design and use them are reviewed. It is argued that haptic information plays a central role in TEs .Given what was asserted in Chapter 12, this seems to support the view that the haptic dimension plays a key role in all visualization, that it is common to all human thought. Having reviewed the ways in which TEs can 'go wrong' in science education, the chapter concludes with a series of recommendations for the encouragement of the production and use of improved TEs. These centre on enhanced classroom skills by teachers, on a focus on the 'nature of science' during practical work, and on the explicit development of the skills involved in TEs.

The chapters in this Section support several broad conclusions. First, that 'design experiments', in which the interactions of groups of students using MERs are studied closely using videotape and perhaps stimulated recall techniques, are a profitable way to explore the value of MERs. Second, that each of a wide range of types of external representation warrant investigation. Third, that groups of blind, visually impaired, fully sighted students, should be investigated. Fourth, that the interaction between visual perception and haptic perception be more extensively enquired into. Fifth, that the role of teachers in supporting the use of MERs be fully explored. Cumulatively, such studies should tell us more about learning with external representations.

Chapter 9
The Educational Value of Multiple-representations when Learning Complex Scientific Concepts

Shaaron Ainsworth

Abstract When people are learning complicated scientific concepts, interacting with multiple forms of representation such as diagrams, graphs and equations can bring unique benefits. Unfortunately, there is considerable evidence to show that learners often fail to exploit these advantages, and in the worse cases inappropriate combinations of representations can completely inhibit learning. In other words, multiple representations are powerful tools but like all powerful tools they need careful handling if learners are to use them successfully. In this chapter, I will review the evidence that suggests that multiple representations serve a number of important roles in science education. I will also consider why the research on the effectiveness of multiple representations shows that all too often they do not achieve their desired educational goals and I consider what can be done to overcome these problems.

Introduction

The use of external representations to help learners come to understand complex scientific concepts is now commonplace. Typical interactive environments such as the three shown below offer learners many different ways to visualize scientific phenomena including video, animations, simulations, and dynamic graphs. SMV-Chem (Russell, Kozma, Becker, & Susskind, 2000) provides examples of real experiments and shows the experimental phenomena with molecular-scale animations, graphs, molecular models, and equations (Fig. 9.1). Connected Chemistry (Stieff, 2005) is a "glass box" simulation which provides a graphical representation of simulated molecules as well as dynamic graphs describing their behaviour and simple numerical displays of system variables (Fig. 9.2). DEMIST (Van Labeke & Ainsworth, 2001) is a domain-independent multi-representational simulation environment. The example shown in Fig. 9.3 is of simulating predator-prey relationships and shows dynamic graphs such as time-series graphs, histograms and phaseplots, animations, a table and an equation.

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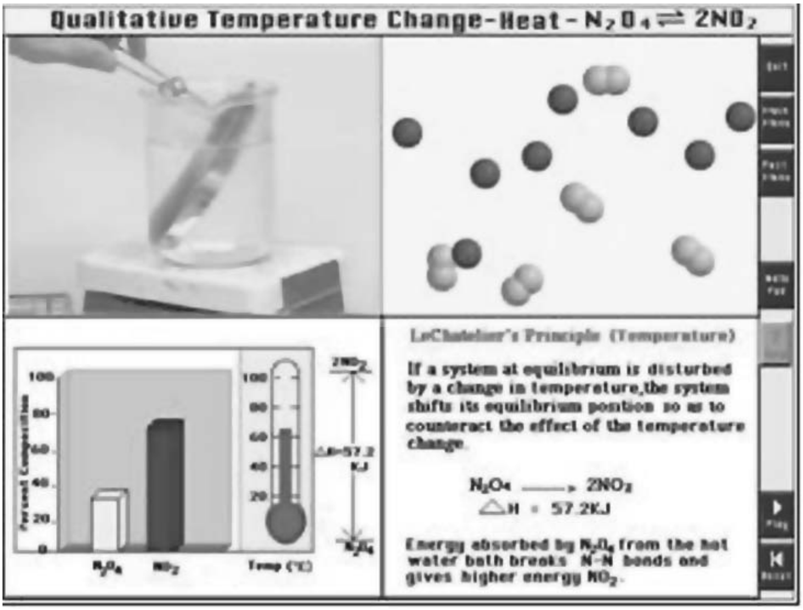

Fig. 9.1 SMV chem

Each environment was designed for different, equally important, educational reasons. They can help learners come to understand the complex forms of visualisations required for professional and expert practice (e.g., phaseplots in DEMIST). They can be designed to give learners indirect experience of phenomena that it is

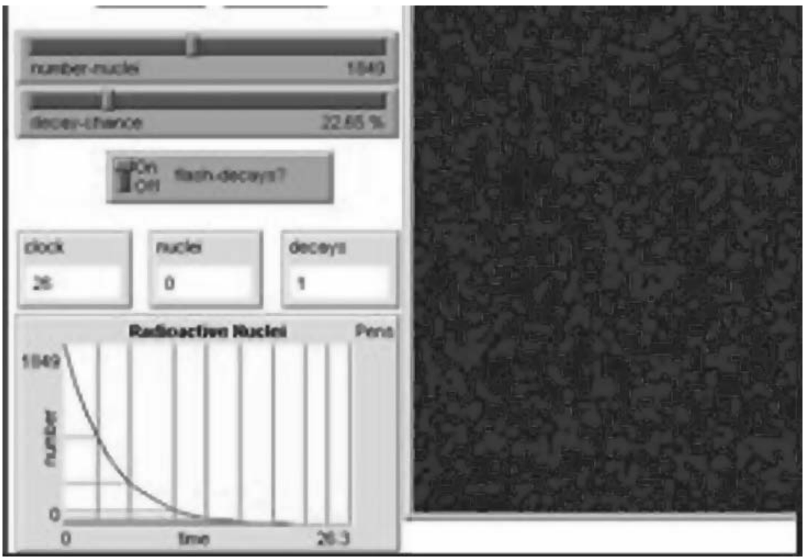

Fig. 9.2 Connected chemistry

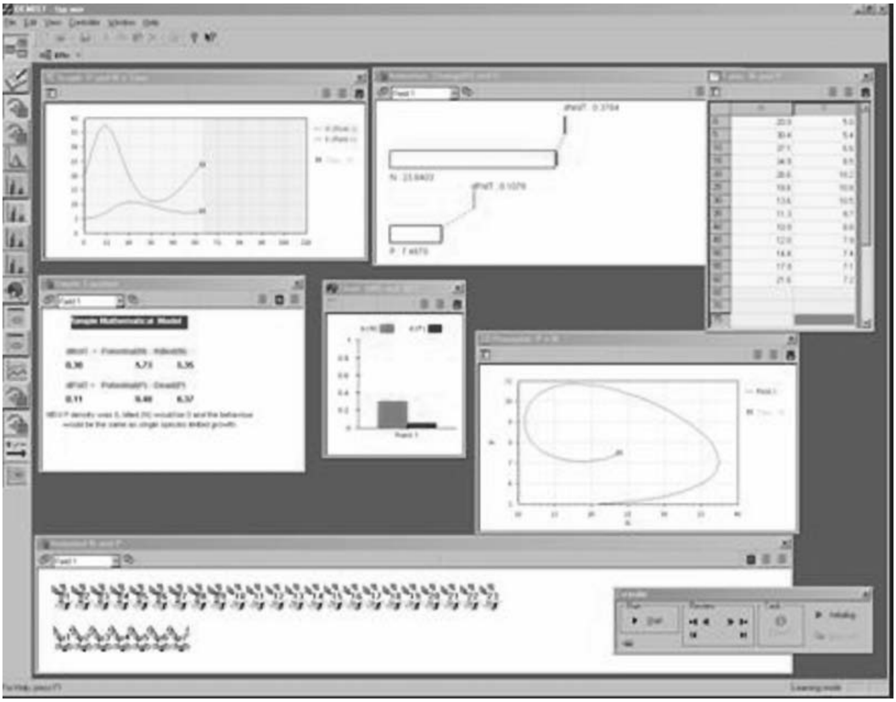

Fig. 9.3 DEMIST

difficult to experience directly in educational settings (such as the video of experiments in SMV-CHEM). They can provide visualisations of phenomena that are impossible to see in the real world yet whose experience will provide understanding that is it difficult to achieve without such representation (e.g. molecular simulations in Connected Chemistry). However, all have one thing in common – they don't just provide a single visualisation: instead they provide multiple representations simultaneously. The purpose of this chapter is to argue that using multiple representations in science education, though commonplace, has particular advantages and disadvantages that should be acknowledged. It will suggest that there are many good reasons behind the decision of designers to include multiple representations but that so doing comes at a cost and that cost can be paid by learners as they become overwhelmed with many new learning demands. It will conclude by considering ways to maximise the benefits of multiple representations without succumbing to these costs.

Advantages of Learning Scientific Concepts with Multiple representations

Multiple representations of scientific concepts are provided for good educational reasons. In this section, the potential advantages of multiple representations will be reviewed, before a later section turns to the complexity that multiple representations can bring to learning.

In the United Kingdom, children learning science in Secondary (High) School follow a National Curriculum that specifies both methods (e.g. Scientific Enquiry) and concepts (e.g. Physical Process). To take one example, children studying science at the ages 14 to 16 might cover the topic of Forces and Motion, which requires them to understand:

- how distance, time and speed can be determined and represented graphically
- factors affecting vehicle stopping distances
- the difference between speed and velocity
- that acceleration is change in velocity per unit time
- that balanced forces do not alter the velocity of a moving object
- the quantitative relationship between force, mass and acceleration
- that when two bodies interact, the forces they exert on each other are equal and opposite

There are many multi-representational learning environments which are designed to help students learn these sorts of topic: two are described below. SimQuest (van Joolingen & De Jong, 2003) is an authoring environment designed to allow researchers and teachers to create instructional simulations for their students. The screenshot of a typical Force and Motion Learning Environment, (Fig. 9.4), uses many different representations to help learners understand the topic. It provides a photograph of the phenomena to be described (top right), a concrete animation of the simulated motorcycle (bottom left), a dynamic time-series graph of the motorcycle's

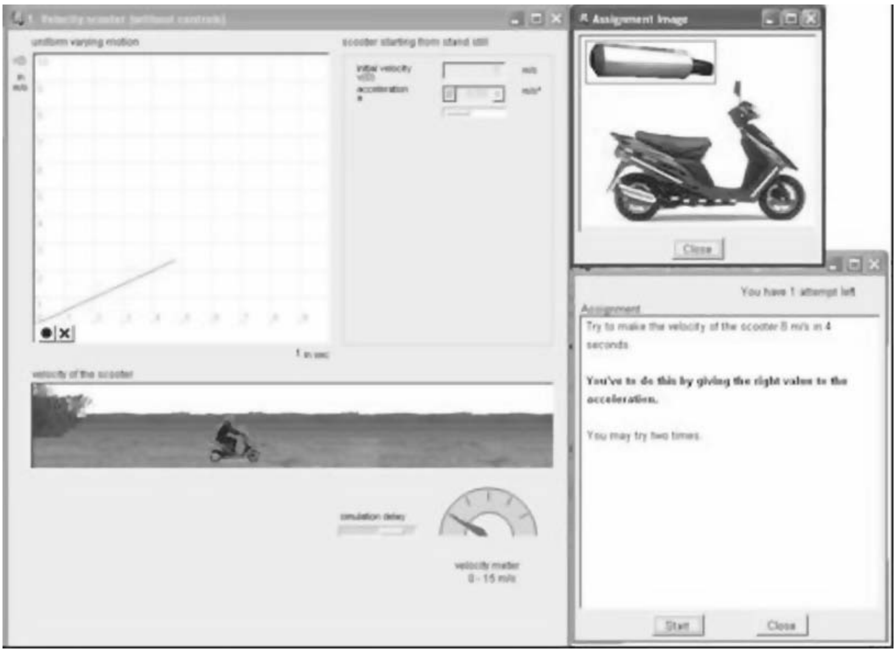

Fig. 9.4 An example of a SimQuest Learning Environment for Force and Motion

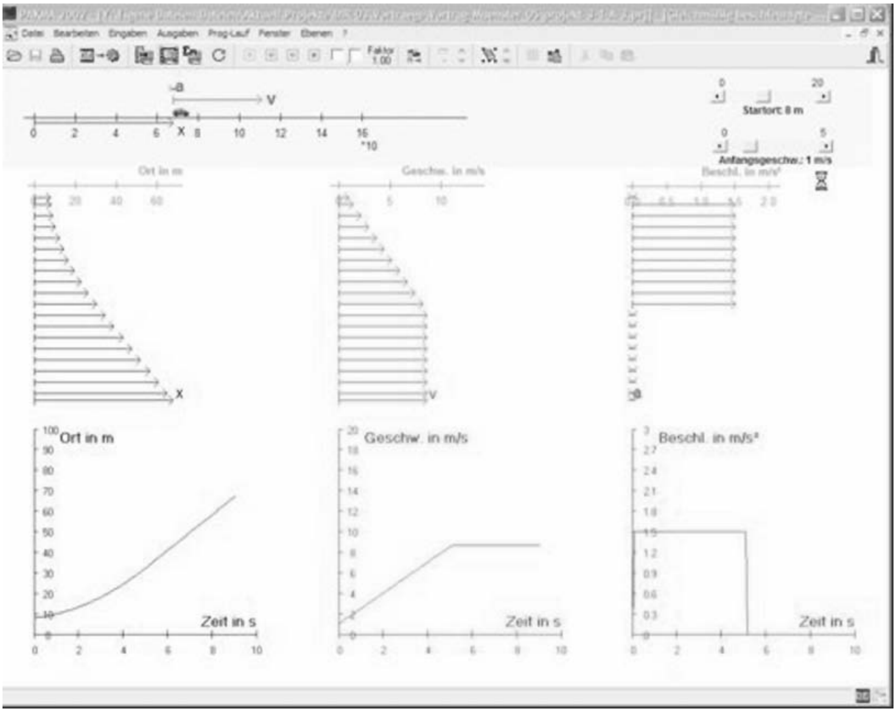

Fig. 9.5 An example of the PAKMA Environment for Force and Motion

velocity (or distance) (top left), and simple numerical displays of the motorcycles current velocity and acceleration (top centre).

PAKMA (Heuer, 2002) is an interactive simulation program that can be used to model force and motion. Fig. 9.5 shows it representing an object's distance, velocity and acceleration. It provides a concrete animation (top left), which is overlaid with vectors to represent the various kinematics concepts (top left), stamp diagrams, which show the object's motion (distance, velocity and acceleration) at previous slices of time (middle row), and dynamic time-series graphs of distance, velocity and acceleration (bottom row).

I proposed a functional taxonomy of multiple representations Ainsworth (1999, 2006) and argue that multiple representations can serve a number of distinct functions for learning (and communication). I will use this functional taxonomy to illustrate the advantages of multiple representations used in the SIMQUEST and PAKMA environments for Force and Motion.

Complementary Roles

The functions of multiple representations fall into three broad classes. Firstly, multiple representations can support learning by allowing for complementary information or complementary roles (see Fig. 9.6).

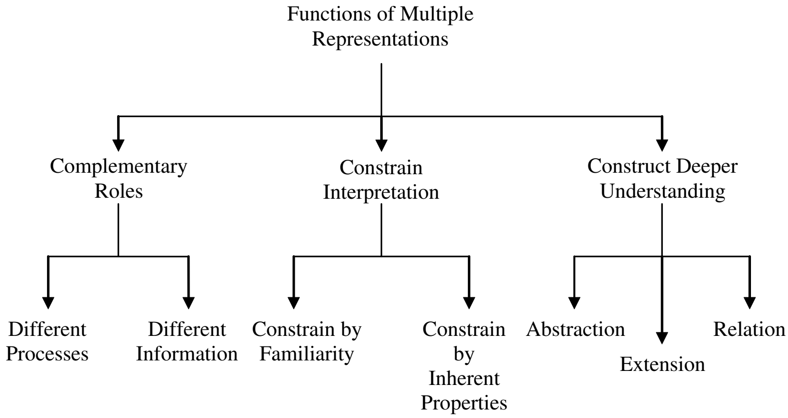

Fig. 9.6 Functions of multiple representations (Ainsworth, 1999, 2006)

The simplest illustration of complementary information in our Force and Motion example would be displaying values for mass, force, friction and velocity. Each representation, be it a graph, an equation, a numerical display, is representing different aspects of a simulated body. The choice of which form of representation to use is therefore likely to depend on the properties of the represented information to be provided. For example, mass might be represented as a simple numerical display as it does not change as the simulation runs, whereas velocity might be represented in a dynamic graph or a table because these representations are time-persistent (Ainsworth & Van Labeke, 2004) and so show how velocity has changed over time. If all this information had to be included in a single representation, then this would either mean that it was represented in ways that were inappropriate to its form (e.g. mass on a time-series graph), at the wrong scale or in the simplest possible way (for example, numerical displays or tables of all the values). So, multiple representations in this case allow different information to be represented in ways that are most appropriate to the learners' needs.

Using multiple representations to support complementary processes rests on the now extremely well known observation that even representations that are informationally equivalent still differ in their computational properties (Larkin & Simon, 1987). For example, diagrams can exploit perceptual processes by grouping together relevant information so making search and recognition easier. Tables make information explicit, emphasise empty cells, allow quick and accurate readoff (of single values) and can highlight patterns and regularities. Equations show compactly the quantitative relationship between variables and invite computational processes.

In forces and motion examples of SIMQUEST and PAKMA, consider the case of trying to determine whether the vehicle is accelerating. If the learner was given a numerical value (e.g. –2) then it is very simple to decide that it is slowing down. It is still easy to see at glance if on object is accelerating, constant, or decelerating from the gradient of the velocity-time graph or simply reading off a single value in an acceleration-time graph. Trying to make this determination in a table requires learners to look at least two entries and then perform a fairly simple mathematical comparison (is the latest value higher, the same, or lower than the previous value?). Whereas if the learner had been given only this equation, $s = ut + \frac{1}{2}at2$ and the current values of s (distance) and u (initial velocity) they would need to first solve the equation for acceleration, $(a=(s–ut) / \frac{1}{2}t2)$ and then substitute values into the equation.

All these solutions require the learner to understand how to interpret the representation (see later) and even the simplest of these still require knowledge. For example, when reading off from a numerical display requires a learner must know the "–" convention for deceleration or how to interpret the downward slope on a velocity-time graph. But, assuming for now that learners know how to interpret these forms of representations, it is obvious that their different computational properties can make this task either trivially easy or extremely complicated (for example, in the equation example).

Consequently, as learning to understand force and motion requires many different tasks to be performed, skills developed and concepts understood, then providing learners with multiple representations with different computational properties presents many possibilities to support learning different aspects of the phenomena.

Constraining Interpretation

Secondly, multiple representations can be used so that one representation constrains interpretations of another one. Often learners can find a new form of representation complex and can misinterpret it. In this case one might use a second, more familiar or easy to interpret, representation to support learners' understanding of the new complicated representation. The role of this simple representation is to constrain the interpretations that learners make of the new representation. In the SIMQUEST example, the constraining representation is the concrete animation of the motorcycle. It moves across the screen to show the learner an object's velocity. This can then constrain interpretation of other more abstract representations. For example, a common misinterpretation of the velocity-time graph is that a horizontal line means that the object is at rest. However, if the learner can see the moving motorcycle at the same time as the velocity-time graph, then may help them understand that a horizontal line means uniform motion rather than no motion.

In the PAKMA example, the stamp diagrams could be considered to be the constraining representation. Each stamp diagram uses the vector arrow overlaid on the animation to show the object' properties in a coordinate plane at defined points in time. Consequently, it is hoped that will help learners understand the corresponding line graphs which are interpolations of these stamp diagrams (see Ploetzner, Lippitsch, Galmbacher, & Heuer, 2006).

The second way that constraining interpretation can be achieved is to rely on the inherent properties of one representation to help learners develop the intended interpretation of the second representation. A number of researchers have drawn attention to the differences between depictions and descriptions. For example, Schnotz (2002) discusses the way that descriptive representations are symbolic in nature whereas depictive representations are iconic. Thus, depictive representations are most useful to provide concrete information and are often efficient as specific information can be more simply readoff.

In our example, a description in text of an objects' motion might be "the motorcycle moved from left to right". However, a depiction would have to be more specific and complete with regard to specific class of information. An animation or a video of a motorcycle would have to commit to a velocity and acceleration for the motorcycle as well. This can be advantageous if you want learners to form a specific understanding of a more descriptive representation and hence constrain interpretation of the description. However, it must also be managed carefully as depictions also have to commit to represent information that may not be important. In this example, one can see the colour of the motorbike, that it is bring ridden by someone with a helmet, etc. Not necessary perhaps for understanding but not especially damaging to understanding either unless the learner decided that Newton's laws are only true for motorcycles with yellow stripes being ridden by men in red jumpers (see later). However, it is also apparent that the motorcycle is going along a road, with trees and with a city in the background. This may encourage learners to apply the intuitive physics they have from real world experience and, in this example, this could lead to confusion as the impact of friction is not being modelled. Consequently, it can be seen that constraining interpretation through the use of depictive representations can be successful but that care must be taken when so doing.

Constraining interpretation by the use of multiple representations is quite different to using multiple representations because they have complementary roles. One implication is that the representation that is designed to perform the supporting role in constraining interpretation is not necessary if the learner has understood the second representation. This might mean that the environment should change to remove constraining representations for different learners or as a learner's expertise grows. In contrast, if the representations are genuinely complementary then one would always expect to be using multiple representations, irrespective of a learners' expertise. It also has implications for the demands facing learners and we will return to this later.

Constructing Deeper Understanding

Multiple representations can support the construction of deeper understanding when learners relate those representations to identify what are shared invariant features of a domain and what are properties of individual representations. Kaput (1989) proposes that "the cognitive linking of representations creates a whole that is more than the sum of its parts". There are many different theoretical accounts of learning that emphasise this use of multiple representations. Cognitive flexibility theory highlights the ability to construct and switch between multiple perspectives of a domain as fundamental to successful learning (Spiro & Jehng, 1990). Dienes (1973) argues that perceptual variability (the same concepts represented in varying ways) provides learners with the opportunity to build abstractions about mathematical concepts. It also can be the case that insight achieved in this way increases the likelihood that it will be transferred to new situations (Bransford & Schwartz, 1999).

Abstraction is the process by which learners create mental entities that serve as the basis for new procedures and concepts at a higher level of organization. Learners can construct references across representations that then expose the underlying structure of the domain represented. In the examples above, abstraction might be supported by providing multiple situations to model. For example, SIMQUEST could illustrate issues of force and motion with motorcycles, cars, skaters, etc. This would allow learners to see that the relationship between the kinematic concepts was not tied to a specific context.

Extension can be considered as a way of transferring knowledge that a learner has from a known to an unknown representation, but without fundamentally reorganizing the nature of that knowledge. For example, learners may know how to interpret the velocity-time graph provided by PAKMA in order to determine whether a body is accelerating. They can subsequently extend their knowledge of acceleration to the other representations.

Finally, relational understanding is the process by which two representations are associated, again without reorganization of knowledge. In the PAKMA example, it may be the case that learners know how to interpret the distance-time graph and the velocity-time graph in isolation. However, they might not know that if they read the velocity from the velocity-time graph then this gives them the gradient of the line on a distance-time graph. The goal of teaching relation between representations can be an end in itself. For example, much emphasis is placed on learning how to construct a graph given an equation.

The differences between these functions of multiple representations are subtle. In extension, the learner starts from understanding one representation well and extends that knowledge to an unknown. In relational understanding, both representations are (partially) known, but the relation between them is unknown. These constructing functions also differs from constraining functions of representations in that all representations contribute to helping learners understand the domain, whereas in the constraining situation the function of one representation is to support understanding of the second.

It should be noted that what functions the representations serve often depends upon learners' knowledge not a designer's intent. For example, one learner coming to PAKMA may be familiar with velocity-time graphs and so extend their knowledge to distance time graphs (extension), but another may already be familiar with both but not have considered their relationship (relation).

Multiple Roles of Multiple Representations

The last section has argued that multiple representations can offer three main advantages for supporting the learning of complex scientific concepts such as force and motion. Furthermore, it has shown that the roles that representations can play depend not only upon the designer's intent but also upon the learner's knowledge and goals. One further factor that should be considered is that any particular combination of representations may also be serving multiple roles simultaneously. An environment may represent velocity through the use of a table, equation, a numerical display, an animation and a graph. In so doing it is allowing for the advantages provided by the different complementary properties of these forms of representation and the different information (e.g. changes over time) they provide It may be taking advantage of the ease of interpretation and familiarity of the numerical display and animation to help learners understand an unfamiliar representation by constraining how they can interpret it Finally, it may be helping learners construct a deeper understanding of force and motion by helping them form abstractions over multiple cases, or relate and extend their knowledge from tables to graphs for example.

Complexity of Learning Scientific Concepts with Multiple Representations

These potential advantages of multiple representations for learning force and motion concepts can only be achieved if learners manage the complex learning tasks associated with their use. This section will review what learners need to know understand about representations in order to learn successfully.

Understanding the Form of a Representation

The most basic competency that learners must develop is to understand the representational syntax. They must understand how a representation encodes and presents information, sometimes called the format of the representation (e.g. Tabachneck-Schijf & Simon, 1998). For example, in the case of the velocity-time graph shown in Fig. 9.4, the format includes attributes such as line on the graph, the labels (what does m/s mean) , and axes (that velocity in metres per second is represented on the Y axis and time (in seconds) on the X axis. They must also learn what the operators are for the representations. Again for the velocity-time a graph, operators to be learnt include how to find the gradients of lines, determine maxima and minima, calculate the area bounded by the line and the axes, etc.

Understanding the form of the representation is not easy for learners, and much research has shown how difficult this is (e.g. Friel, Curcio, & Bright, 2001). For example, Preece (1993) reports that 14–15 year old children found some pupils had trouble with reading and plotting points on graphs, they interpreted intervals as points, and confused gradients with maxima and minima. Scanlon (1998) also found that negative slopes and negative values on velocity-time graphs caused particular problems.

Additionally, the operators of one representation are often used inappropriately on another representation. The most famous example with velocity-time graphs is when they are interpreted using operators appropriate for pictures (e.g. Leinhardt, Zaslavsky, & Stein, 1990). When learners are asked to draw a velocity-time graph of a cyclist travelling over a hill, they should select a U shaped graph, yet many show a preference for graphs with a hill shaped curve. Elby (2000) proposes that this is because learners tend to rely on intuitive knowledge – what-you-see-is-what-you-get and that this is cued by the most compelling visual attribute of a representation (e.g. straight lines mean constancy, hill shape means hill). Learning to correctly apply operators for a representation can therefore involve learning to ignore this intuition.

Understanding the Relation Between the Representation and the Domain

Even if learners understand the form of the representation, they still need to understand how this representation relates to the specific topic it is representing. Evidence suggests that learners do not build domain – independent models of representation but instead use interpretation as an inherently contextualised activity (e.g. Roth & Bowen, 2001), strongly affected by learners' conceptions of and familiarity with the domain.

One key problem that learners face is trying to determine which operators to apply to a representation to retrieve the relevant domain information. In the Force and Motion domain, learners often examine the height of line, rather than its gradient when attempting to determine the velocity of an object from a distance-time graph (Leinhardt et al, 1990). Scanlon (1998) suggests that many learners have developed over-generalised rules for selecting operators (e.g. gradient equals "something", the area under a graph equals "something"). She found that pairs of students interpreting motion graphs would therefore use these general rules irrespective of the particular graph (distance, velocity, acceleration) they were interpreting. For example, they would determine the gradient of the graph and state it as the average velocity if they were working with a velocity-time graph as well as correctly with a distance-time graph. In other cases, however, the rules for these operators were overly selective. For example, Scanlon cites the example of a learner who believed that you could only apply "distance = area under the velocity-time graph" when the graph did not go through the origin.

These problems do not only arise with abstract representations. There is considerable evidence suggesting that even concrete representations (such as fingers when children learn to count) still need to be related to the domain. For example, in the PAKMA environment, the iconic representations of the arrows and stamp diagrams were introduced to provide an intermediate representation between the animation and the abstract graphs. However, Ploetzner et al. (2006) compared students learning about kinematics with either just the animation and the line graphs, the animation, line graphs and arrows, or the animations, line graphs, arrows and stamp diagrams. The students given the additional representations did not perform any better than those without these representations and for harder concepts, even did worse.

Finally, it is worth remembering that one of the main reasons that learners are provided with multiple representations is that they have limited knowledge of the domain that we wish to help them develop. Experts, by contrast, have the advantage of their subject matter knowledge when faced with the task of relating a new representation to the domain (e.g. Chi, Feltovich, & Glaser, 1981). This knowledge will be organised around deep structural knowledge and principles, will be rich and connected to situations where it can be applied and will be available with little effort. However, learners are often seduced by surface features of problems, their knowledge is fragmented and they do not have fluid access to it. Consequently, learners are at particular risk of misrelating new representations to the domain as they have neither the representational knowledge nor domain knowledge to provide support for this task.

Understanding how to Select an Appropriate Representation

In many multi-representational environments, not all representations are available at the same time. In this case, learners have to select the most appropriate representations for their needs. If this is the case, they may have to consider what goal they are seeking to achieve, what representations are available and what are their individual preferences. For example, when solving Force and Motion problems, learners may need to focus on the task they are solving. If their current task is to find out the position from which an object started and they are currently working with a velocity-time graph, they should learn to select the distance-time graph. However, if they need to determine acceleration, they should learn that the distance-time graph is not ideal. They may also need to identify the nature of their personal preferences, for example, do they prefer to learn from tables or graphs? If so, would it be a good idea at this time for them to stay with their preferred form of representation or would it be good to try to focus on their least preferred representation to learn its value?

Understanding how to Construct an Appropriate Representation

In the examples shown above, learners were presented with representations and then required to interpret them. However, learners may also be required to construct the representations themselves. They may be given specific instructions of the representation to construct such as “draw a velocity-time graph of a body which starts with an initial velocity of 0ms and then continues to accelerate at the rate of 9.8 m/s2 for 30 seconds. Find the average velocity” Alternatively, they may be presented with a problem such as “a body starts with an initial velocity of 0 ms and then continues to accelerate at the rate of 9.8 m/s^2 for 30 seconds, find the average velocity” which does not tell them which representations would be helpful. A further possibility would be to give learners the velocity-time graph of this situation and then ask them to construct other representations such as an acceleration time-graph or a table of velocity against time. In the first case, learners must know how to construct the appropriate representation, in the second case, they must know how to select an appropriate representation to construct before interpreting it correctly and in the third case, they must know how to interpret the first representation and the construct a second representation on this basis.

There is a lot of evidence that knowing how to interpret a representation does not mean that you know how to construct a representation correctly (e.g. Cox, 1996). Furthermore, knowing how to construct a representation does not guarantee that you can then use it to solve the problem you constructed it to solve. For example, Scanlon (1998) found that some learners solving a problem like the first one described above could use the area under the velocity time graph and divide by the time or take the mid point of the graph. However, just as many then ignored the constructed graph and used their knowledge of the motion equations and further learners misused equations or as described earlier then used the wrong operators.

There are many educational benefits from encouraging learners to construct their own representations, not least that we want learners to be able to do so – imagine a world where people could read but not write. In addition, it may be the case that constructing your own representations leads to better understanding than interpreting a given representation (see Van Meter & Garner, 2005). Grossen and Carnine (1990) found that children learned to solve logic problems more effectively if they drew their responses to problems rather than selected a pre-drawn diagram. Another innovative use of construction was explored by Schwartz and Martin (2004) who allowed students to invent representations to help them understanding descriptive statistics and compared them to students who had been given solution and allowed to practice them. No student in the invented condition developed the correct solution. However, when comparing which group of students could then learn from a standard lecture and apply the solution to novel problems, the group who had invented solutions were better than the group who had practiced with the correct solution. Consequently, we need to consider allowing students construct their own representations, even if these representations are not ultimately the ones they will go on to use.

Understanding how to Relate Representations

If learners are working with an individual visualisation, then they still need to master the cognitive tasks outlined above. However, there is one process that is unique to learning with more than one representation – that of relating different representations. Unfortunately, there is good evidence that this can be extremely difficult for learners, yet it is a fundamental characteristic of expertise (e.g. Kozma, Chin, Russell, & Marx, 2000). For example, Tabachneck, Leonardo and Simon (1994) report that learners of economics did not attempt to integrate information between line graphs and written information when both interpreting and constructing graphs. Similarly, Yerushalmy (1991) examined fourteen year olds understanding of functions after an intensive three month course with multi-representational software. In total, only 12% of students gave answers which involved both visual and numerical representations. Combining inappropriate representations can even completely inhibit learning. Ainsworth, Bibby and Wood (2002) contrasted children learning estimation with two representations, either mathematical, pictorial or a mixed system of one pictorial and mathematical representation. By themselves, picture and mathematical representations helped children learn but those children who studied with the combination knew no more at the end of the study than they had at the beginning.

It is also difficult to know how to support this process. For example, whether it is beneficial to teach learners to relate representations may depend upon a learner's prior knowledge. Seufert (2003) found that only learners with an intermediate amount of prior knowledge benefited from help with translation between representations. High prior knowledge learners did not benefit as presumably they could make these links for themselves. Low prior knowledge students also did not benefit because they became overwhelmed by too much new information.

Other approaches to helping learners relate representations include making sure they use common labels and conventions, for example, always using blue to indicate distance, green to represent velocity and red for acceleration (as in PAKMA), refer always to distance or position but not distance and position, etc. It may also be the case that the order in which representations are introduced to learners is crucial. For example, Ploetzner (1995) built a cognitive model of how to solve 1-D motion problems with constant acceleration. He then compared the results of his cognitive model to learners' behaviour to show how qualitative knowledge needs to be coordinated with quantitative knowledge for successful problem-solving performance to result. Ploetzner, Fehse, Kneser, and Spada (1999) then tested this prediction by examining collaborating pairs taught with different sequences of qualitative and quantitative representations. Those learners who had first learnt qualitative knowledge were able to gain more from collaboration than those who had first learnt quantitative knowledge. Moreover, software tools that are designed to help in this process may not do so. One common approach is known as dyna-linking – where you act upon one representation and see the results of those actions in another. Dynamic linking of representations is assumed to reduce the cognitive load upon the student – as the computer performs translation activities, students are freed to concentrate upon their actions on representations and their consequences in other representations. However, direct evidence for the benefits of dyna-linking are hard to find. Van der Meij and de Jong (2006) compared different versions of a SIMQUEST environment for teaching moments, which varied whether the system dyna-linked the representations. Overall, there was little evidence for the benefits of dyna-linking.

The inescapable conclusion of this research is that relating representations is an extremely complicated task. Little is currently known about how learners achieve this integration (Reed, 2006) and attempts to help learners do so by providing instructional support or software tools are far from proving invariably successful. Furthermore, failure to relate representations can leave learners without the additional benefits that the multiple representations were designed to provide and can even completely inhibit learning.

Conclusion

This chapter has reviewed evidence to suggest that the learning of complex scientific topics is commonly, even invariably, supported by the use of multiple representations.

It has argued that there are many roles that different combinations of representations can play in supporting learning. However, it has suggest that the benefits of multiple representations do not come for free – learners are faced with a number of complex tasks and as the number of representations increases so do these costs.

So, what is the system designer to do when faced with deciding how to use multiple representations to support the acquisition of complex scientific knowledge? A number of possible frameworks exist and some researchers suggest design principles (e.g. Mayer, 2001). However, that for many of the complex representational systems used to support science learning we may not yet at the point of producing definitive principles – instead there are a number of heuristics that could be used to guide design.

The first heuristic is to use only the minimum number of representations that are you can. So, if you can use one representation do so. But, if you can't consider whether the representations that you think are necessary really are required.

Secondly, carefully assess the skills and experience of the intended learners. For example, do they need support of constraining representations to stop misinterpretation of unfamiliar representations or would this extra representation not provide any new insight without a great deal of work by the learner. Alternatively, they may be so experienced that the constraining representation is not needed and just adds additional work for no tangible benefit.

Thirdly, consider how to sequence representations in such a way to maximise their benefits. Even if you have eight informative ways to visualise a concept, don't introduce all eight simultaneously. Allow learners to gain knowledge and confidence with fewer representations before introducing more.

A fourth heuristics is to consider what extra support you need to help learners overcome all the cognitive tasks associated with learning with multiple representations. Are there help files or exercises to ensure that learners know how to understand the form of the representation? Is the topic to be learnt familiar to the learners or do learners need additional help in relating the representation to the domain? Has the system been designed to help learner see the relation between representations? For example, are consistent labels, colours and symbols used and are representations that need to be related placed close to one another.

Finally, consider what pedagogical functions the multi-representational system is designed to support. If the primary goal is to support complementary functions, then it may be sufficient that learners understand each representation without understanding the relation between them. The task for the learner is to identify when to select particular representations for particular tasks. Learning may be hindered if they spent considerable time and effort in relating representations unnecessarily and so designers may consider ways to either discourage learners from doing this (e.g. by not making representations co-present or by automatically relating representations). If the goal is to constrain interpretation it is imperative that the learner understands the constraining representation. Consequently, designers must find ways of signalling the mapping between representations without overburdening learners by making this task too complex. If the goal is for learners to construct a deeper understanding of a domain, if they fail to relate representations, then processes like abstraction cannot occur. Moreover, although learners find it difficult to relate different forms of representations, if the representations are too similar, then abstraction is also unlikely to occur. Consequently, it is difficult to recommend a solution to this dilemma. But if you need learners to abstract over multiple representations then you should provide considerable support for them to do so, by providing focused help and support on how to relate representations and giving learners sufficient time to master this process.

Multiple representations are powerful tools to help learners develop complex scientific knowledge. But like all powerful tools, they require carefully handling and often considerable experience before people can use them to their maximum effectiveness. Beginners using powerful tools do not achieve the same results as experts and so we should consider how these tools can be designed to allow learners to develop their expertise. Moreover, beginners do not learn without support from others, either peers or teachers. Although this chapter has focused upon what system designers can do to create powerful learning environments, we also need to consider how the learning environment is embedded within particular social contexts.

References

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

Ainsworth, S. E. (1999). The functions of multiple representations. *Computers & Education, 33* (2–3), 131–152.

Ainsworth, S. (2006). DeFT: A conceptual framework for considering learning with multiple representations. *Learning and Instruction, 16*(3), 183–198.

Ainsworth, S. E., Bibby, P., & Wood, D. (2002). Examining the effects of different multiple representational systems in learning primary mathematics. *Journal of the Learning Sciences, 11*(1), 25–61.

Bransford, J. D., & Schwartz, D. L. (1999). Rethinking transfer: A simple proposal with multiple implications. *Review of Research in Education, 24*, 61–100.

Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation in physics problems by experts and novices. *Cognitive Science, 5*(2), 121–152.

Cox, R. (1996). *Analytical reasoning with multiple external representations.* University of Edinburgh Scotland: University of Edinburgh Press.

Dienes, Z. (1973). *The six stages in the process of learning mathematics*. Slough: NFER-Nelson.

Elby, A. (2000). What students' learning of representations tells us about constructivism. *Journal of Mathematical Behavior, 19*, 481–502.

Friel, S. N., Curcio, F. R., & Bright, G. W. (2001). Making sense of graphs: Critical factors influencing comprehension and instructional implications. *Journal for Research in Mathematics Education, 32*(2), 124–158.

Grossen, B., & Carnine, D. (1990). Diagramming a Logic Strategy – Effects on Difficult Problem Types and Transfer. *Learning Disability Quarterly, 13*(3), 168–182.

Heuer, D. (2002). PAKMA 2002 – Interactive simulation, measurement, reproduction, modelling and analysis in physics; CD-ROM. Hannover: Schroedel Verlag.

Kaput, J. J. (1989). Linking representations in the symbol systems of algebra. In S. Wagner & C. Kieran (Eds.), *Research issues in the learning and teaching of algebra* (pp. 167–194). Hillsdale, NJ: LEA.

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

Larkin, J. H., & Simon, H. A. (1987). Why a diagram is (sometimes) worth 10000 words. *Cognitive Science, 11*(1), 65–99.

Leinhardt, G., Zaslavsky, O., & Stein, M. M. (1990). Functions, graphs, and graphing: tasks, learning and teaching. *Review of Educational Research, 60*, 1–64.

Mayer, R. E. (2001). *Multimedia learning*. Cambridge: Cambridge University Press.

Ploetzner, R. (1995). The construction and coordination of complementary problem representations in physics. *Journal of Artificial Intelligence in Education, 6*(2/3), 203–238.

Ploetzner, R., Fehse, E., Kneser, C., & Spada, H. (1999). Learning to relate qualitative and quantitative problem representations in a model-based setting for collaborative problem solving. *Journal of the Learning Sciences, 8*(2), 177–214.

Ploetzner, R., Lippitsch, S., Galmbacher, M., & Heuer, D. (2006). Students' Difficulties in Learning Physics from Dynamic and Interactive Visualizations. In S. A. Barab, K. E. Hay, & D. T. Hickey (Eds.), *Proceedings of the Seventh International Conference of the Learning Sciences (Vol 2)*. (Vol. 550–556). Mahwah, NJ: Lawrence Erlbaum Associates.

Preece, J. (1993). Graphs are not straightforward. In T. R. G. Green, S. J. Payne, & G. C. van der Veer (Eds.), *The psychology of computer use* (pp. 41–56). London: Academic Press.

Reed, S. K. (2006). Cognitive architectures for multimedia learning. *Educational Psychologist, 41*(2), 87–98.

Roth, W.-M., & Bowen, G. M. (2001). Professionals read graphs: A semiotic analysis. *Journal for Research in Mathematics Education, 32*, 159–194.

Russell, J., Kozma, R., Becker, D., & Susskind, T. (2000). SMV: Chem; Synchronized Multiple Visualizations in Chemistry. New York: John Wiley.

Scanlon, E. (1998). How beginning students use graphs of motion. In M. W. Van Someren, P. Reimann, H. P. A. Boshuizen, & T. de Jong (Eds.), *Learning with multiple representations* (pp. 9–40). Amsterdam: Elsevier Science.

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

Schwartz, D. L., & Martin, T. (2004). Inventing to prepare for future learning: The hidden efficiency of encouraging original student production in statistics instruction. *Cognition and Instruction, 22*(2), 129–184.

Seufert, T. (2003). Supporting coherence formation in learning from multiple representations. *Learning and Instruction, 13*(2), 227–237.

Spiro, R. J., & Jehng, J.-C. (1990). Cognitive flexibility and hypertext: Theory and technology for nonlinear and multi-dimensional traversal of complex subject matter. In D. Nix & R. J. Spiro (Eds.), *Cognition, education and multi-media: Exploring ideas in high technology*. Hillsdale, NJ: LEA.

Stieff, M. (2005). Connected chemistry – A novel modeling environment for the chemistry classroom. *Journal of Chemical Education, 82*(3), 489–493.

Tabachneck, H. J. M., Leonardo, A. M., & Simon, H. A. (1994). *How does an expert use a graph ? A model of visual & verbal inferencing in economics.* Paper presented at the 16th Annual Conference of the Cognitive Science Society, Georgia Institute of Technology, Atlanta, Georgia.

Tabachneck-Schijf, H. J. M., & Simon, H. A. (1998). Alternative representations of instructional material. In D. Peterson (Ed.), *Forms of representation* (pp. 28–46). Exeter: Intellect Books.

van der Meij, J., & de Jong, T. (2006). Supporting students' learning with multiple representations in a dynamic simulation-based learning environment. *Learning and Instruction, 16*(3), 199–212.

van Joolingen, W. R., & De Jong, T. (2003). SIMQUEST: Authoring educational simulations. In T. Murray, S. Blessing, & S. E. Ainsworth (Eds.), *Tools for advanced technology learning environments* (pp. 1–32). Amsterdam: Kluwer Academic Publishers.

Van Labeke, N., & Ainsworth, S. (2001). Applying the DeFT framework to the design of multi-representational instructional simulations. In J. D. Moore, C. L. Redfield, & W. L. Johnson

(Eds.), *Proceedings of the 10th international conference on AI in education* (pp. 314–321). Amsterdam: IOS Press.

Van Meter, P., & Garner, J. (2005). The promise and practice of learner-generated drawing: Literature review and synthesis. *Educational Psychology Review, 17*(4), 285–325.

Yerushalmy, M. (1991). Student perceptions of aspects of algebraic function using multiple representation software. *Journal of Computer Assisted Learning, 7*, 42–57.

Chapter 10
Learning Chemistry Using Multiple External Representations

Mary B. Nakhleh and Brian Postek

Abstract This chapter focuses on how students used various multiple visual and auditory external representations to develop their understanding of limiting reagents. They used the Synchronized Multiple Visualizations of Chemistry (SMV Chem) program. SMV Chem allowed learners to use five external representations of a given chemistry topic in any order or combination that they chose. The four visual external representations consisted of a real time video of a chemical reaction (macroscopic level of understanding), a computer animation of the reaction (microscopic level), a graphical representation (symbolic level), and a text representation of a mathematical problem concerning limiting reagents. Each visual external representation had an accompanying audio track to narrate the action that occurred during the representation. The audio track could be selected or not, according to the user's choice. The module demonstrated the limiting reagents concept with a vinegar and baking soda reaction. We chose this module because the topic of limiting reagents provided students with many opportunities to explore the macroscopic, microscopic, symbolic, and mathematical levels in developing their understanding of the chemistry. Specifically we sought to identify the representations that were useful and then the particular characteristics that made those representations effective in helping students create their understanding.

Overview

"Visualizations" have become an active area of research in chemical education. Unfortunately, the term "visualization" is often used but seldom defined. Therefore, we think that a few words to clarify our thinking about visualizations are in order. We argue that "representation" might be a better term to use in our investigations. Representations can be visual, auditory, tactile or even olfactory. Many types of representations can include visual elements, such as videos, pictures, diagrams, graphs, and animations, but they remain distinctly different types of representations. And these representations convey different types of information. McKendree, Small,

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Stenning, and Conlon (2002) defined a representation as “a structure that stands for something else: a word for an object, a sentence for a state of affairs, a diagram for an arrangement of things, a picture for a scene” (p. 59). We accept this definition of a representation with a few additions. First, we distinguish between external representations that are presented to the learner and internal representations that are constructed by the learner. Second, we recognize that science disciplines contain many more types of representations than they enumerate, such as graphs, molecular diagrams, and animations. Third, different science disciplines may have even further fine-grain detail; for example, in chemistry we have to recognize that representations may convey information at either the level of bulk properties of matter (macro-level) or at the level of molecular interactions (molecular level) or in fact a combination of these levels.

McKendree et al. also make the important point that certain representations may fit particular problems or subject areas (such as the use of letter variables in algebra), but students must know how to use a representation, or when given multiple representations, choose the representation that best represents the task at hand. In addition to choosing the proper representation for a given problem or task, the representation that the student uses must be interpreted for the context of the problem and be transformed meaningfully in order to construct new and useful information.

There may indeed be a proper representation for a single student for a single type of problem that works effectively, but the question remains, which representation is that? In reality it may not be possible for an instructor or author of curricular materials to create a single representation that works for all students, but it may be possible to identify what representations students find the most useful for creating meaning. We hope to identify which, if any, representations are used for creating meaningful transformations of information, and what aspects of those representations allow for a meaningful transformation of information by investigating how student use a software program that provides synchronous, multiple “visualizations” of chemistry, i.e. SMV Chem (Russell, Kozma, Becker & Susskind, 2000; Russell et al., 1997). In our terminology, we refer to these visualizations as multiple external representations (MERs) (Ainsworth, 1999).

Previous Studies of the Use of Visual Representations in Chemistry

Table 10.1 displays a summary of some studies that have investigated the use of visual representations in chemical education. We noted several trends in this literature. First, all of the studies were technology-based, and second, many of the studies concentrated on molecular-level representations in the form of animations or modeling. Third, the findings are not uniformly positive in terms of student learning. Fourth, a distinction needs to be made between static and dynamic representations. This implies some consideration of the role of time in a representation. A picture seems to be emerging of complex interactions between learners and external representations, particularly when multiple external representations are available.

Table 10.1 Studies of visual representations in chemical education. All studies are computer-based unless otherwise indicated

	Topics	Representations	Findings
1. Sanger, Brecheisen and Hynek (2001)	Osmosis & diffusion	Molecular animation	Improved conceptual understanding of PNM*
2. Williamson and Abraham (1995)	Gases, phase change, equilibrium, IMF**	Molecular animation	Dynamic visuals promote conceptual understanding
3. Sanger and Greenbowe (2000)	Electron flow in galvanic cells	Molecular animation	Animations can distract students from a non-verbal task
4. Barnea and Dori (1996)	Molecular configurations	3-D molecular modeling	NSD*** but modeling perceived positively
5. Kozma and Russell (1997)	Transforming between representations	Video clips, molecular animations, text, graphs	Novices chunk representations based on surface features
6. Russell et al. (1997)	Modules on general chemistry topics	Video clips, molecular animations, text, graphs	Enhanced conceptual understanding
7.Wu, Krajcik and Soloway (2001)	Building molecular models	Molecular modeling	Enhanced ability to transform between 2-D and 3-D models
8. Hakerem, Dobrynina and Shore (1993)	Water and molecular networks	Simulation	The program promoted conceptual change
9. Nakhleh, Donovan and Parrill (2000)	Introductory organic chemistry	Web-based tutorial with text, drawings and 3-D molecular models	Weaker students benefited. Visual aspects were a major theme.
10. Nakhleh, Donovan and Parrill (2000)	General chemistry topics, especially liquids, coordination chemistry & molecular structures	Web-based supplementary materials with text, pictures, animations & molecular models	NSD*** in performance in the course, but users showed more complex understanding of the topics.
11. Kelly and Jones (2006)	Dissolving of sodium chloride	Molecular animation	Better explanations of particle structures and the dissolving process, but incorrect concepts sometimes retained.

*PNM: Particle nature of matter
**Intermolecular forces
***No significant difference between groups

For example, Sanger et al. (2001) studied the effects of computer animations that depict the processes of diffusion and osmosis on student conceptions of those topics. The authors reported that students that viewed computer animations of the diffusion of perfume molecules and osmosis of water molecules developed more accurate conceptions of these processes based on ideas of the random motion of molecules.

Williamson and Abraham (1995) studied the use of animations in two treatment settings, a lecture with supplementary computer animations and a computer laboratory assignment. The authors reported that students that used a computer visualization program depicting the particulate nature of matter in lecture and laboratory settings scored significantly higher on a particulate nature of matter test than students than the control group. The authors concluded that 1) animations may increase conceptual understanding by prompting the formation of dynamic mental models of the phenomena and 2) students that viewed static visuals may have "(a) formed static mental models that provided an incomplete understanding of the dynamic nature of particulate matter or (b) failed to form any mental model, leaving them with only a macroscopic view of the phenomena" (p. 532).

Sanger and Greenbowe (2000) studied how computer animations that described electron flow in a copper-zinc galvanic cell affected conceptual change. The authors reported that the animation group did not perform significantly better on the visual questions, and the conceptual change instruction group performed better on the verbal questions (with the animation having no effect). The authors concluded that animations were distracting when a task did not require a student to visualize and that conceptual change instruction was effective in helping students answer visual questions as long as the students participated in lecture.

These three studies posed a question that was important to our study. In two cases the use of visual representations at the molecular level increased conceptual understanding, but in one study these representations did not increase conceptual understanding. Sanger and Greenbowe (2000) hypothesized that the computer animations were not significantly more effective than crude animations used in classroom instruction at producing higher conceptual understanding. What aspects make animations more effective than crude drawings remains an open question.

A precursor to the SMV Chem Program that we used was 4M:CHEM. Kozma and Russell (1997) used 4M:CHEM to investigate how undergraduate chemistry students and professional chemists grouped representations, and how they transformed one representation to another (for example, transforming an equation into a graph). The researchers found that experts used their conceptual understanding to form larger groups of representations where the novices constructed smaller groups based on surface features. Russell et al. (1997) also reported that students using the 4M:CHEM program to study equilibrium were able to reduce the number of inappropriate statements. The researchers found that scores on a posttest (pretest/posttest setup) were significantly higher, which they attributed to a better conceptual understanding of equilibrium.

These studies seem to indicate two important ideas. The first study on 4M:CHEM found that students made connections between multiple representations, albeit based on surface features. The second study also showed that students could create a greater understanding of concepts, even using simple surface features.

Finally, Nakhleh et al. (2000) conducted a study in which multiple representations were available to the student. They investigated students' use of the Educational Materials for Organic Chemistry (EMOC) website which was available for the use of students in organic chemistry. They asked students to discuss EMOC in terms of its perceived advantages and disadvantages and their general like or dislike for the website. They also compared website users and non-users. The EMOC website provided students with supplemental materials for organic chemistry that included highly visual, dynamic, interactive, and guided inquiry based learning tools. Students reported that the EMOC supplemental materials were an advantage, and they generally liked the format and materials of the website as a whole. The nonusers performed better than the users when questioned about organic chemistry materials, although the website users felt that they benefited from the use of the website. The authors speculated that the difference in performance between users and nonusers may be accounted for as difference in performance prior to using the website and therefore the users of the website were more motivated to seek extra help. More important for our present study, the students consistently indicated a preference for visualization, both external representations and internal representations. They would consistently make statements indicating that a representation "helped me see the chemistry better."

Kelly and Jones (2006) investigated how students' explanations of the dissolution of sodium chloride were affected by viewing two animations of the particulate nature of the dissolution of sodium chloride. They found that the particulate animations had a positive influence on the explanations the students provided of both particulate structures and the functional aspects of dissolution, and they often incorporated features displayed in the animations. However, the authors also reported that participants continued to retain incorrect previous conceptions of dissolution. They speculated that the participants had attempted to retain those previous conceptions and to fit their incompletely understood new knowledge within the old framework.

Previous Studies into Multiple Representation

The chemistry studies discussed above did not identify any specific characteristics that made the "visualizations" effective in helping students create their understanding. However, we were aware that the broader literature on multiple external representations (MERs) was beginning to indicate that sometimes MERs could work together to produce learning benefits (Ainsworth, Wood, & O'Malley, 1998) and sometimes MERs seemed to hinder understanding (Schoenfeld, Smith, & Arcavi, 1993; Ainsworth, Wood, & Bibby, 1996). Therefore, we examined the studies in Table 10.2 for further information about MERs.

Moreno and Mayer (2002) investigated the effects of varying information modality (narration, text and combined narration-text) and level of immersion on retention, performance, and transfer for viewing a multimedia game (Design-A-Plant; Lester, Stone, & Stelling, 1998). The authors found that retention, transfer, and program ratings were significantly higher in participants that received information verbally

Table 10.2 Studies of representation modes

Study	Topics	Representations	Findings
1. Moreno and Mayer (2002)	Effect of information mode & immersion on retention, performance & transfer	Modes: Narration, text & narration-text Immersion: Desktop display & virtual reality environment	Immersion has no major effect on learning, but modality does affect learning. Modality is independent of medium.
2. Mayer and Anderson (1992)	Effect of information modes on problem solving and verbal retention	Modes: Animation with concurrent narration, animation with successive narration, animation only, narration only, no instruction	Concurrent groups performed significantly better than other groups.
3. Mayer, Heiser and Lonn (2001)	Effects of interesting but irrelevant information	Main mode: Animation with concurrent narration. Irrelevant modes: Text & video	Multiple representations can hinder learning by competing with relevant information or by overloading the brain's ability to process information.
4. Ainsworth, Bibby and Wood (2002)	Effects of multiple representations in learning primary-level mathematics	Pictures, mathematical symbols, and mixed pictures and symbols	Students in the mixed condition failed to improve, possibly due to translation difficulties.
5. Ainsworth and Van Labeke (2004)	Review of studies of the role of time in dynamic representations	Simulations using time-persistent, time-implicit, time-singular or static representations	Multiple representations may complement or hinder learning because different representations convey different information.

(narration) or verbally with text (combined narration-text) compared to receiving the same information in text form only. They also concluded that a stronger sense of immersion did not have a major effect on learning and that modality did effect learning. They also found that an effective modality in one type of media was effective in another form of media; therefore, it was not the media that made the modality effective.

Earlier, Mayer and Anderson (1992) conducted similar experiments on the effects of various combinations of narration and animations on problem solving and verbal retention. The experiments used computer animations of a bicycle air pump and an automobile braking system. They reported that the group that received animation with concurrent narration performed better on problem solving than the other groups (sequential alternations of animation and narration, animation only, narration only, and no instruction). In Mayer's studies we found the first hints that narration (an auditory representation) might be a powerful aid to understanding.

The results of the study are consistent with what Mayer and Anderson (1992) defined as the contiguity principle. This principle is based on dual coding theory (Clark & Paivio, 1991; Mayer & Anderson, 1991; Paivio, 1971,1990) that states that a learner can make three basic connections in multimedia situations that involve words and pictures: 1) a connection between external verbal information and the learner's internal verbal representation of that information, 2) connections between external pictorial information and the learner's internal visual representation of that information, and 3) referential connections between corresponding elements in the learner's verbal and visual representations (Mayer and Anderson, 1992). Due to the limits of working memory, the contiguity principle states "the effectiveness of multimedia instruction increases when words are presented contiguously (rather than isolated from one another) in time or space," (Mayer and Anderson, 1992, p. 444). This effect was demonstrated in the results.

Mayer et al. (2001) investigated the effects of additional text and interesting but conceptually irrelevant details and video (known as seductive details) on viewing an animation with concurrent narration. They conducted four experiments. In experiment 1, participants that received on screen text and seductive details remembered significantly fewer ideas on the retention test, and produced fewer creative solutions on the transfer tests. In experiment 2, participants that received no text retained significantly more ideas and created significantly more creative solutions on the transfer test compared to the text groups. In experiment 3, participants that did not receive the irrelevant video clips recalled more ideas on the retention test (though the results failed to reach statistical significance), and they generated significantly more solutions on the transfer test. In experiment 4, participants that viewed the irrelevant video clips *after* the animation retained more ideas than those that viewed the video clips prior to the animation, though the difference failed to reach statistical significance. The participants that viewed the video clips after the animation also generated significantly more solutions than participants that viewed the video prior to the animation.

The authors concluded that these results were consistent with what they defined as a *redundancy effect*, and a *coherence effect* (Harp & Mayer, 1997, 1998). The redundancy effect was defined as "adding redundant on-screen text to a narrated animation detracts from multimedia learning." (Mayer et al., 2001, p. 195). This effect is consistent with the *split attention hypothesis* that onscreen text may compete with animation for visual attention, thereby reducing the viewers' ability to notice relevant aspects in either representation (Mayer, 1997; Mayer & Moreno, 1998). When a single audio track is used concurrently with a single video track in a representation, there is a minimal load on the brain's audio and visual processing channels that allows a viewer to perform the active cognitive processes needed for meaningful learning (Mayer et al., 2001). When multiple visual tracks are provided (text and animation in this case) as well as an audio track, the processing channels in the brain carry a larger load, hindering the active cognitive processes needed for meaningful learning.

Support for the coherence effect was demonstrated in experiments 1, 3, and 4, where irrelevant details were added to the animations. The effect of the interesting but irrelevant details caused viewers to activate inappropriate prior knowledge that they then tried to fit into the new knowledge. The interesting but extraneous details may have had a positive effect on increased emotions and interest, but the effect on learning was hindrance.

In sum, Mayer's work gave us three important ideas about MERs. First, verbal narration combined with a visual representation, such as text or animation, was helpful in learning content. Mayer hypothesized that audio and visual inputs are processed in different centers in the brain and therefore the information carried in these representations could complement rather than hinder. Second, MERs that used the same channel, such as the visual input mode, might actually hinder learning because of an overload on the processing center. An example would be trying to use both a video and an animation simultaneously. Third, irrelevant details might hinder correct processing because they caused the learner to cue up inappropriate internal knowledge representations.

Finally, Shaaron Ainsworth's work has provided us with some very helpful ways of thinking about MERs. Ainsworth (1999) argued that multiple representations could play three major roles. First, they could mutually complement each other, second, a familiar representation could constrain and explain the interpretation of a more unfamiliar representation and, third, a combination of representations could work together to help student construct a deeper understanding of the topic. And of course, MERs could also interact to hinder understanding. Ainsworth argued that in the case of complementary roles, the use of multiple representations allowed a user to build an understanding through the information presented in each representation. Each representation could contain some information necessary to the task, representations could share some of that information, or perhaps one or more representations possessed some unique information not shared by the other representations. Multiple representations that were complementary allowed the user to create greater understanding via sharing or building upon all the information available.

In some cases multiple representations can constrain one another (Ainsworth, 1999). Here the purpose is not to create new information, but to assist the user in interpreting an unfamiliar representation through the use of a more familiar representation. For example, Ainsworth (1999) gave an example of interpreting velocity vs. time graphs using SkaterWorld, (Pheasey, O'Malley, & Ding, 1997). This program provided students with a dynamic cartoon of a skater and a velocity vs. time graph, that changed concurrently. According to Ainsworth, as the user manipulated the velocity, the graph changed to reflect the motion of the skater in the cartoon. An example with the SMV Chem program could be the video and graph representations. Action in the video and graph was concurrent and synchronized. Therefore, the students could have used the graph to explain the video, but the video may have been the more familiar representation, helping students to understand the graph. These constrained representations could assist in remediating misconceptions generated by certain representations, such as time vs. velocity graphs, or in clarifying ambiguities or uncertainties. Finally, multiple representations might be used to construct a deeper understanding of the topic. Students might use multiple representations to construct their understanding of a subject by organizing information and thoughts across several types of representations. This use of MERs might result in better learning than through using a single representation. For example, Mayer's work found that video and concurrent audio or animation and concurrent audio seemed to be more effective than either alone.

Ainsworth et al. (2002) have also pointed out that successful learning with multiple representations involved the ability to translate information between representations. Ainsworth et al. explored primary students' learning of estimation skills using paired pictorial, mathematical or mixed pictorial/mathematical representations. Children using the mixed representation experienced difficulties in learning to estimate, and the authors attributed these difficulties to the fact that they had to translate information between fundamentally different types of representations.

Another factor that is critical in scientific representations is the role of time in dynamic representations. Ainsworth and Van Labeke (2004) analyzed the role of time in a simulation of predator-prey populations and argued that time could play three distinct roles in dynamic representations. First, there were representations in which time was displayed over a range of values, such as a graph showing the changes in concentration of reactants over time. This was termed a *time-persistent* representation. Second, some representations, such as predator-prey population plots, implied a role for time but did not show time as a variable in the graph. This was termed a *time-implicit* representation. Third, a simulation could display a *time-singular* representation, such as the number of predators or prey on any given day. A time-singular representation differed from a static representation (such as a picture in a book) in that the time-singular representation could change, whereas a static representation could not change.

Ainsworth and Van Labeke argued that these different representations of time conveyed different types of information and that they had different computational properties. For example, time-persistent representations allowed learners to compare values of variables at different times and to display at all times a complete time history of the process being studied. This might allow the representation to function somewhat as an "auxiliary memory" (Nakhleh & Krajcik, 1993, 1994). A time-singular representation might be harder to interpret because the learner had to carry the time history of the process in memory in order to extract all relevant information. Ainsworth and Van Labeke stated that research into these aspects of multiple representations is still limited but badly needed if we are to effectively use technology to design instruction.

It is important to note that many of the previously discussed studies put students into situations where they had no ability to select the representations that might benefit them. These experiment/control studies were helpful in elucidating some of the ways in which representations might impact learning, but they did not investigate how students might use these representations to structure their own learning. Our study complements and extends the prior work in that our students were studied interacting with the program in an in-depth interview environment so that the students were free to select their own path and could discuss the reasons for their choices with us.

Studies of MERs Using the SMV CHEM Program

Ainsworth's taxonomy of MERs guided our investigation into the ways that students used the representations, and the reasons they gave for their choices. The rest of this chapter describes our ongoing investigations into how students have used multiple visual and auditory representations to develop their understanding of limiting reagents chemistry, using the SMV Chem program. SMV Chem was interactive in that it allowed learners to use five representations of a given chemistry topic in any order or combination that they chose. The program provided a series of modules that dealt with various general chemistry topics. For this study, we selected the limiting reagents module. This module demonstrated the limiting reagents concept through analyzing a vinegar and baking soda reaction. We chose limiting reagents because the topic provided students with many opportunities to explore the macroscopic, microscopic, symbolic, and mathematical levels in developing their understanding of the chemistry. Specifically we sought to identify the particular characteristics that made the visualizations effective in helping students create their understanding.

The four visual representations for this module consisted of a real-time video that represented the macroscopic level of understanding, a computer animation that represented the microscopic level, a graphical representation (symbolic level) consisting of an animated bar graph in which the heights of the bars changed according to the amount of carbon dioxide produced, and a text representation of a mathematical problem connected to the concept of limiting reagents. Each of these visual representations had an accompanying audio track that provided narration for the action that occurred when watching the representation. The audio track could be selected or not, according to the user's choice. Fig. 10.1 shows the visual representations that the learner can select to start the program. A button on the screen controls the audio track.

Phase I and Phase II of the study have been completed. Phase III is currently underway. Phases I and II were guided by two questions:

1. What representations were the most useful to students for constructing understanding?
2. What characteristics of the useful representations did students use to construct their understanding?

Phase I Participants

Three students from the first semester general chemistry for science and engineering majors volunteered to participate in interviews in Phase I. First-year general chemistry students were targeted because the intent of Phase I was to have the students use the SMV Chem program as part of a homework assignment. The participants had covered the topic of limiting reagents in lecture and had completed a homework assignment dealing with limiting reagents prior to their participation in the interview.

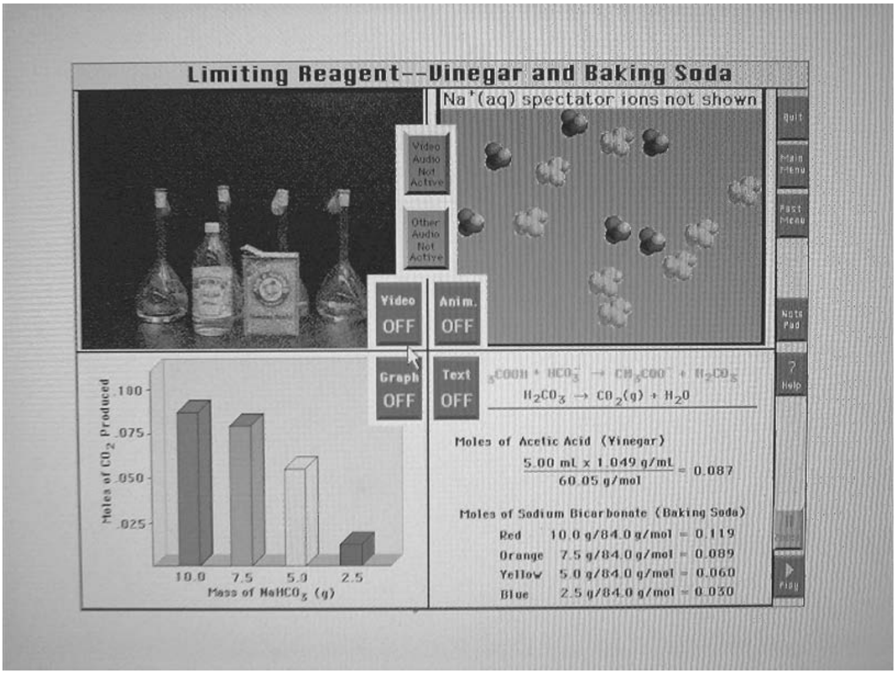

Fig. 10.1 SMV Chem visual representations

In the spring semester a second group of first-semester general chemistry students used module as part of their Web-based homework.

Phase I Context

The three volunteers who participated in the interviews learned how to use the program as part of the interview. SMV Chem required QuickTime to view the representations; therefore, students who used SMV Chem as part of their homework assignment were given the choice to use the program in the university computer labs or on a properly equipped personal computer. Instructions for using the program were provided on WebCT. In this paper we focused on the data that emerged from the student interviews.

Phase I Data Collection

We used a semi-structured interview protocol with the students. The interview included the guided use of SMV Chem (one representation at a time) with questions being asked upon the completion of a given representation. The students were asked to "think aloud" while using the representations if possible. After being exposed to all of the representations, the participants were asked to use any combination of representations that they might find helpful to enhance or create a better understanding of the concept of limiting reagents. Participants were then asked to comment on how they found their choices useful and what aspects of the representation(s) made those choices useful. Participants were next asked to work through a problem set designed to relate to each of the representations and to comment on how the program helped them to solve the problems. Fig. 10.2 displays a problem taken from the Phase I interview.

> You are given 4 flasks labeled A, B, C, and D. Each flask contains the same volume of the same concentration acetic acid (100ml of 5% by volume conc.). Securely attached to each flask are balloons that contain varying masses of baking soda.
> Assuming that no gas can escape from the balloons/flask, how you think the balloons will look after the reaction is complete in all 4 flasks?

The balloons attached to flasks A and B contain different amounts of baking soda, but both amounts are more than what is needed to react with the acetic acid completely. The balloons attached to flasks C and D contain amounts of baking soda that are less than the amount needed to completely react with the acetic acid.

The semi-structured format allowed us to probe students' thoughts about the representations. If a participant voiced thoughts that deviated from the interview protocol, we explored that deviation before returning to the protocol. Students were not asked questions that had simple answers, and they were encouraged to respond freely in a naturalistic manner.

The interview protocol contained three major sections. In the first section students explored the representations, and then they were asked questions about the representations. The second section probed their preferences for multiple representations in any sequence or combination. Students were asked to use any combination or sequence that they thought would be helpful. In the third section students worked through a problem set that related to the representations in the module. The students were asked to think aloud while they worked on the problems. Each interviewee was also asked if the module had been helpful in any way for working the problem.

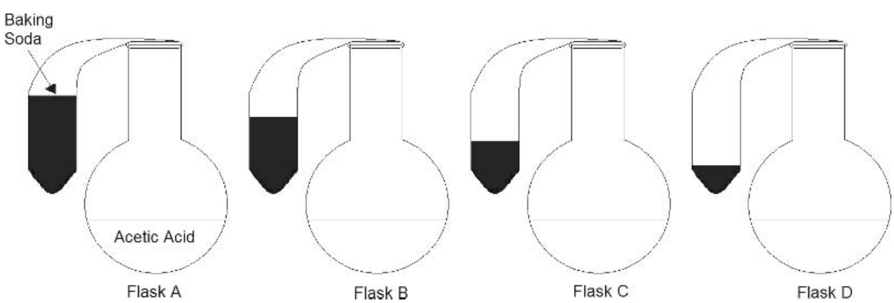

Fig. 10.2 Sample problem from the Phase I interview

Phase I Data Analysis

The interview transcripts were analyzed using an open coding scheme as described in Strauss and Corbin (1998) . Three levels of coding emerged: (1) The representation being used (primary level), (2) the interviewee's evaluation of the representation (secondary level), and (3) the interviewee's mention of specific aspects of the representation that determined the secondary level coding.

Passages of the transcript could be multiply coded. As an example, in Interview 3 the student stated that "Well I think the visuals are really helpful." In this case, the student did not state the specific representation, so we either asked what representation was being referenced or checked the video recording of the interview. The passage referred to the video, so the primary level was coded as Video (V). The secondary level was coded as Helpful (+). Finally, the tertiary level was coded as Visual (Vis) because it was the visual aspects of the video representation that were considered helpful in the context of the passage. The passage was completely coded as "V / + / Vis." Sometimes the primary level contained 2 codes, such as V, T / secondary / tertiary, where T stood for a text representation.

Finally, in the event that an interviewee did not indicate the particular aspects of a representation, the passage was not coded at the tertiary level, but only the primary and secondary levels. Inter-rater reliability checks were conducted for all levels of coding and found to be excellent (primary, 0.96; secondary, 0.91; tertiary, 0.93).

Phase I Results

Three trends emerged from the Phase I interviews. First, the macroscopic representation (video) of limiting reagents was the most useful in student construction of understanding whereas the microscopic representation (animation) was the least useful. Second, the audio track was definitely considered another representation and warranted further investigation. Third, the students' construction of understanding was affected by the sequence of representations they selected. Further, this sequence seemed idiosyncratic to them.

The video was the most useful representation, the animation was the least useful, and the graph and text were split between useful and not. The video depicted a hands-on demonstration, something that could be performed by anyone, regardless of chemistry background. However, the animation required at least some background knowledge of molecules, chemical reaction and bonding to be clearly understood. The students indicated that the speed of the animation was too fast to be useful (corrected for Phase II and III); that aspect may account for the animation's perceived lack of helpfulness.

An example of the audio track being considered as a representation can be found in Interview 2 where the student was discussing the graphical representation and its accompanying audio track:

> I2(F03): Uh yeah, it would be helpful but . . . the audio and the graph was just right but I feel that the video should have been present as well at this time. Not the audio from the video, just the video (p. 8, lines 123–5).

At another point in this interview, the student compared the video representation, the graphical representation and their accompanying audio tracks:

> I2(F03): . . . when I was seeing the graph and uh the video at the same time I was able to correspond both of them easily and I think that the audio which was used this time [graph audio] better explained as well (p. 9, line 130–2).

The student in Interview 1 also mentioned the audio while watching the text representation with its accompanying audio:

> I1(F03): . . . hearing somebody say it and seeing, seeing how . . . for me that's the way to hear it and see it at the same time and then I can still get it forever (p. 14, lines 208–10).

This student implied that seeing the calculation in text form while simultaneously hearing the explanation allowed him to understand the problem.

The third emergent trend indicated that both the sequence and combinations of representations appeared to be important to the students and were idiosyncratic. When asked what combinations were best for creating an understanding, the interviewees had their individual choices, and they also clearly indicated the order in which they would use the representations. For example, the student in Interview 1 clearly indicated a preference for using the video with either the graph or the animation. This is interesting because all of these representations are visual. Therefore, according to Mayer, we might expect that any combination of them would create an overload in the visual processing center of the brain. Perhaps the student was talking about using the representations in sequence rather than in combination. Alternatively, the graph was actually a very close symbolic mirror of the images in the video representation, so perhaps the two representations were similar enough to pose no major processing problems.

> I1(F03): Umm, in terms of combinations I'd say that these two were would work the best [video and graph] if you were just watching to the other (B: the video and the graph?). Yeah, the video and the graph. And then the uh, the video and animation, would be, another, is another good combination, but you'd wanna see that after you saw the video and the graph (p. 25, lines 397–400).

It is also telling that this student clearly indicated that he/she would start with the video and graph, which depict processes occurring on the macro level, and then move to the video and animation, where he/she might then attempt the more difficult feat of translating between the macro level and the molecular level interpretations of the process.

In Interview 2 the student clearly expresses a preference for using the video and the graph in a definite sequence. He/She would start with the video and then alternate between the video and the graph. Apparently the student is using each representation to constrain and clarify the other, as discussed in Ainsworth's taxonomy. We also note that this sequence would keep the student firmly on the macro level of observation and interpretation.

> I2(F03): Like I said . . . before, I'll go to the video. After that I would do this [animation and graph], then I would see this graph, after and then I would see this graph with the video again see how clarified it further, and last but not least I would see the other [text] (p. 15 lines 221–3).

In Interview 3 the student expressed a preference for a sequence using the video and then, interestingly, the audio track for the text representation. He/She was using the program, in general, for understanding limiting reagents. By "problem" the interviewee was referring to the mathematical operations required to determine the limiting reagent, as demonstrated in the text representation. The interviewee liked how the video demonstrated the concept of limiting reagents but preferred to work out the math his/herself to determine which substance was limiting.

> I3(F03): I would probably watch the video, umm, once maybe twice, . . . for the concepts in there, I would probably listen to the text audio once and then work out the problem by myself (p. 26, lines 376–8).

The interviewees each had a specific sequence for the individual representations or combinations of representations. We argue that this would indicate that the interviewees were using the representations in a constructivist manner to build their own cumulative understanding rather than relying on single representations.

Phase II Participants

Again three students from the first-semester general chemistry course volunteered to participate in Phase II. These students were interviewed using a revised protocol developed from our findings in Phase I.

Phase II Context

SMV Chem and a new related problem set were offered as an optional addition to the weekly homework assignment on limiting reagents. This new problem set contained more complex problems designed to encourage a greater depth of thought, and less rote memorization. The problems were designed to prompt the use of the different representations. The interview participants had all worked through the module and related problem set prior to the interview.

Phase II Data Collection

With insights from Phase I, modifications were made at the primary level of the coding scheme. A code for the use of audio was added, as it was now considered a representation. A code "All" (A) was also added, in order to simplify coding for the occasions when participants mentioned all representations rather than coding for An, Au, A, G, V, and T. Third, a code for the program in general was created (Gen).

The use of "Gen" was used when a participant mentioned the program as a whole or in general rather than a specific representation.

At the secondary level, a "placeholder" (code "0") was added. In the event that an interviewee mentioned a characteristic of a representation, but did not indicate whether that representation was helpful in creating an understanding, the placeholder was used to prevent confusion in comparing across levels.

Two modifications were made to the tertiary level. First, several additional codes were created for the tertiary level. For example, we added codes for motion, problem solving, mathematical operations, and personal experiences. Second, the tertiary level was modified by allowing multiple coding, similar to primary/secondary level coding. Inter-rater reliability checks for each level of coding in Phase II were conducted and found to be excellent (primary, 1.00; secondary, 0.94; tertiary, 0.93).

Phase II Results

The trends that were found both support and expand the findings of Phase I. As in Phase I, the students indicated that the video and representations were very important. Further, they saw the audio as complementary to other representations. The animation was criticized for its speed and excessive detail, but the students were quick to point out its potential usefulness for understanding molecular-level processes. The text representation was viewed largely as a template for problem solving, and the graph representation was viewed as complementary to the video.

Video. In all three interviews, the video was viewed as a positive representation because students saw the video as giving a sense of a real-time occurrence and real-life reinforcement akin to lecture demonstrations and lab experiments. However, it is interesting to note that the students were using the video representation in different ways.

The student in the first interview related visualizations to learning for younger students but recognized that "people still learn like that." This student also found the fun factor motivating.

> I1(F05): The video. Its... its fun. You know its actually like a lot of fun thing. Like I said, it relates to you when back in the day when you were watching... even they have it now. Fun, science programs for kids... and in many ways people still learn like that. People still need something like that.

The student in the second interview possibly used the representation as an overview of the experiment to understand the procedures involved as well as the outcome of the experiment. Interestingly, this student did not seem to regard the graph or text representations as helpful. Possibly he/she was simply trying to relate lecture material to lab and found that the video was the most helpful representation.

> I2(F05): The video, representation with the experiment, that actually explained a lot of things in lab what was actually happening in lab. Because even though you are working this stuff hands on in lab, you're being told what to do, you actually don't know why you are doing what you are doing, but if you're seeing someone else do it, it kinda makes more sense,

> seeing it. Umm, as for the graph and the text, that had nothing to do with my understanding of lecture material or the, um, lab, as he explained a couple of things like why there was a limiting reagent and things like that, but the video was the most helpful.

The student in the third interview appeared to be using the video to check on his/her predictions as to what would happen next in the experiment. In this case, the role of time seemed to be important. The student was comparing the different balloons with different amounts of baking soda in them and predicting how large each one would get when the reaction with acetic acid produced the CO_2 gas. Therefore, the time-persistent nature of the video would have helped the student make those comparisons and predictions.

> I3(F05): The video I thought was really helpful because umm, like when he poured the baking soda into the acetic acid, you could see how the carbon dioxide would fill the balloon more on the one with more baking soda than the one on the far right which had a lot less baking soda. You can see the reaction, they're saying [Both the audio and video were being used.], OK, this balloon isn't going to be as big because the baking soda is only going to react with this much acetic acid and just showing what's actually happening, numbers are like helpful, you can't really go wrong with numbers, but seeing an actual object that actually represents what they're trying to say, I think that's one aspect of this program that really helps.

Audio. The audio was also viewed as a positive representation in the sense of a verbal narration that reinforced what the student was seeing. The audio representation was mentioned as a useful representation due to the user using several senses and as a narration for what is being seen. All three of the students seemed to view the audio as complementary to other representations. This is consistent with arguments that audio and text may be processed differently in the brain, and therefore could reinforce each other (Mayer & Moreno, 2002; Mayer et al., 2001). This is also consistent with Ainsworth's taxonomy of constructive and destructive interactions of representations (Ainsworth, 1999).

The student in the first interview really seemed to buy into the idea of using multiple inputs in order to stimulate learning. He/She seemed to value using multiple representations simultaneously and specifically mentioned using a combination of visual, auditory and kinesthetic inputs. It is also interesting to note that this student specifically connects the module with learning lecture material. No mention was made of laboratory work,

> I1(F05): And it was really good to have it because ... the best way of learning I was taught that the more senses ... the better if you are going to be encoding into long-term memory. So, I'm listening, I'm looking, so that I'm using two of my senses, and I could be writing down and I could actually feel what I am writing down kinda thing. So I think the audio is good. Just having the images would be doing the lecture all over again, but you're trying get more in depth and not be just like the lectures but have something different. Because some people don't understand what the lecture is talking about. And its like... a different way to look at the lecture the way it was.

The student in the second interview clearly liked the audio and seemed to indicate that he/she could use the audio as a complementary representation to various visual representations.

> I2(F05): I like the audio, it was very helpful, that way I can follow along even if I can't understand what the text or I'm actually um, visual type and I can follow along with the volume.

The student in the third interview was talking about looking at the video representation and using the audio as a complementary representation. He/She closely connected the steps in the audio with the steps being performed in the video and valued that process of integration because it was different from pencil and paper representations or textbook representations. He/She seemed to value this alternative approach to learning chemistry.

> I3(F05): It was definitely clear, like as he was talking you could follow it really easy, saying "I'm gonna pour the baking soda in the acetic acid, and this one is gonna be a lot, this balloon on the left is gonna be a lot bigger than the balloons on the right," and you know. . . I guess when you hear what he is saying all along, hearing it, and seeing it in other ways than on pencil and paper, its all these alternatives, definitely somebody who learns differently than by just by sticking their face in the book really helps change their view on chemistry.

Animation. The animation was viewed in an interesting manner. The animation was viewed negatively because it moved at an uncomfortably fast rate and contained too much action and too many details to view at that speed. However, students commented that the animation, if slowed down and decluttered, could be potentially useful for helping them visualize the molecular level. The animation representation was mentioned in these two manners across all three interviews.

The student in the first interview seemed to think that having a molecular-level animation was a good idea. He/She seemed to want to use a combination of video and animation representations to help relate the macroscopic level of observation to the molecular level where theory is important. In a very real sense, chemistry is observed on the macroscopic level and interpreted on the molecular level, and this student seems to have grasped that concept.

> I1 (F05): Um hm. But I think this was a good idea [animation rep] I don't want you guys to remove the molecules because it. . . its something that you can actually visualize what's happening actually happening at the microscopic level because all you are seeing is the macroscopic level, you'd be seeing you know you're seeing that there [video], but if you go a little bit more in depth, and a lot of people, some people like seeing molecules like that and really interested to see more in depth. . .

The student in the second interview also wanted to keep the animation representation and also indicated that the task would influence his/her choice of representation. He/She appeared to couple the video representation with procedures to follow and the animation with learning underlying theory.

> I2 (F05): Yeah. Limiting reactants, things like that, anything that you need to have, um, a, glass or beaker or something that you are actually mixing things in, yeah, the video. But if I'm learning something that I just need to know the bonding molecular theory or um, intermolecular forces, or something like that, I think the animation. . .

The student in the third interview was also task-oriented but had a somewhat vague idea of the molecular level as being exclusively concerned with quantum theory. He/She thought that the animation was probably helpful for problems that specifically required quantum theory but did not seem the animation as helpful for other types of problems. To experts, the activities of molecules both constrain and explain the bulk processes observed on the macro level.

> I3 (F05): Those were the ones that were really the most helpful, seeing them like the quantum scale, can be helpful, but for the given problem, I don't think it was entirely necessary, like for, if you were doing, a lot of limiting reagent problems, like the, you don't need to see it on that scale in order to really get it. So, I don't, I really haven't been exposed to too many problems but, on limiting reagents and on the, that needed a quantum representation. It's helpful but, I didn't really use it.

Difficulties in using the animation were mentioned as well. These difficulties centered on the dynamics of the representation. The student in the first interview focused on the number of details displayed on the screen. Interestingly, he/she seemed to have considered using the audio as a complementary representation and concluded that it would have been information overload. This would seem to be an example of two representations that, in their present form, would interfere with learning.

> I1 (F05): Yes. The one that I was talking about that was really confusing, and that it just, there's so much things going on, like if I put it with both the audio and it going on, just watching it, it could drive you mad!

The student in the second interview focused on both the speed of the animation and the number of details on the screen.

> I2 (F05): But still, the molecules are moving too fast and I can't tell it looks like sometimes there's 2 reds in the box no green molecules, sometimes it looks like 2 green molecules and no red molecules and I'm not sure what is being what is happening because even the label at the top is moving too fast to actually understand it.

The student in the third interview brought up the important issue of color blindness and did not even mention the speed or clutter. This emphasizes the importance of considering physiological factors when designing MERs.

> I3 (F05): OK. I'm actually red and green color blind. So, when its, when they are saying that the red and green I wasn't, I might not have been too sure which one they were talking about, with those colors. I have little, like the same green in the chem lecture, like there might be diagrams going on, I'll be like, I think I see what is going on, but then what I see is different from what the teacher is saying.

Text. The text was regarded as helpful in a problem solving sense, but it was viewed both positively and negatively. In all three interviews, the text representation was mentioned as most useful for helping with or teaching problem solving. This was probably because the text representation was basically an example of how to solve a typical limiting reagent problem. However, the students seemed to focus on different functions for the template. For example, the student in the first interview seemed to regard the text simply as a template for dimensional analysis, i.e. keeping the units straight.

> I1 (F05): It seems the units inside the calculations would help, but, and really that much, and then when you have... it's just right now it's orientated to give you the answer, and to help you figure out the answer. This doesn't really explain as well how, like, this is exactly

> happened, this was cancelled out, because this was on top and this was on the bottom cancel it out. It just pretty much shows, this is what you got to do, and this is the answer.

However, the student in the second interview seemed to use the template idea for both setting up the formula and dimensional analysis.

> I2 (F05): ... basically I used the text when I am working out the problems and I'm kinda unsure of what I am supposed to be doing. Uh, I used it for the formula to be sure that I had the correct equation and I also compared with the moles of the vinegar and the baking soda that I was using, and be sure that I had the correct milliliters of the vinegar, that was in the problem.

Finally, the student in the third interview seemed to use the template concept as a method of analyzing the different parts of the problem.

> I3 (F05): Like if had, if you were calculating like the number or the different number of grams of the limiting, or the excess reagent shown in the example problem, because you don't have, like you have all the things you need to calculate a limiting reagent problem but it doesn't show you how to solve a limiting reagent problem, it just shows you the different parts of it.

Graph. Students seemed to have viewed the graphic representation as complementary to the video. The graph was seldom mentioned and then only as reinforcement to the video, not as being particularly useful by itself. It is important to note that the video showed a sequence of balloon-capped flasks inflating to varying degrees according to the concentrations of reactants and that the graph was a set of bars whose heights corresponded to the sizes of the balloons in the video. Also, it is important to note the role of time in each representation. The bars in the graph and the balloons in the video both "inflated" at the same rate. Therefore, time was both persistent and dynamic in each representation. Clearly, the students thought that the video and graphic representations constrained and explained the other on the macroscopic level.

The student in the first interview simply indicated that the video constrained and explained the graph for him/her. In this passage we transcribed the gas as CO2 rather than CO_2, as we had no indication whether the student was thinking molecularly.

> I1 (F05): The graph, I kind of didn't understand it alone... watching it with the video kind of helped because it just gave me like a better understanding of what was going on with the video with this (points at graph and video) like what physically was going on with the video with this (graph) like what was physically going on like you could see the balloon getting bigger but it actually shows you what is increasing and what is staying behind if you have more of this how big that goes how much CO2 is produced like you can relate that to the balloon.

The student in the second interview also used the video to help him/her understand the graph. This student, however, seemed to focus on the amount of reactants present rather than on the changes in the balloons and bar graph.

> I2 (F05): The graph, I'd have to say, took me a while to figure out which, which was x and y axis. Umm, once I found that out I went, I took the numbers and went back to compare it to the numbers labeled on the flask of the baking soda being added to the vinegar [in

the video representation]. And then I was able to see what was happening. Umm, the mass of the carbon dioxide produced, that was totally confusing. I didn't know what they were talking about, so I was concentrated on the mass of the sodium, uh, baking soda they would use.

The student in the third interview seemed to combine the video and graph representations in order to understand the reaction, and then he/she went to the text representation to study the calculations.

I3 (F05): . . . because the, the video of the baking soda actually going into the vinegar and the bar graph was a good enough representation that I was able to see it, and then I looked at the text to see how the, what the calculations were, for that. . . Those were the ones that were really the most helpful. . .

Implications and Future Studies

We hope that the results we have presented thus far into our research have illustrated some of the benefits of paying attention to how MERs interact to constrain, explain, complement and/or hinder learning. We were encouraged to observe that students were indeed able to utilize logical combinations and sequences of MERs to construct their understanding and that they were able to articulate their reasons for those choices. We also noted that although students might select the same representation (such as the text) and the same function (such as a template), they focused on different aspects of the function so as to construct their own task-mediated understanding.

We also noted that, for chemistry at least, the video representation on the macroscopic level seemed to be the preferred point of entry into learning about limiting reagents. From that point on, students seemed to construct combinations and sequences of representations to accomplish the task before them. Therefore, one implication for teaching might be to ensure that modules using MERs have a video representation on the macroscopic level and that this representation be explicitly synchronized with the other video representations. Second, students might also need control over the speed of these representations, particularly the animations. Third, all representations should be uncluttered and stripped of extraneous details. Fourth, the nature of the task is of particular importance in getting students to observe macroscopically and explain molecularly. Simply asking students to solve numeric problems, while important, do not seem to encourage full use of all the information available in the representations. Fifth, the audio representation is a vital link in building understanding because of its ability to be used simultaneously with visual representations.

MERs represent an exciting new area of chemical education research, and we hope that this research may help designers to create new programs to help students learn through the use of multimedia / interactive representations.

References

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

Ainsworth, S. E., Bibby, P. A., & Wood, D. (2002). Examining the effects of different multiple representational systems in learning primary mathematics. *The Journal of the Learning Sciences, 11*(1), 25–61.

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

Ainsworth, S. E., Wood, D. J., & Bibby, P. A. (1996). Co-ordinating multiple representations in computer based learning environments. In P. Brna, A. Paiva, & J. Self (Eds.), *Proceedings of the European conference of artificial intelligence in education* (pp. 336–342). Lisbon: Edicoes Colibri.

Ainsworth, S. E., Wood, D. J., & O'Malley, C. (1998). There's more than one way to solve a problem: Evaluating a learning environment to support the development of children's multiplication skills. *Learning and Instruction, 8*(2), 141–157.

Barnea, N., & Dori, Y. J. (1996). Computerized molecular modeling as a tool to improve chemistry teaching [Electronic version]. *Journal of Chemical Information and Computer Sciences, 36*, 629–636.

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

Hakerem, G., Dobrynina, G., & Shore, L. (1993, April). *The effects of interactive, three dimensional high speed simulations on high school students' conceptions of the molecular structure of water*. Paper presented at the annual meeting of the National Association for Research in Science Teaching, Atlanta, Ga. Retrieved June 17, 2003, from ERIC.

Harp, S. F., & Mayer, R. E. (1997). The role of interest in learning from scientific text and illustrations: on the distinction between emotional interest and cognitive interest. *Journal of Educational Psychology*, 89, 92–102.

Harp, S. F., & Mayer, R. E. (1998). How seductive details do their damage: a theory of cognitive interest in science learning. *Journal of Educational Psychology*, 90, 414–434.

, Kelly, R. M., & Jones, L. L. (2006, April). *Exploring how animations of sodium chloride dissolution affect students' explanations*. Paper presented at the National Association for Research in Science Teaching, San Francisco, CA.

Kozma, R. B., & Russell, J. (1997). Multimedia and understanding: expert and novice responses to different representations of chemical phenomenon. *Journal of Research in Science Teaching*, 34, 949–968.

Lester, J. C., Stone, B. A., & Stelling, G. D. (1998). Lifelike pedagogical agents for mixed-initiative problem solving in constructivist learning environments. In A. Kosba (Ed.), *User modeling and user-adapted interaction* (pp. 1–46). Boston, MA: Kluwer Academic.

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

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

Mayer, R. E., & Anderson, R. B. (1992). The instructive animation: helping students build connections between words and pictures in multimedia learning. *Journal of Educational Psychology, 84*, 444–452.

Mayer, R. E., Heiser, J., & Lonn, S. (2001). Cognitive constraints on multimedia learning: when presenting more material results in less understanding. *Journal of Educational Psychology, 1*, 187–198.

Mayer, R. E., & Moreno, R. (1998). A split-attention effect in multimedia learning: evidence for dual processing systems in working memory. *Journal of Educational Psychology, 90*, 312–320.

Moreno, R., & Mayer, R. E. (2002). Learning science in virtual reality multimedia environments: role of methods and media. *Journal of Educational Psychology, 3*, 598–610.

Moreno, R., & Mayer, R. E. (2002). Learning science in virtual reality multimedia environments: role of methods and media. *Journal of Educational Psychology*, 92, 117–125.

McKendree, J., Small, C., Stenning, K., & Conlon, T. (2002). The role of representation in teaching and learning critical thinking. *Educational Review, 54*, 57–67.

Nakhleh, M. B., Donovan, W. J., & Parrill, A. L. (2000). Evaluation of interactive technologies for chemistry websites: Educational materials for organic chemistry website (EMOC). *Journal of Computers in Mathematics and Science Teaching, 19*, 355–378.

Nakhleh, M. B., & Krajcik, J. S. (1993). A protocol analysis of the influence of technology on students' actions, verbal commentary, and thought processes during the performance of acid-base titrations. *Journal of Research in Science Teaching, 30*(9), 1149–1168.

Nakhleh, M. B., & Krajcik, J. S. (1994). Influence of levels of information as presented by different technologies on students' understanding of acid, base, and pH concepts, *Journal of Research in Science Teaching, 31*(10), 1077–1096.

Paivio, A. (1971). *Imagery and cognitive processes*. New York: Holt, Rinehart and Winston.

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

Pheasey, K., O'Malley, C., & Ding, S. (1997). A distributed collaborative micro-world to teach Newtonian mechanics. In S. Vosniadou, K. Matsagouras, K. Maridaki-Kassotaki, & S. Kotsanis, *7th European conference for research on learning and instruction*. Athens: Gutenberg University Publications.

Russell, J. W., Kozma, R. B., Becker, D., & Susskind, T. (2000). *Synchronized multiple visualizations of chemistry* [CD-ROM]. John Wiley and Sons.

Russell, J. W., Kozma, R. B., Jones, T., Wykoff, J., Marx, N., & Davis, J. (1997). Use of simultaneous-synchronized macroscopic, microscopic and symbolic representations to enhance the teaching and learning of chemical concepts. *Journal of Chemical Education, 74*, 330–334.

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

Sanger, M. J., & Greenbowe, T. J. (2000). Addressing student misconceptions concerning electron flow in aqueous solutions with instruction including computer animations and conceptual change strategies. *International Journal of Science Education, 22*, 521–537.

Schoenfeld, A. H., Smith, J. P., & Arcavi, A. (1993). Learning: The microgenetic analysis of one students' evolving understanding of a complex subject matter domain. In R. Glaser, *Advances in instructional psychology volume 4,* (pp. 55–175). Hillside, NJ: Earlbaum.

Strauss, A., & Corbin, J. (1998). *Basics of qualitative research: Techniques and procedures for developing grounded theory* (2nd ed.). Thousand Oaks, CA: Sage.

Williamson, V. M., & Abraham, M. R. (1995). The effects of computer animation on the particulate mental models of college chemistry students. *Journal of Research in Science Teaching, 32*, 521–534.

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

Chapter 11
Representational Resources for Constructing Shared Understandings in the High School Chemistry Classroom

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Abstract This chapter reports on the use of representational resources within a computer-based environment, called *ChemSense*, to support high school chemistry students' representational practices and their understanding of key chemical concepts. In designing *ChemSense*, we hypothesized that it would provide students with symbolic resources they could use to jointly construct representations of observable physical phenomena and to explain these phenomena in terms of underlying chemical entities and processes. This study examines the role that these representational resources play in supporting students' representational practices and their emerging chemical understanding. To elucidate how *ChemSense* supports the development of representational practice and chemical understanding, we provide an analysis of students' conversation while they use *ChemSense* in the laboratory. Our findings indicate that students use *ChemSense* to construct their shared understanding of chemical phenomena in a common representational space. Their representations serve as key symbolic resources in students' collaborative efforts to generate coherent explanations of the phenomena they are investigating. On the basis of our analysis we conclude that when using representational resources as part of collaborative investigations, the nature of students' conversation becomes more "chemical" and students deepen their understanding of the molecular nature of physical phenomena that have, as a result, become chemical.

Introduction

In an important sense, chemistry is the practice of using representations to understand molecular phenomena (Hoffmann & Laszlo, 1991). In the history and current practice of chemistry, understanding molecular properties and processes has been a challenge, in large part because molecules and their properties are not available

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to direct perception. Consequently, chemists have designed a range of representational systems that mediate between something that they cannot see and something that they can. Some representations—such as formulas, equations, and structural diagrams—are generated by the scientists themselves to conceptualize, plan, and interpret the results of the research they are conducting. Some representations are generated by research instruments, such as spectrographs and chromatographs, which give physical manifestation to certain aspects of molecules, such as the mass of their structural components. And some representations, specifically graphical molecular models, are generated by scientists using computer technology.

However they are created, making meaning with representations is a core practice of the chemistry community and is essential to the understanding that chemists have of their domain. In an observational study of chemists in their laboratories, Kozma, Chin, Russell, and Marx (2000) found that chemists used a variety of representations together to construct an understanding of the chemical phenomena they investigated in their experiments. Chemists used structural diagrams to describe the composition and geometry of the compounds that they were trying to synthesize. They used diagrams and chemical equations to reason about the reaction mechanisms needed to transform reagents into products and the physical processes that would support these transformations. Chemists analyzed various instrumental displays and printouts to verify the composition and structure of the compounds that they were trying to synthesize. As they worked together to understand the results of their investigations, chemists made references to specific features of the printouts (e.g., peaks on nuclear magnetic resonance or mass spectra) as warrants for claims that the desired products were obtained. In the course of their collaborative work, they both draw on and contribute to the shared understanding of their domain as it is encoded in their representational systems. In this regard, the meaning of the symbolic representations and the physical phenomena to which they refer are mutually constitutive and reify one another (Roth, in press). That is, the meaning of the chemical representations emerges out of chemists' interaction with the specific phenomena in the laboratory, and at the same time the laboratory phenomena become socially constructed as "chemical" through the use of these representations.However, the deep understanding and rich representational practices of chemists stand in sharp contrast to those of chemistry students. In Kozma's (2000a) observations of university students enrolled in an organic chemistry course, there was little use of representations during their wet-lab experiments. The primary interaction among student lab partners was focused on setting up equipment, troubleshooting procedural problems, and interacting with the physical properties of the reagents they were using (e.g., was their crystalline product washed enough or dry enough). Unlike the discourse of chemists, Kozma observed very little discussion among students about the molecular properties of the compounds they were synthesizing or the reaction mechanism that might be taking place during their experiments.

The poor representational practices of students in the laboratory observed by Kozma correspond to results from other studies (Hinton & Nakhleh, 1999; Gabel, 1998; Nakhleh, 2002; Kozma & Russell, 1997). Too often, students do not relate phenomena they perceive in the laboratory (reagents precipitating or changing color) to underlying entities and processes (bonds forming or breaking between atoms) (Bunce & Gabel, 2002; Hinton & Nakhleh, 1999). At the same time, students are able to solve chemical equations but do not know how these connect to the aperceptual chemical phenomena they represent (Dori, Barak, & Adir, 2003; Hinton & Nakhleh, 1999; Nakhleh, Lowrey, & Mitchell, 1996). As a result, the representations and related practices that are so meaningful and useful to chemists are relatively meaningless to students, and they are not able to use these to develop a chemical understanding. As Krajcik (1991) points out, although students frequently become good at manipulating chemical symbols, they often treat them as mathematical puzzles without possessing an understanding of the chemistry that corresponds to these symbols.

The root cause of this problem, we believe, is the way representations are typically used in chemistry courses. Standard chemistry textbooks are filled with problems at the end of each chapter for which students manipulate various representations to get the correct answer, but these problems do not correspond to experienced laboratory phenomena. Or as part of their laboratory report, students are asked to compute the concentration of reagents at different temperatures, but their procedures are mechanical and not part of authentic laboratory investigation. The lack of connection between representations and their meaning is due to the disconnection between representational use and the practice of laboratory chemistry.

In the design experiment reported in this paper, we address this problem. We report on the use of representational resources in a high school chemistry laboratory that were designed specifically to support the development of students' skills in the use of representations in a laboratory context and the development of their understanding of the chemical nature of the phenomena that they investigate. In this report, we describe the computer-based environment that we designed, called *ChemSense*, and we list the theory-based hypotheses embedded in the particulars of its design. We examine the impact of the use of the environment on the representational competence and chemical understanding of high school chemistry students. We also analyze the conversation of students while they use *ChemSense* in the laboratory to elucidate the mechanisms by which *ChemSense* supports the development of representational practice and chemical understanding.

Theoretical Perspective

The theoretical perspective we take in our research and design is situative. In brief, situative theory posits that the concrete details of settings shape social and psychological processes of participants through the constraints and affordances of the material, informational, and social systems that characterize the setting (Greeno, 1998; Roth, 1998, 2001). *Constraints* are those characteristics that structure and to some extent limit the range of possible actions within the system. *Affordances* are those resources in the environment and enabling characteristics of the person or group that increase the range of possible actions in certain ways.

Situative analyses emphasize communication and reasoning about and with physical objects (tools, artifacts, etc.) and events in the setting of an activity. *Representations* serve a special function within the situative theoretical perspective since representations do not have meaning in themselves. Rather, meanings are characterized as relationships between the representations and the objects and events to which the representations refer but that are not present. As such, representations—such as written or drawn symbols, iconic gestures or diagrams, and spoken, gestured, written, or drawn indices—are not intended to be treated as objects themselves but as things that "stand for" or "refer to" other objects, representations, or situations. That is, the meanings of representations do not inhere in the qualities of the representations themselves but are derived as people interpret them, thereby constructing semiotic, "refers-to" relations between occurrences of the representation and entities or events that they designate. Creating these refers-to relationships is an important practice of a community and a source of their shared understanding.

As people engage in activities in a community, they become "attuned" to the affordances and constraints of the material and symbolic resources of its various settings. Crucial to the function of any social system or community are the conventions of interpreting meanings of representations. Likewise, attunements to the constraints and affordances of these conventions are essential for an individual's emerging participation in the practices of a community.

From a situative perspective, learning can be viewed largely as a progressive attunement to disciplinary ways of seeing and using representations within a community (Goodwin, 1995; Greeno & Hall, 1997; Stevens & Hall, 1998). Accordingly, recent efforts to examine science learning *as* participation in legitimate scientific activity—its particular discursive and behavioral forms, including experimentation and analysis—have focused increasingly on the characteristics and social use of scientific representations (Lemke, 1990; Roth, 1995). From the situative perspective, Greeno (1998) characterizes classrooms that are oriented to these practices as ones that encourage students to participate in activities that include the formulation and evaluation of conjectures, examples, applications, hypotheses, evidence, conclusions, and arguments—consequently promoting conceptual growth and skill acquisition in relation to these participatory activities. In such classrooms, discussions are organized to foster not only students' learning of the subject-matter domain but also their learning to participate in the discourse practices that organize the discussions. Students in these settings use representations to express their understanding of key concepts in the domain and, perhaps more importantly, to learn to use those representational systems in developing and sharing their understandings of questions, hypotheses, and arguments in the domain. Such student practice reflects recent thinking in pragmatics (e.g., Clark, 1996), ethnomethodology (e.g., Schegloff, 1992), linguistic anthropology (e.g., Hanks, 1999), and learning theory (Barron, 2003) that emphasizes the role of discursive representations and phenomenal objects as referential resources in establishing intersubjectivity and shared attention in the joint construction of meaning.

Using the situative perspective, we have designed a representational system—*ChemSense*—to support students' representational practices in the context of structured activities and laboratory investigations. The intent of our design is both to support student understanding of key chemical concepts and to develop their skills in using representations in this context.

Representational Technology and *ChemSense*

The *ChemSense* environment offers an ensemble of tools that enable students to create their own representations of chemical phenomena (Schank & Kozma, 2002). The basic premise of the *ChemSense* design is that these tools will be used within a social context of structured, collaborative investigations of physical phenomena in the wet lab. Students use the tools in *ChemSense* to construct their shared understanding of chemical phenomena in a common representational space and do this within a classroom and task context that includes physical lab equipment and data collection probeware. The environment has specific affordances and constraints designed to support and shape the representational practices and shared meaning making within an emerging student chemistry community in ways that are analogous to those of chemists.

Figure 11.1 shows the basic layout of *ChemSense* as used in the study. The environment contains a set of tools—drawing, animation, graphing, and text tools—for creating and viewing representations and a threaded discussion section for peer review. The environment also includes a reference periodic table and a simple HTLM editor for creating Web-friendly lab reports. The tools within *ChemSense* are simple by design, containing only the primitive components necessary to construct a full array of chemical structures.

Several examples of student-generated items can be seen in Fig. 11.1. In the center of the window is an animation that students created to show the process of sodium chloride (NaCl) dissolving in water. To create this animation, the students constructed individual frames that stepped through the breaking of ionic bonds between the Na^+ and Cl^- ions and the subsequent "hydration," or surrounding of the ions by the water molecules. To the right of the animation is the display of a dynamic graph that shows student-collected data on the change in the amount of dissolved oxygen in a solution. These data were collected at the lab bench through the use of probeware (developed by PASCO Scientific, Roseville, CA) and imported into the *ChemSense* environment. Other features and functions are shown in the figure, such as the navigation structure (left), periodic table (top right), and a student-created text entry in the threaded discussion that poses a question about solutions (top center).

In its use, *ChemSense* requires students to make critical design decisions while creating representations, and in this way it is designed to shape the way students think and talk about representations, physical phenomena, and underlying chemical entities and processes. To highlight this point, an example student activity will be discussed—the dissolving of salt (NaCl) in water. This activity was investigated by lab groups in this study and is analyzed in detail in later sections of the article. But for the moment we will use this example as a way to illustrate the use of the features

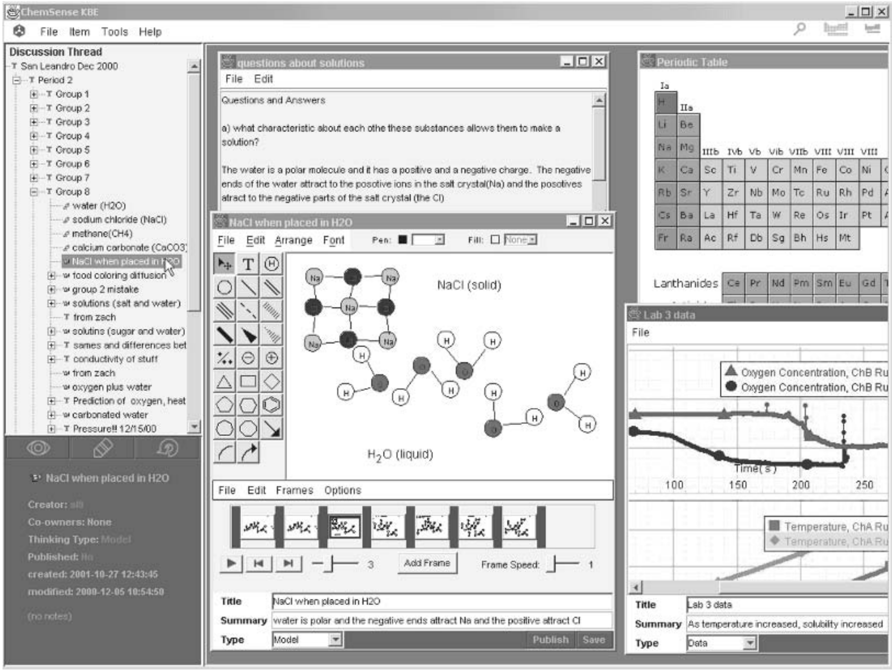


Fig. 11.1 The *ChemSense* workspace, showing a sample high of school student work

and functions of *ChemSense*, as well as the rationale around which these features and functions were designed.

In this sample activity, students are asked to create a nanoscopic-level representation showing what happens when sodium chloride is dissolved in water. Since this dissolving process takes place over time, the students use the animation tool to build their representation of this dynamic process. Upon opening a new animation window, they are confronted with a set of design decisions regarding how to represent their understanding of the salt dissolving process. They are immediately confronted with a series of decisions: What does a water molecule look like? What is the structure of sodium chloride? What happens to the water and sodium chloride structures as they meet? A specific design decision in the development of *ChemSense* was *not* to provide a complete menu of preconstructed molecules so that students would be confronted with these very decisions.

As students begin creating, for example, a water molecule, they make choices from the animation tool palette (Fig. 11.2) to create their representation. As seen in Fig. 11.2, the palette contains only basic, elemental representational components such as atoms, bonds, and organic structures. The students use these basic building blocks to construct their representation as they negotiate a new set of decisions around the construction of the molecule: Which atoms are involved? How many are there of each kind? What type of bond exists between atoms? Which atoms are bonded to which? What are the spatial arrangements of the atoms? How do

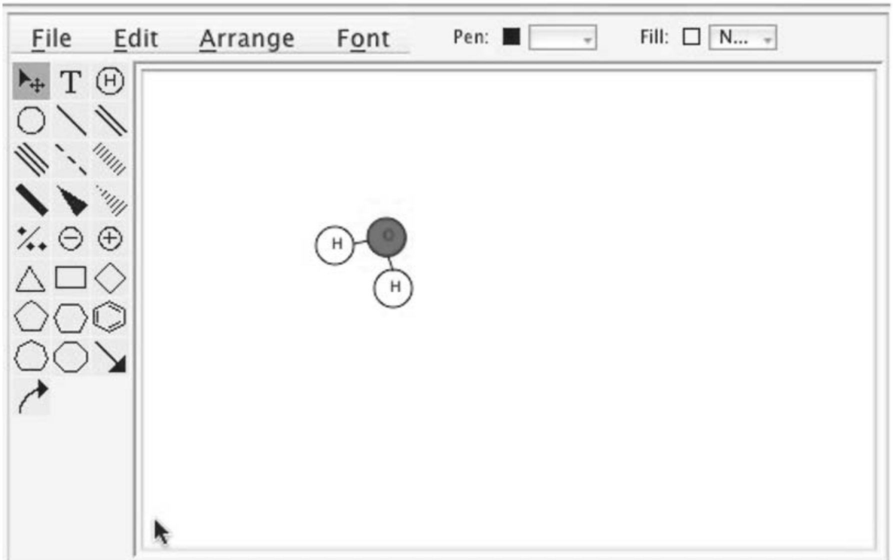


Fig. 11.2 The *ChemSense* drawing tool palette. The palette (left) contains basic chemistry components—atoms, bonds, structures—that students use to create representations

these arrangements change over time? As is the case of all molecular structures in *ChemSense*, a student cannot simply select a "water molecule" option and stamp out a set of H_2O molecules.[1]

The *ChemSense* environment also gives students the means to coordinate nanoscopic representations with observable phenomena by using probeware.[2] This feature allows students to import graphical or tabular data directly into their representations from bench-top investigations and other inquiry-based activities (Krajcik et al., 1998; Roth & Bowen, 1999). For example, students collect wet-lab data such as temperature or dissolved oxygen content and import the data into *ChemSense*. They are then able to create and run two representations—a nanoscopic-level representation showing the underlying process and a tool-generated representation showing the change in observable properties. The goal of using two representations that show parallel changes at the nanoscopic and physical levels is to get students to construct "refers to" relationships and to use representations at the nanoscale to explain the emergent properties of what they see on the lab bench. The empirical, data-generated representations (e.g., graphs) say more than the physical

[1] To avoid tedium, once the student designs one molecule, she can easily group the components of the molecule, copy them, and then stamp out multiple copies of her design.

[2] PASCO data collection tools, which students used in conjunction with *ChemSense* for this study, allow collection of real-time chemical data, such as temperature, pH, and dissolved oxygen, over a specified time period. Using a small "interface box" that is connected between the individual probes and the computer, data are collected directly into the computer, at which point they can be represented, analyzed, and imported into *ChemSense*.

manifestations of chemical reactions on the lab bench (e.g., the salt dissolving in water) and allow chemistry students to think and talk about the nanoscopic entities and phenomena that account for the physical changes. Our intent is that data-generated representations will help students confirm or disconfirm what they *think* is going on at the nanoscopic level with what actually happens on the lab bench.

ChemSense is used in the context of specially designed curriculum units and investigative activities that scaffold student use of interconnected forms of visual and discursive representations and ask students to describe, explain, and argue about the chemical experiments they are conducting on the lab bench. In addition the "knowledge-building" function of the environment allows students to peer-review each other's work through threaded discussion and commentary. For example, a teacher may include as part of an activity a section toward the end of a unit that asks students to "review the work of two other lab groups and ask two questions related to the chemistry in their representation." As part of their "assignment," each lab group is responsible for providing critical feedback on other students' work. Used appropriately, this function further supports the possibility for students to collectively arrive at new understandings of scientific concepts by asking students to probe other students' thinking (compare with Bell & Linn, 2000; Brown & Campione, 1996; Greeno, 1998; Kozma, 2000b; Linn, Bell, & Hsi, 1998; Pea, 1992, 1994; Scardamalia & Bereiter, 1994).

Together, the *ChemSense* tools and pedagogical activities are intended to help students bridge the gap between what they can see and the underlying processes that drive chemical reactions—to use representational practices to develop their chemical understanding. Our overall design hypothesis is that students' ability to readily generate representations at the nanoscopic level helps them move from simply depicting surface features of chemical phenomena to understanding chemical phenomena in terms of underlying molecular entities and processes. Consequently, our analysis of this learning process focuses on the role of *ChemSense* in enabling two important and interrelated lines of development: representational competence and chemical understanding.

Representational Competence

A major goal in our design of *ChemSense* is that while using various representations to negotiate a shared understanding of chemistry, students will become progressively attuned to a chemical way of using representations to analyze phenomena. "Representational competence" is a term we use to describe a set of skills and practices that allow a person to reflectively use a variety of representations, singly and together, to think about, communicate, and act on aperceptual physical entities and processes (see Kozma, 2000c). While those with little representational competence in a domain rely primarily on the surface features of representations to derive meaning (Chi, Feltovich, & Glaser, 1981; diSessa, Hammer, Sherin, & Kolpakowski, 1991; Kozma & Russell, 1997) or on the mechanical application of symbolic rules (Krajcik, 1991), those with more skill have come to use a variety of formal and informal representations together to explain a phenomenon, support a claim, solve a problem, or make a prediction within a community of practice (Amman & Knorr Cetina, 1990; Dunbar, 1997; Goodwin, 1995; Kozma & Russell, 1997; Kozma et al., 2000; Woolgar, 1990). For chemists, the act of using representations to successfully construct chemical understanding at once constitutes the meaningfulness of the representation and confirms the user's ability to participate in this representational, meaning-making activity (Kozma et al., 2000). One can neither understand chemistry without using representations nor use representations of the domain without some understanding of chemistry. These skill sets mutually evolve and constitute each other. Consequently, representational competence is the complement of chemical understanding, the first focusing on the activity of using representations and the second focusing on the resultant meaning construed from this activity.

To characterize this skill set, we propose a conceptual structure that organizes representational competence into characteristic patterns of representational use at five stages or levels (Table 11.1). This structure corresponds to a developmental trajectory that generally moves from the use of surface features to define phenomena, which is characteristic of novices within a domain, to the rhetorical use of representations, which is characteristic of expert behavior.

We use this structure to analyze the extent to which the design features of *ChemSense* and the corollary laboratory activities and social discourse support students' emergent representational competence. For this study, we developed assessments that engage students in the use of representations to describe and explain chemical phenomena. They are paper-and-pencil assessments not used in a social context. Consequently, the assessment focuses primarily on levels 1–4. We have also developed sets of rubrics to code and analyze these assessments and other representational acts.

Chemical Understanding

A second goal in our design of *ChemSense* is that while constructing and using representations students will come to have a deeper understanding of laboratory phenomena in terms of underlying chemical concepts. A distinguishing characteristic between expert and novice use of chemical representations is that novices associate various representations by their common superficial features, whereas chemists associate them by their shared underlying, fundamental concepts (Kozma & Russell, 1997). The underlying, fundamental chemical concepts referred to in our analysis can be systematically organized to provide a comprehensive, nanoscopic-level framework that characterizes crucial aspects of chemical phenomena and constitutes a curriculum of sorts that we want students to understand as a result of using *ChemSense*.

To this end, we have developed five fundamental chemical dimensions or "themes"—connectivity, aggregation, geometry, concentration, and state—that correspond to basic curricular themes set out in the *AAAS Benchmarks* (AAAS, 1993) and cut across all traditional introductory chemical topics, such as acid-base

Table 11.1 Summary of representational competence levels

Level	Description
Level 1: Representation as depiction	When asked to represent a physical phenomenon, the person generates representations of the phenomenon based only on its physical features. That is, the representation is an isomorphic, iconic depiction of the phenomenon at a point in time.
Level 2: Early symbolic skills	When asked to represent a physical phenomenon, the person generates representations of the phenomenon based on its physical features but also includes some symbolic elements to accommodate the limitations of the medium (e.g., use of symbolic elements such as arrows to represent dynamic notions, such as time or motion or an observable cause, in a static medium, such as paper). The person may be familiar with a formal representational system, but its use is merely a literal reading of a representation's surface features without regard to syntax and semantics.
Level 3: Syntactic use of formal representations	When asked to represent a physical phenomenon, the person generates representations of the phenomenon based on both observed physical features and unobserved, underlying entities or processes (such as an unobserved cause), even though the representational system may be invented and idiosyncratic and the represented entities or processes may not be scientifically accurate. The person is able to use formal representations correctly but focuses on the syntax of use, rather than on the meaning of the representation. Similarly, the person makes connections across two different representations of the same phenomenon based only on syntactic rules or shared surface features, rather than the shared, underlying meaning of the different representations and their features.
Level 4: Semantic use of formal representations	When asked to represent a physical phenomenon, the person correctly uses a formal symbol system to represent underlying, nonobservable entities and processes. The person is able to use a formal representational system based on both syntactic rules and meaning, relative to some physical phenomenon that it represents. The person is able to make connections across two different representations or transform one representation to another based on the shared meaning of the different representations and their features. The person can provide a common underlying meaning for several kinds of superficially different representations and transform any given representation into an equivalent representation in another form. The person spontaneously uses representations to explain a phenomenon, solve a problem, or make a prediction.

Table 11.1 (*Continued*)

Level	Description
Level 5: Reflective, rhetorical use of representations	When asked to explain a physical phenomenon, the person uses one or more representations to explain the relationship between physical properties and underlying entities and processes. The person can use specific features of the representation to warrant claims within a social, rhetorical context. He or she can select or construct the representation most appropriate for a particular situation and explain why that representation is more appropriate than another. The person is able to take the epistemological position that we are not able to experience certain phenomena directly and that these can be understood only through their representations. Consequently, this understanding is open to interpretation, and confidence in an interpretation is increased to the extent that representations can be made to correspond to each other in important ways and that these arguments are compelling to others within the community.

reactivity, electrochemistry, solubility, kinetics, and thermodynamics. Although any given *ChemSense* activity may focus on a subset of the themes, taken together, the themes fully portray the molecular world imagined by chemists to account for observable phenomena. Each theme involves molecular arrangements or changes in structure that correspond to critical aspects of explaining chemical reactivity. A basic understanding of these substantive chemical themes will help the reader understand both the purposes of our design and the subsequent analyses of student discourse and learning.

Three of the representational themes—connectivity, geometry, and aggregation—relate primarily to structural issues. For example, the properties of water (e.g., liquid at room temperature, 100°C boiling point, dipole moment, ability to solvate, high heat capacity) are related to the unique structural identity of water molecules (two hydrogen atoms and one oxygen atom with the H-O-H connectivity, arranged in a "bent" geometry) and the way they interact with other nanoscopic species (supramolecularity). Representing the visualization of structural changes taking place in chemical phenomena could involve changes in connectivity (bonds breaking and forming), changes in geometry (the spatial relationships between atoms in molecules and networks), and changes in aggregation (supramolecularity).

The other two representational themes—changes in state and concentration—describe the energy and motion of aggregations of molecules. These themes cover descriptions most commonly associated with the physical chemical attributes of thermodynamics (state) and reaction rates (concentration.) Below are short descriptions of the themes and then a discussion of the relationship between these themes and the design of the *ChemSense* environment.

Connectivity. Connectivity describes the connection between atoms within a particular molecular structure as a critical attribute of its chemical identity. These patterns of connectivity are often associated with certain perceptual qualities of a compound (group of molecules), such as predicting and explaining observed properties and/or reactivity (e.g., solubility in and/or reaction with water).

Geometry. Geometry centers on shape-related aspects of a molecule. There are two related aspects to molecular geometry. First are the static or fixed spatial relationships in molecular structure (average bond distances and bond angles). Second are the dynamic relationships that change over time (bond vibrations and rotations, and the more severe changes that accompany chemical reactions).

Aggregation. Aggregation refers to the emergent properties of a substance that arise from the spatial arrangement of many individual molecular entities, whether they are molecules, individual atoms, or ions. For example, aggregation forces determine why some salts dissolve in water and others do not, and why some chemical compounds mix while others do not.

State. State describes the energy relationships that exist within a set of molecules (one or more "bonded" or connected atoms) or individual elements (group of individual, "unbonded" or unconnected atoms). Applied heat, light, and the heat generated during mixing are the three most common sources of energy that influence changes in state. When molecules absorb or emit energy in the form of heat or light, the molecules undergo a change in state (e.g., "state of matter," such as going from liquid to solid; thermodynamic states more generally, such as water at 10°C going to water at 50°C). The average energy of a collection of molecules will determine the state in which a substance exists.

Concentration. Measures of concentration usually express the number of molecules per unit volume. When materials combine to undergo chemical reactions, large collections of molecules mix and collide with one another. Changes in concentration affect the number of collisions that take place—the higher the concentration, the greater the number of collisions and the greater the likelihood that a productive collision (i.e., some change occurs) will take place.

These five chemical themes guided the design of the *ChemSense* tools and directed development of the curriculum and assessments used in our work. We designed *ChemSense* so that students would make decisions related to these themes; the *ChemSense* tools specifically afford opportunities for students to represent and talk about the spatial and temporal aspects of the themes. Understanding chemical phenomena at both the nanoscopic and macroscopic levels involves models that explain change with respect to time, and in chemistry, these models relate observable chemical phenomena (reactivity) with the arrangements of atoms, atoms within molecules, and atoms and molecules within networks and aggregates (structure).

Going back to our "dissolving salt in water" example, we can show how some of these themes are instantiated. As the students make decisions about the construction of a water molecule, their choices in both the types of bonds and the bond angles of the water molecule have implications for how the molecule will interact with other molecules. Here they are making *geometry*-related decisions. In the case of H_2O, the molecule is "bent" rather than linear. Because of this geometry, the molecule is polar (has unequal charge distribution), which aids in the "dissolving process" when NaCl is added to it. This decision regarding the geometric aspects of the water molecule has implications for how it will interact with the NaCl, since NaCl is "bonded" in a much different weaker way.

Continuing with this example, when the students have created a set of water molecules and begin to represent the NaCl being added to the water, they now have to show what changes, if any, take place in the NaCl and water structures. The students observe from their wet lab that the salt seems to "mix into" the water—it disappears—but that there is not an accompanying change in heat as measured by a thermometer probe. They may wonder if they need to represent a physical or chemical reaction taking place.

The students know from using a conductivity probe that the water alone does not conduct electricity, but a graph of conductivity shows that as more salt is added the solution's ability to carry a current increases. They have also been told that water molecules are "polar," but for some reason do not support an electrical current independently. They may think, "What could be happening to the NaCl after it is added to the water so that it supports a current?" As the students begin to think and talk through their representation, their decisions about changes in the spatial relationship of the atoms, ions, and molecules over time all contribute to their understanding of how the changes in connection between the various components are critical attributes of chemical identity (the "connectivity" theme.)

Since NaCl is an ionic compound, opposing electrical charges hold the Na^+ and the Cl^- ions together. When NaCl is added to the water, the combination of the polarity of the water molecules (due to the *geometry* of the molecule) along with the actual number of water molecules colliding with the NaCl (*concentration*) causes the NaCl to break into its separate ions. As the students create their animation of this process, they are working with several themes in the context of a wet lab, the classroom, and the *ChemSense* environment to support their representation. It is just this type of interaction that the *ChemSense* tool and curriculum units were specifically designed to support.

The *ChemSense* tools used in the context of physical phenomena and structured classroom activities were designed to promote student thinking about representations and the chemical themes. We designed *ChemSense* resources and activities to help students focus on and understand one or more of the five themes by asking them to create animations and other representations of chemical entities and processes to reflect the spatial arrangements and temporal changes between molecules and by prompting them to discuss and revise the representations they create. The *ChemSense* environment, used along with an investigative laboratory and collaborative activities, provides a unique set of tools for students to represent and discuss their chemical ideas. The purpose of our research is to examine the role that these representational resources play in supporting students' representational practices and their emerging understanding of the nanoscopic entities and processes that underlie observable chemical phenomena.

Design Hypotheses

The purpose of design experiments, generally, is to bridge theory and educational practice (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Design-Based

Research Collective, 2003; Brown, 1992; Collins, Joseph, & Bielaczyc, 2004). The intent is to both test the theories embedded in a specific design and contribute to the development of sound educational practice. Such research both documents the successes and failures of a specific design as it functions in authentic educational settings and contributes to the understanding how theoretical claims about teaching and learning can be transformed into effective learning in educational settings.

The *ChemSense* software and the corollary laboratory activities constitute an implicit set of theoretically based hypotheses about how this design will support and shape students' emergent understanding of chemistry and the development of their representational skills. In this section, we make these hypotheses explicit to serve as a guide for our subsequent analysis.

1. The *ChemSense* environment provides students with a variety of symbolic resources that they can use to jointly construct representations of the observable physical phenomena they are investigating within a set of structured collaborative activities and to explain or describe these phenomena in terms of underlying chemical entities and processes. These resources afford and constrain thinking and discourse in certain ways.

   a. The use of specific symbolic features of *ChemSense* (e.g., "balls," "sticks," etc.) to generate a representation of specific aspects of molecular-level composition and structure (e.g., number and kinds of atoms in a molecule, relative arrangement or spatial relationship among these, atom-to-atom connections) promotes students' understanding, representation, and discussion of molecular geometry (shape), connectivity, and aggregation.
   b. The use of specific symbolic features of *ChemSense* to generate a representation of specific aspects of intermolecular phenomena (e.g., number and proportion of molecules, relative placement of molecules) promotes students' understanding, representation, and discussion of concentration and state.
   c. The use of the animation function of the *ChemSense* environment to represent changes within and between symbolic elements and expressions that represent the dynamic nature of molecular structures and reactions (e.g., changes in connectivity, concentration, or state) promotes students' understanding, representation, and discussion of dynamic chemical processes.

2. The ability to refer indexically to various representations constructed within *ChemSense* increases spoken discourse (e.g., describing, explaining, arguing) about both the nature of the representations and the phenomena that they are meant to represent, particularly when these activities are structured into the task or encouraged or modeled by the teacher.
3. The functionalities of the *ChemSense* tool that promote student decisions about representational elements (e.g., bonds, angles, atoms) make it likely that students will understand—and therefore meaningfully use—representational elements from other sources (including teachers and textbooks) in their class environment and integrate them into the representation they are constructing.

4. Over time and with regular use of *ChemSense* tools in the context of structured laboratory activities, students become progressively attuned to these resources and their representations become increasingly complex, infused with scientific meaning, integrated in social practice, and central to teacher-student and student-student interactions, thus promoting both chemical understanding and representational competence.

Study Design

The design-based research described in this paper is focused on the use of *ChemSense* in the context of an authentic chemistry laboratory experience and on exploring the underlying mechanisms by which representations influence understanding in science classrooms. We pose two sorts of questions appropriate to the early stages of design research (Shavelson, Phillips, Towne, & Feuer, 2003): (1) to describe what happened and (2) to explain how it happened. First, we wanted to examine the extent to which students' chemical understanding and representational skill increased while using *ChemSense*. Second, in analyzing students' use of various features and functionality of *ChemSense*, we wanted to examine the extent to which the theory-based hypotheses built into the design of *ChemSense* might serve as tentative causal mechanisms that account for students' emerging chemical understanding and representational skill. To these ends, we used a combination of quantitative and qualitative methods. Our quantitative analyses of pretests, posttests, and student-created *ChemSense* presentations focused on students' chemical understanding and representational competence. In this regard, we document and analyze student understanding and use this analysis to identify segments of the videotaped class sessions that might shed light on the mechanisms that influenced students' conceptual and representational development, particularly in relation to the affordances the tools provided for learning. In keeping with the purposes of design research (Cobb et al., 2003), our ultimate interests are to refine the design of *ChemSense* and contribute to a theoretical base for informed educational practice.

Students, Tasks, and Contexts

The study was conducted with junior-level (grade 11) chemistry students at a San Francisco Bay Area high school serving an ethnically diverse, moderate-income community.[3] These students met for one-and-a-half hours each day, five days a

[3] The largest student ethnic groups at the school include Hispanic (28%), Caucasian (26%), African-American (18%), Asian (16%), and Filipino (9%). Thirty-seven percent of students' parents hold a college degree, a figure close to the California state average. The school's Academic Performance Index in 2001 was 5 out of a possible 10 when compared with all California schools, and 8 out of 10 when compared with schools with similar demographic and achievement profiles. Only 14% of its students enroll in chemistry or physics courses, compared with an average of 36% statewide.

week, for one semester and engaged in a variety of activities—lecture, group work, and laboratory investigations. According to their teacher, the students engaged in critical thinking and frequently used representations, creating two- and three-dimensional models of molecules as part of their curriculum.

For the study, we worked with students in two class periods (N = 24, N = 19). Within each class period, students were assigned by their teacher to lab groups of two or three students, based on student compatibility. Each group studied a 2-week-long unit on solubility (the "Solubility Module") using the *ChemSense* environment. Over the 2 weeks, students spent approximately 15 hours using *ChemSense* in conjunction with wet-lab setups and PASCO data collection tools.

The Solubility Module builds on the National Science Education Standards (National Research Council, 1996) to develop skills in inquiry, scientific discourse and explanation, and content knowledge related to structure and properties of matter and chemical reactions. The Solubility Module was designed by the *ChemSense* team (including the regular classroom teacher of the students in this study) to help students connect macroscopic observations of phenomena with nanoscopic representations and carefully examine this connection to explain observable phenomena in terms of the underlying mechanisms. This module covered a wide range of concepts related to the solubility of solids, liquids, and gases: vapor pressure and solution equilibrium, molecular solvation, miscibility, dispersion, colligative properties of solutions, and factors affecting solubility. Two of the five organizing themes—connectivity and geometry—were the predominant dimensions governing the underlying mechanisms in the solubility module. The students followed an inquiry-based approach of asking questions, carrying out student-designed investigations, analyzing data, drawing conclusions, and presenting findings (Krajcik et al., 1998).

The Solubility Module included a wide range of activities, such as creating representations in *ChemSense*, collecting data using probeware during a wet-lab investigation, and creating an HTML presentation with the built-in HTML editor. The teacher introduced the module and informed students that the work they did for this unit counted for a grade. While students worked on the various solubility activities, the teacher assumed the role of observer and "commentor," walking the lab aisles perusing student work on the computer monitors and querying them on their lab setups, data collection, and representations. By design, we wanted the teacher to be present in the classroom and available to interact with students but only provide minimal help to them during the study.

Instruments and Scoring Rubrics

A variety of instruments were used in this study to assess chemical understanding and representational competence. For the quantitative analysis, pretests and posttests developed by the *ChemSense* team and based on solubility concepts and related representations were used. Identical pretest and posttest measures were used so we developed by the *ChemSense* team and based on solubility concepts and related representations were used. Identical pretest and posttest measures were used so we could focus on fine-grained changes in representational use and student understanding on an item-by-item basis between test occasions. Because the intervention was 2 weeks long, we were not overly concerned with memory or "advanced organizer" effects between test occasions.

The test consisted of eight open-ended items that focused on connectivity, geometry, and representational issues related to solubility concepts. The response format allowed students to show their chemical understanding and representational ability in various ways. For example, one question asked students to use drawings and words to show their understanding of what a saturated solution looks like at the nanoscopic level, and another question asked students to create a graph showing how the amount of a solid that is dissolvable in a liquid changes with temperature.

The tests were scored by using connectivity, geometry, and representational competence rubrics. The connectivity and geometry rubrics were applied to different test items, depending on the chemistry content of the item—some items were scored with only one rubric, while others were scored with both rubrics. Each rubric focused on specific elements and attributes of a student's response. In the case of the geometry rubric, the award of a "correct" or "incorrect" score for an item was based on specific features of a student's response. For example, on one item students received a "correct" for showing the correct "bent shape" of a water molecule in their drawing. In contrast, the connectivity rubric was based on a more holistic scoring approach. Here an item response score from zero to four was based on overall features of the whole response. We highlight a more detailed example of the scoring in the analysis section. All items were scored by two raters; rater 1's scores were used as the actual test item scores, while rater 2's scores were used to validate rater 1's scores. High correlation ($r > .80$) between raters' scores was established. The representational competence rubric was designed to identify how students generated their representations and how they expressed their understanding through these representations. Similar to the connectivity scoring rubric, the representational competence rubric was applied in a holistic manner, based on a one to four scale. Only item 6 was scored with this rubric. Again, we highlight a more detailed example of the scoring in the analysis section.

Quantitative Analysis and Findings

As stated above, the primary purpose of our quantitative analyses was to describe "what happened" by examining the extent to which students' chemical understanding and representational skill increased while using *ChemSense*. In this regard, we relied on the results of our assessment instruments.

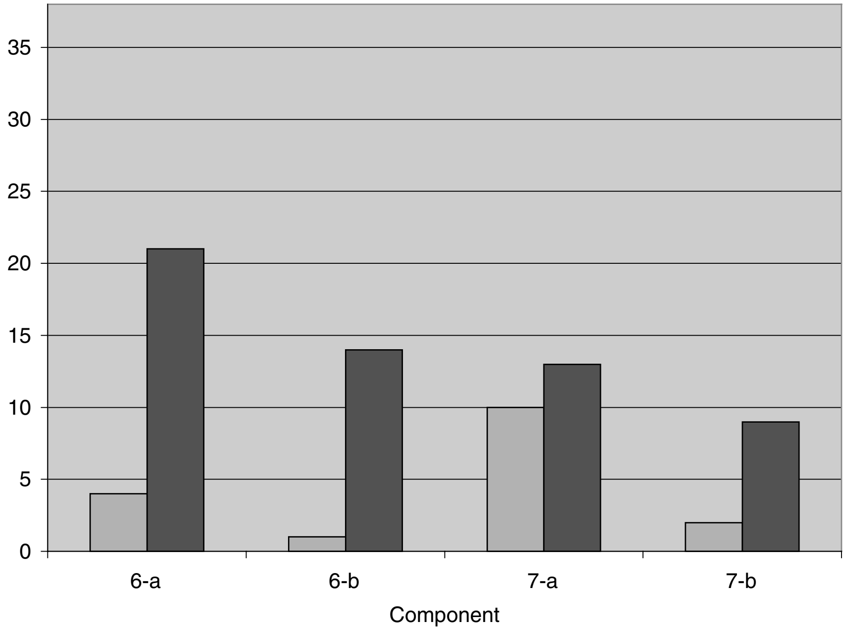


Fig. 11.3 Frequency distribution of pretest and posttest score for geometry (number of students who correctly answered given item component)

Chemical Understanding

Assessments of chemical understanding focused on two themes: geometry and connectivity. Analyzing pretest and posttest scores across these measures, we found that students' chemical understanding of solubility showed a considerable gain following the *ChemSense* solubility activities.[4] Fig. 11.3 shows pretest and posttest score comparisons across items for geometry. For all items there was a gain between test occasions.

Two items on the test were scored with the geometry rubric. These two items were broken down into four components: 6-a, 6-b, 7-a, and 7-b. Each component was scored as either "correct" or "incorrect." Student scores on these components showed a substantial change from pretest to posttest. What do these scores mean? What were students able to do at posttest that they weren't able to do at pretest?

Table 11.2 provides a description of each of the geometry components. Test item six (components 6-a, 6-b) asked students to create a four-frame storyboard showing how an ionic compound dissolves in water over time. Test item 7 (components 7-a, 7-b) asked students to describe a polar substance and explain why and how it dissolves in water.

[4] Because several students in our study were not able to complete both the pretest and the posttest, the number of students for which test data exist is slightly less than the number of students who participated in the *ChemSense* activities.

Table 11.2 What students were required to show as part of their geometry score

Component	What Students Were Asked to Do
6-a	Show correct bent structure of water molecules
6-b	Show correct alignment of water molecules to Na^+ and Cl^- ions
7-a	Show correct polarity of water molecules
7-b	Show correct orientation of polar molecules with each other

At pretest, few students were able to represent the bent shape of a water molecule, show the charge distribution on a water molecule, show how water molecules align with each other, or correctly show the alignment of water molecules with positive and negative ions. After working through the Solubility Module, students were much more readily able to show the molecular shape and the alignment of water molecules with each other and with dissolved ions.

The connectivity rubric was applied to seven pretest/posttest items. Table 11.3 describes the various levels of the connectivity rubric. In general, the rubric was designed to capture student representation and discussion of changes in bonding and the related rate issues, as well as use of appropriate chemical representations and the linking of nanoscopic and macroscopic representations. By "appropriate" chemical representations, we are referring to the use of commonly accepted iconic representations to convey chemical meaning (e.g., two lines drawn between atoms to represent double bonding, electrostatic alignment between molecules to represent hydrogen bonding).

Figure 11.4 shows the distribution of students across levels at pretest and posttest. For space considerations, we present an overall connectivity level for the seven items. Here we summed the number of students at each level for each item and divided by the number of items. This effectively gave us an overall or "average" connectivity rating at pretest and posttest. In other words, Fig. 11.4 shows the number of students who scored at each level on connectivity at the two test occasions. The comparison between the numbers of students at each level at pretest and posttest

Table 11.3 General connectivity scoring criteria

Level	Description
4	Accurate representation of bonding changes, relevant kinetic (rate) issues, and connection of nanoscopic and macroscopic phenomena; use of appropriate structural drawings to represent changes.
3	Partial representation of bonding changes, relevant kinetic (rate) issues, and connection of nanoscopic and macroscopic phenomena; use of appropriate structural drawings to represent changes.
2	Partial representation of bonding changes, relevant kinetic (rate) issues, and connection of nanoscopic and macroscopic phenomena; does not use appropriate structural drawings to represent changes.
1	Incorrect representation of bonding changes, relevant kinetic (rate) issues, and connection of nanoscopic and macroscopic phenomena; does not use appropriate structural drawings to represent changes.
0	Little or no discussion of relevant connectivity issues; does not use appropriate structural drawings to represent changes.

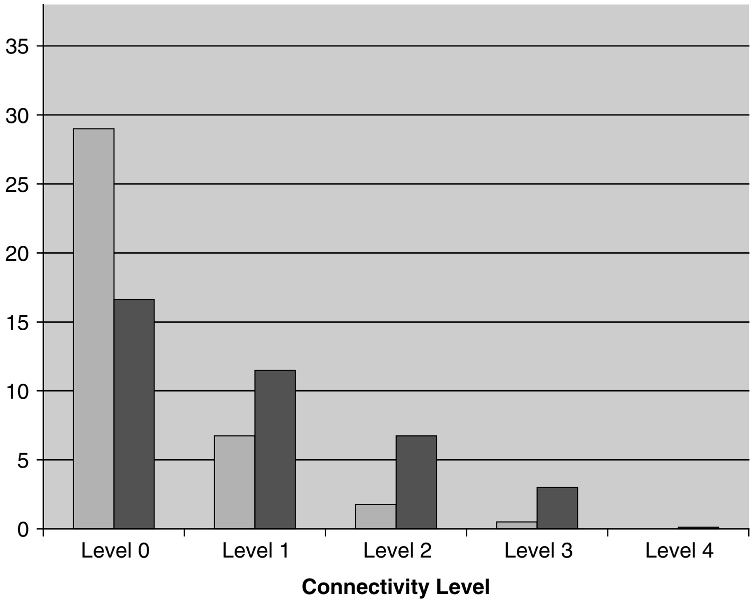


Fig. 11.4 Number of students at each connectivity level at pretest and posttest, based on an average of seven items

shows a positive shift in students' understanding of connectivity-related issues. Note that this increasing trend from pretest to posttest is representative of each connectivity item score—that is, each connectivity item showed a similar positive shift from pretest to posttest. This pronounced although modest trend away from little or no discussion of connectivity issues indicates at least a partial understanding of bonding changes and rate issues.

Representational Competence

For the representational competence rubric, we used our five-level conceptual scheme to score students on their attunement to the formal representations of chemical phenomena. As such, we rated the overall quality of a student's response rather than its "correctness." Only one item was appropriate for scoring with the representational competence rubric—-the item that asked students to create a four-part storyboard showing the process of NaCl dissolving in water.

Figure 11.5 shows the distribution of students at each level at pretest and posttest. It is important to note that representational competence focuses on the extent to which students are attuned to the use of formal chemical representations. This differs from the "chemical accuracy" of the representations, on which students were given a chemical understanding (geometry, connectivity) score.

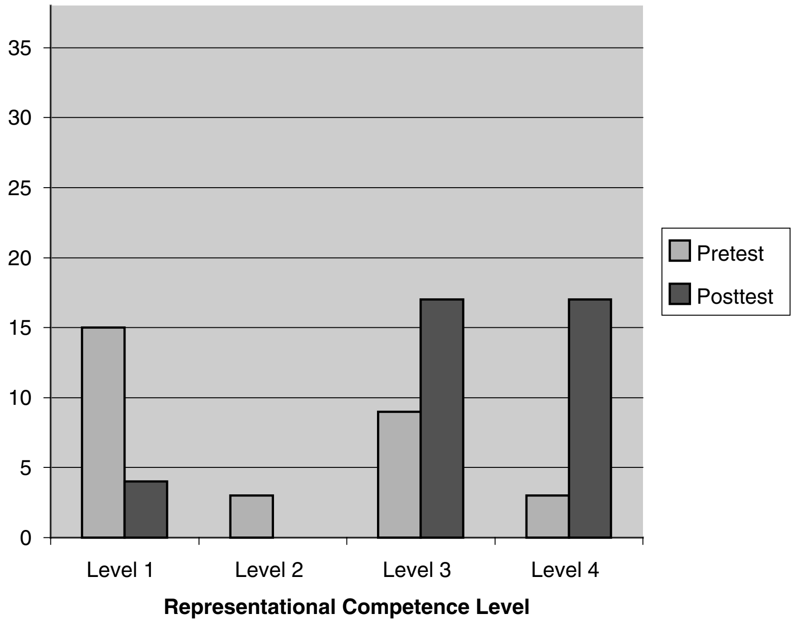


Fig. 11.5 Distribution of student scores for representational competence[5]

At pretest, approximately half of the students' representations were at a "representation as depiction" level (level 1). At level 1, the students were rather limited in their ability to use representations to explain physical phenomena. They tended to use representations as isomorphic, iconic depictions of a phenomenon at a point in time. A handful of students on the pretest showed "early symbolic skills" (level 2)—their representations had a mix of both surface features of the phenomenon but also used nonstandard symbolic elements to show particular behaviors. However, nonperceptual entities were not represented. Approximately a quarter of the students displayed "syntactic use of formal representations" (level 3)—a mix of observed physical features and unobserved, underlying entities or processes was represented. A handful of students displayed a "semantic use of formal representations" (level 4). Here students were able to correctly use formal chemical symbols to represent the underlying, nonobservable entities and processes. As expected, no students showed "reflective, rhetorical use of representations" (level 5), since the assessment was not designed to test this level of representational competence (the reason for its omission from Fig. 11.5).

At posttest, there was a distinct shift in students' representational abilities—the vast majority of students were at representational competence levels 3 and 4. That is, students moved from a straight depiction of the physical observations at the macroscopic level to using formal representations to represent the underlying,

[5] At pretest, nine students left item #6 blank. At posttest only one student left this item blank.

nanoscopic-level phenomena. The fact that no students scored at level 2 at posttest brings into question the utility of this rubric. This issue will be discussed in the Discussion section at the end of the paper.

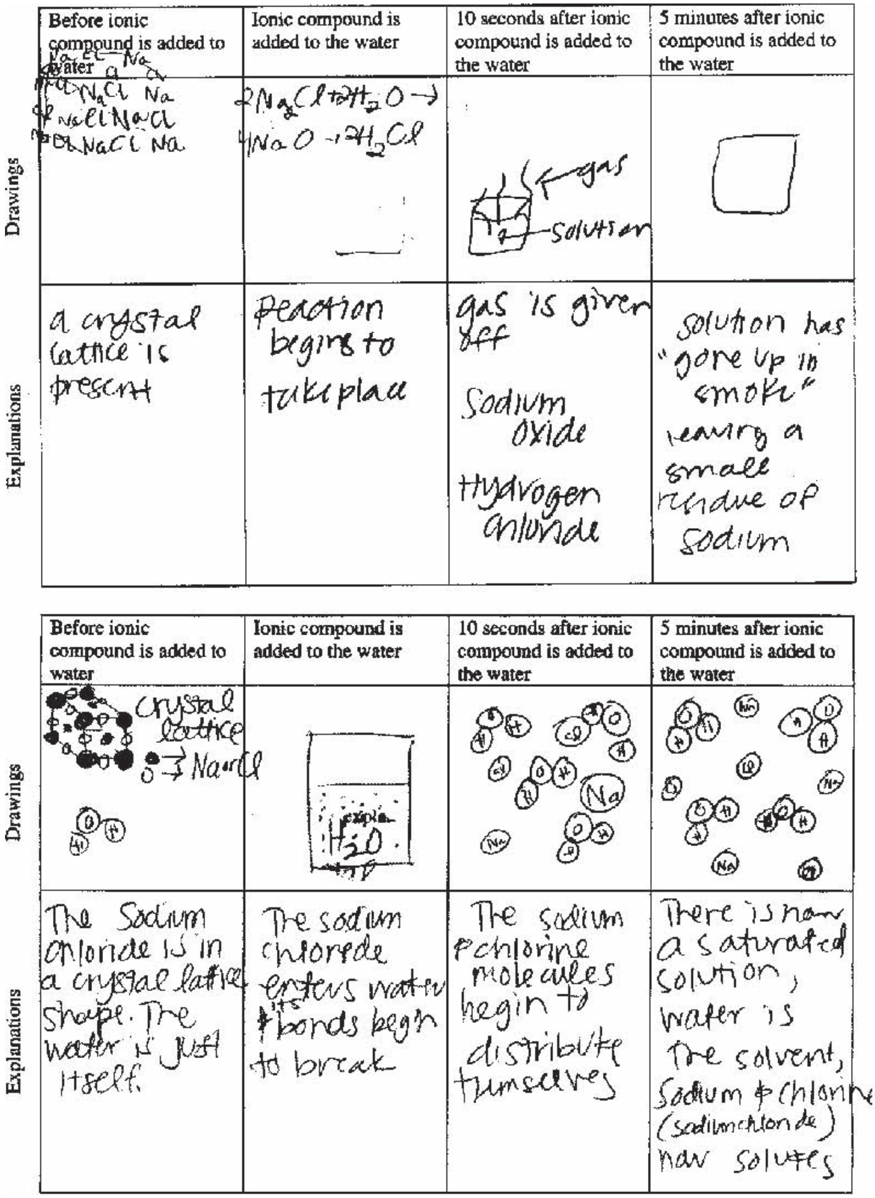
Examples of Scoring

To provide a more detailed picture of the scoring process, here we present a test item example and work though the scoring using each of the three scoring rubrics—geometry, connectivity, and representational competence. Each rubric is used as a different conceptual lens through which to examine the student's response to this complex item. The item for this example is a four-step "storyboard" question asking students to draw and explain at the nanoscopic level how NaCl dissolves in water. This item allowed students the opportunity to show their understanding of a solubility-related *process* and represent it accordingly. We will compare pretest and posttest responses for a given student.

Figure 11.6 shows a sample pretest response for our example test item. At pretest, the student completed all frames of the storyboard. However, instead of creating nanoscopic-level representations, the student provided a macroscopic-level drawing of the solution and a representation of the ionic lattice using the symbols "Na" and "Cl" to represent nodes in the lattice.

Using our geometry scoring rubric, this student could potentially receive points for two aspects of the response: correct polarity of the water molecules represented and correct alignment of molecules with each other. In this case, the student did not receive any "geometry" points because the response did not include a spatial representation of the H_2O molecules or the Na^+ or Cl^- ions. At posttest, it can be seen that the student accurately represented the bent shape of the water molecules, so a point was awarded. However, even though all the different entities were represented accurately—correct H_2O molecules and Na^+ and Cl^- ions—the student did not accurately represent the orientation of the water molecules relative to the ions. To receive credit for this answer, the student should have shown a convergence of multiple water molecules around a single ion and correctly shown the oxygen side of each water molecule pointed inward toward each Na^+ ion and the hydrogen side inward toward each Cl^- ion.

At pretest, the student received a level 0 score on connectivity since there were no diagrammatic or text representations of the change in the relationship between entities over time. In particular, the student did not represent the breaking up of NaCl into Na^+ and Cl^- ions or represent the connection between the macroscopic environment and the associated molecular description. At posttest, the student provided a series of representations and supportive text that showed the change in NaCl over time. Here the student showed the crystal-like lattice structure of NaCl before it was added to the water and showed the resulting dissociation of the Na and Cl once the crystal was placed in the water. However, the student did not show the dissociated Na and Cl in the water as ions—they are missing positive and negative



Pretest Posttest

Fig. 11.6 Sample pretest and posttest responses charges. The student did provide a macroscale representation of water in a container but did not draw a connection between this and the molecular-level representations shown in the other frames. Also, the student did not represent the correct "connection" between H_2O molecules and the ions after dissociation. The student received a posttest level 3 score for providing an accurate but partially complete discussion of connectivity.

With regard to representational competence, the text descriptions and representations at pretest provide evidence that the student operated at a "surface level"—the discussion centered only on observable, macroscopic-level features. The student used representations as depictions of what might be seen at the lab bench, providing only an "isomorphic, iconic depiction of the phenomenon at a point in time." This student's response at pretest received a level 1 score. At posttest, this student demonstrated a more complex attunement to the formal representation of the underlying process. Here the student used accepted chemical symbols (space-filling molecules) to represent the underlying, nonobservable entities and processes and provided an accurate description of the dissolving process. The student showed a semantic and social use of formal representations, using these representations to explain the physical phenomena rather than simply depicting what could be seen. Note that even though this student received a very high score for this item on representational competence (level 4), the student's connectivity and geometry scores were lower because of the missing chemical information.

Our quantitative findings suggest that during the sessions in which *ChemSense* was used along with structured laboratory activities, students developed their representational competence, as well as a deeper understanding of the geometry and connectivity-related aspects of solubility. Referring again to the design research literature (Shavelson et al., 2003), our quantitative analysis helped us to understand "what happened" with respect to student learning. In light of these findings, our next step was to investigate "how this happened" by following our quantitative "leads" into the video analysis. By looking at student's representational and discursive practice as an integrated locus for learning, we attempted to gain insight into the mechanisms through which generation and use of representations iteratively lead to greater competence in using representations in developing chemistry understanding.

Qualitative Analysis: Episodes from a *ChemSense* Session

Having established with our quantitative analyses that some learning took place, our qualitative inquiry focused on *how* students learned by using the *ChemSense* tool. The inquiry was shaped by two interrelated considerations: the substance of what students learned and the way in which our design hypotheses might explain this learning. We used videotape to capture a detailed view of how two groups of students interacted with each other, with *ChemSense*, and with the laboratory apparatus as they worked through the Solubility Module. These data provided us with more-direct access to students' representational practices than was possible with the paper-and-pencil representational competence assessment and allowed us to understand the role that *ChemSense* played in shaping these practices and student understanding.

Consistent with a design research approach (Shavelson et al., 2003), we used our quantitative findings as an index for the specific moments in students' *ChemSense* activities that could best account for changes in student scores. Specifically, we analyzed the patterns of pre-post item responses of these two groups of students to understand "what happened" with respect to student learning. On the basis of this analysis, we were able to identify and analyze portions of the videotapes that documented the particular *ChemSense* activities in which students were most likely to have increased their chemical understanding and representational competence to better understand "why it happened." We did not intend our analysis necessarily to reveal the characteristic way in which most students in the study interacted with the tools and one another in the *ChemSense* environment. Rather, we wanted to understand important dimensions of this interaction and closely study an example of how learning *can* happen in the environment.

The two groups we taped included a total of five students: one group consisting of one boy and two girls and the second group consisting of two girls. The students came from a variety of ethnic and social backgrounds. All were juniors in high school. The two groups were chosen by the teacher on the basis of their ability to work well together and the likelihood that they would have a high level of verbal interaction. The purpose of the videotaping was to provide us with a supply of student discourse that we could use for analysis. Thus, it was imperative to have reasonably verbal and interactive students, given that we were limited to working with only two groups. We recognized that the student behaviors within these groups were not necessarily typical and therefore not generalizable. Rather, by focusing on a particular example, we hoped to illustrate how specific features of the *ChemSense* representational tools can influence student interactions and thinking, as predicted by the design hypotheses, without making claims that these specific interactions were typical of all the students in the class.

Because our qualitative analysis was intended to explain how students learned what they did, we wanted to analyze the classroom activity most closely matching the representational activity called for by the test item for which students showed the highest gain in score across the pre- and posttest measures. This item—item 6, discussed above in relation to the quantitative findings—asked students to create a four-frame storyboard of the process of NaCl dissolving in water (see Fig. 11.6). While there were a number of classroom activities during the 2 week-long unit, the one that most closely matched the test item—and, consequently, the one to which we looked for evidence of how students came to learn the associated chemical principles—called for students to do the following:

- Using the *ChemSense* drawing tool, create a drawing that shows (a) Water as a liquid (b) Sodium chloride as a solid. Using the *ChemSense* animation tool, show what happens at a nanoscopic level when sodium chloride is added to water. Make sure you show what the solution looks like!

Except for some minor clarifications about the particulars of the assignment, the students had little guidance from the teacher or other adults in the classroom. This assignment was given on the second full day that students were using *ChemSense*. Before this assignment, students engaged in two introductory *ChemSense* activities (creating specific molecules and animating the dispersal of food coloring in water at the nanoscopic level). Although students were instructed to "show what happens at a nanoscopic level" for the target activity, their assignment in many important ways was not determined by the instructions. Students themselves needed to make practical decisions along the way: what should be shown, how it should be shown, and what their representations meant in this contextual situation.

The extended example we discuss below comes from one collaborative session that illustrates some ways in which using the *ChemSense* tool can support specific representational practices and contribute to conceptual and representational development. We purposefully chose this example because it illustrates how use of *ChemSense* might have influenced the learning process in relation to test item 6. Moreover, this extended example is long and rich enough to allow us to analyze student discourse and activity in terms of our hypotheses. The example serves as a case study of the types of ways in which *ChemSense* can support changes in students' capacity to represent their understanding through the use of tools that allow them to generate what they consider coherent representations of chemical phenomena. Most importantly, we see evidence that the *ChemSense* tools provide an additional set of symbolic resources for students to draw on as they construct their intersubjective meanings.

Episode 1. Representational Competence: Moving from Depiction of Surface Features to Deeper Symbolization of Underlying Mechanisms

In our first episode, students shift from depicting the observable features of a phenomenon to symbolizing the chemically more important nanoscopic aspects of the phenomenon. This shift occurs in two brief phases, each of which helps solidify students' orientation to a nanoscopic level of representation. In the first phase, students decide to create elaborated molecules rather than amorphous dots; in the second phase, they abandon the strategy of depicting macroscopic features of the phenomenon altogether. These changes support the hypothesis that features of the tool—specifically, those that facilitate the generation of iconic representations of atoms and molecules—shape the conceptualization of the ideas students represent by moving students away from macroscopic depictions of observable phenomena to representations of nanoscopic entities (Design Hypothesis 1a). Generally, we see in this episode an example of how the particular types of representations afforded by the tool support a particular type of discourse and a particular type of understanding.

As the episode begins, Rebecca and Kimmy face the problem of how to represent water in accord with the class assignment. They begin to draw a cup as they had done for previous assignments—what they call their "usual cup" (see Fig. 11.7). They quickly shift from a focus on this physically observable level (blue background in rectangular container) to a deeper, chemically more interesting representation

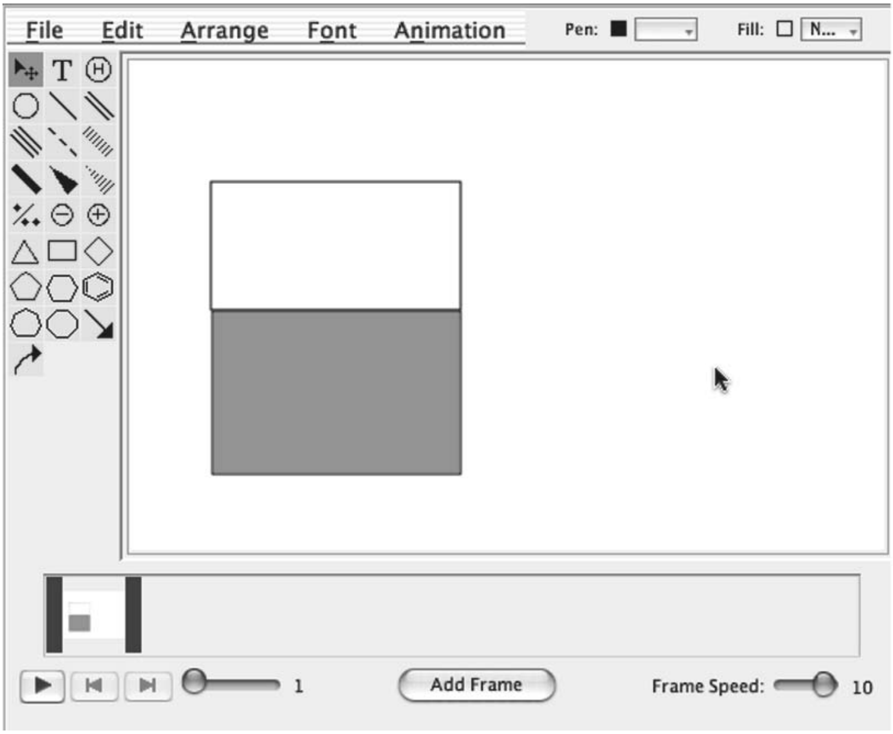


Fig. 11.7 Screenshot of students' depiction of a cup

of liquid water as discrete bits of aggregated matter (beginning with iconic depictions of hydrogen molecules). After Kimmy asks Rebecca if she should show their "usual cup" with water in it, Rebecca signals the importance of the nanoscopic representation and Kimmy introduces the word "molecules" while asking Rebecca if molecules should be represented. It is important to emphasize that the students' assignment instructs them to create nanoscopic images but does not specify what a nanoscopic image is or should look like. The previous day, in order to create nanoscopic animations of food coloring dissolving, the group had used structurally amorphous dots to represent molecules of food coloring, and they did the same to represent water molecules. With this recent experience, Kimmy asks if, for this animation, they should represent the nanoscopic level using molecules or just dots. The full segment follows:

R: In the first frame—we'll make a cup.
K: Water.
R: Our usual cup.
K: Yeah. Two dimensional. Want me to do it?
R: You can do it, yeah.
K: With water in it?

R: Yup. It has to be the nano—nanoscopic water, so we have to do the, uh. . .
K. The molecules?
R: Yeah.
K: The tiny ones or should they just be dots?
R: It should be small this time, really small
K: Should we make. . .
R: Make them, make those though. . . [pointing to the screen, hydrogen on the periodic table icon; see Fig. 11.8]
K: Out of those?
R: Yeah.

The dialogue here illustrates that certain features of the *ChemSense* tools help shape students' inclinations and choices in developing their animation. Even though the students had been drawing their "usual cup" in previous activities, they are challenged by the prospect of producing one of these cups with *ChemSense*, which does not provide a cup-drawing tool. *ChemSense* does, however, provide an atom-drawing tool that the students can use to construct molecules, which they quickly recognize is useful in their situation. The atom-selection tool before them on the screen is a shared representational resource, and as they look at it together, one of the students points to it—specifically, to the place on the periodic table representing hydrogen—and tells her partner to "make those," both students having experienced that the tool will generate individual atoms of hydrogen if they click on the "H."

Representationally, students are confronted with the basic problem of transposing their common-sense depiction of observable phenomena (depiction at level 1 or 2 in terms of our representational competence rubric) into a representation of the same phenomena at the nanoscopic level (a level 3 portrayal of unobserved causal entities

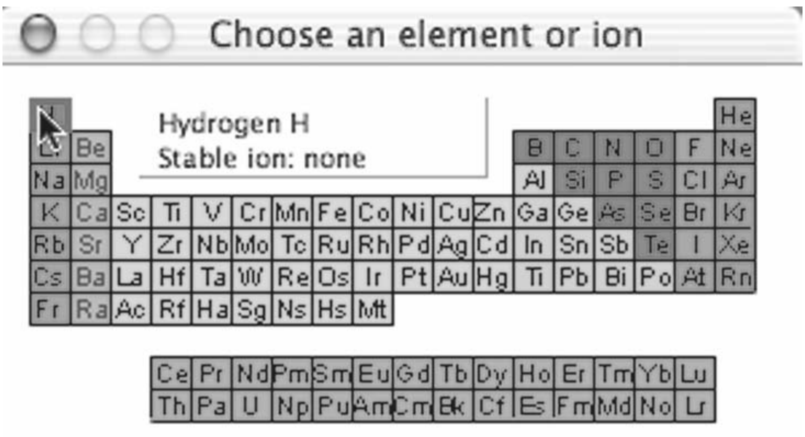


Fig. 11.8 Screenshot of the atom-selection tool

and processes). This problem prompts students to use (and subsequently develop) their understanding of the aggregate, particulate nature of matter to transform their representation from a straightforward depiction of a container of water to a molecular depiction of H_2O. Ultimately, Rebecca says that depicting the cup is unnecessary and that they should show just water and sodium chloride.

The students' decision to depict molecules without a container is expressly linked to their shared experience of having previously used the *ChemSense* knowledge-sharing capacity to view an animation made by another group, which they were instructed to comment on at the end of the assignment they had just completed. Unlike Kimmy, Danny, and Rebecca, students in the other group had not depicted any type of container for the particles of food coloring and water in their animation. Fifteen or so minutes later, while the students are working to construct an image of their "usual cup," Rebecca suggests that they use the other groups' representation as a model for a new approach. We see here some evidence that as students use the representational tools, they are able to relate their emerging visual representations to other visual representations in their social environment, building on one another's pictorial contributions in much the same way that interlocutors build on one another's discursive contributions (Hypothesis 3).

R: You know what we could do—we don't even need to have a cup, though. We could just have the sodium chloride, I mean the water and the sodium chloride, like you know how that other group did when we looked at [their animation]?

K: Yeah.

At this point, we see the students shift to generating representations of phenomena fully at the particulate level, with representations that detail the structure of H_2O and NaCl molecules. Their interactions suggest that they have interpreted the assignment as requiring this level of detail to adequately show the process by which NaCl dissolves in water. Their decision to show the structure of molecules also could indicate that they are anticipating the specific representational features of the ionic reaction they will animate, with NaCl bonds breaking in the dissolving process. In this way, they would be establishing conditions for exploration of the relevant geometry and connectivity issues that relate to the creation of the molecules and animation of the dissolving process. At the same time, as students work toward adding a greater level of detail to the molecular representations, they note that they "don't even need to have a cup." In this way, they explicitly *abstract away* from the irrelevant detail of their "usual cup" (Roth, 1998)—a macro-level representation unnecessary, in this situation, for representing underlying phenomena. Although it is not possible to state that students' representations would be substantially different given a different set of tool affordances, we see here evidence that the tool supports the type of attunement the students undergo toward a more sophisticated use of formal representations.

Episode 2. Chemical Understanding: The Geometric and Connective Aspects of Turning Atoms of Hydrogen to Molecules of H_2O

After Kimmy has depicted a number of hydrogen atoms, the group moves from this subtask to the main task of depicting molecules of H_2O. The students now face a new set of representational design decisions and chemical concepts, including the ratio of hydrogen to oxygen and the basic structure of a water molecule. As Kimmy is moving the hydrogen atoms she has created apart from one another (see Fig. 11.9), Rebecca interrupts her, saying, “Just put them all together kind of; we have to make water…” while making a small circular gesture toward the screen that probably is intended to reinforce the idea that the atoms on the screen should be closely gathered in space. As she makes her own gesture, using the cursor to circle around the hydrogen atoms, Kimmy counters that they “have to put, like, oxygen” in that space. Rebecca agrees by saying, “Oh, yeah.” At this point, the girls have used the visual plane of the computer screen to establish a shared plan for depicting water molecules as a combination of hydrogen and oxygen.

But Rebecca then adds, after a 2-second pause, “One oxygen to every two hydrogen.” It seems that based on Kimmy’s gesture circling the hydrogen atoms while saying that she needs to add oxygen, Rebecca recognizes Kimmy’s misunderstanding and intention to add multiple oxygen molecules to each hydrogen. Kimmy responds, “It is, huh!” and then immediately opens the periodic table tool and begins to generate oxygen atoms. After a few seconds, Kimmy notes that she had not been thinking about the ratio of one oxygen to two hydrogen, saying, “Yeah, I forgot about that.” She makes a cluster of oxygen atoms and begins to move these atoms to

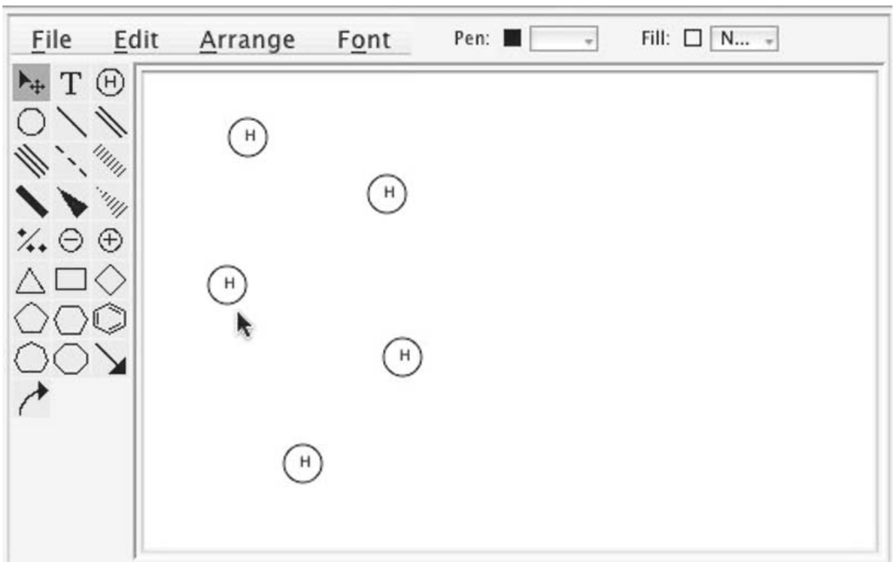


Fig. 11.9 Hydrogen atoms

form water with the hydrogen. As soon as she does so, leaving a little space between the oxygen and hydrogen, presumably to insert bonds, Rebecca offers, "Instead of just making the lines, we could just connect them and put them right next to each other so they're bonded" (see Fig. 11.10).

In the process of creating their representation, the students are explicitly and implicitly making a series of consequential decisions. First, they decide on one type of atom they need—hydrogen—selecting it from the periodic table tool *ChemSense* provides. Second, they decide that they need multiple copies of this atom, and confirm that each copy is the same size as the others, a quality of their representation that they apparently value. Third, they decide that they need additional atoms, which they also can readily generate from the tool. As the students proceed to create their representation, they face a fourth decision regarding the number of atoms in each water molecule and a fifth decision regarding the spatial arrangement of the atoms within each molecule. In what order should the molecules be aligned (H-O-H or H-H-O)? Should the molecule be linear or bent? If bent, at what angle? These issues regarding the molecule's shape, bond angles, and arrangement of atoms relate fundamentally to the geometric structure of the molecule and support conceptual development in the area of understanding molecular geometry. Finally, these students must decide how to represent the intramolecular bonds, with lines or by close proximity.

At each of these decision points, although *ChemSense* makes it easy for students to create atoms, molecules, and bonds through specialized drawing palettes, it does not provide any constraints that would steer the students away from making the "wrong" kinds or number of atoms for a water molecule, the wrong angles, or the wrong bonds. Because of what the tools afford and, importantly, how they constrain,

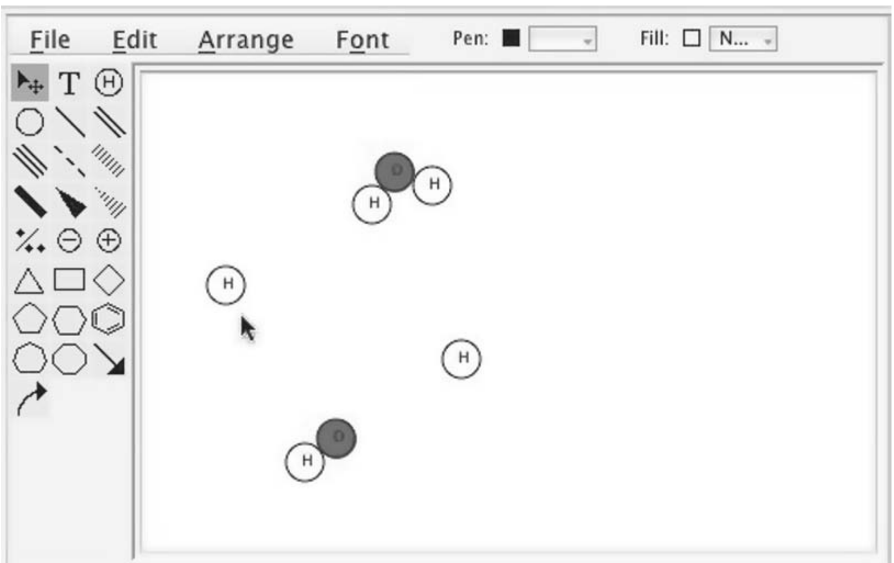


Fig. 11.10 Moving hydrogen and oxygen atoms

key chemical issues, particularly the stoichiometric and geometric issues related to the nature of H_2O, come to the fore in the students' efforts. The students are no longer just showing water or generating a representation of a number of hydrogen atoms. As they work to physically construct each molecule, the tools both "remind" them of the chemistry and require them to proceed in accord with their best understanding of how water molecules are structured. They cannot avoid considering how H_2O molecules are structured because they are creating a representation of these very molecules, a process that makes them specify the key material attributes of their representations, especially those related to the stoichiometric (constituent atoms) and geometric characteristics of H_2O (Hypothesis 1a).

Episode 3. Chemical Understanding: State, Connectivity, and Geometry of H_2O. Representational Competence: Considering How to Adequately Represent Intermolecular Bonds

In this episode, Rebecca instructs Kimmy to orient the water molecules so as to imply the intermolecular hydrogen bonding that takes place between water molecules in the liquid state. Rebecca shows Kimmy how to reconfigure the molecules to orient them differently and readily move them close enough together to signify that the water in their drawing is in the liquid state (see Fig. 11.11). Otherwise, as Rebecca notes, the molecules are "just floating all over like with gas."

R: You can make [the molecules] with a water [sic] and two hydrogens [facing] that way, so it's faced different. [pointing toward one side of the screen]
K: Make them different you want?
R: You [need to] make different shapes and different positions because you know how water is all connected sort of? Like it's not just floating all over like with gas, it's liquid water. So... you can just take ... the hydrogen, you can move those around so you can make different shapes like that.
K: That'll connect to oxygens.

Again, we see an example in which the students apply their understanding of chemistry to the process of generating particular details of their representation. The students' chemical knowledge—related in this case to the themes of state, geometry (for liquid as opposed to solid or gaseous water), and connectivity—intertwines with their sense of what constitutes an adequate representation of hydrogen bonding (Hypotheses 1a and 1b). Just before this episode, the students agreed that proximity suffices as an adequate indication of intramolecular bonds between atoms. In this instance, the students decide that proximity *and* the orientation of molecules (oxygen of one water molecule aligned with a hydrogen of another water molecule) serve as much needed indices of intermolecular bonds—specifically, the bonds responsible for holding water in the liquid state.

The students' decision is triggered by what they have come to realize is the ambiguity of their representational meaning—does their *ChemSense* animation of H_2O look liquid or gaseous? Arranging iconic, ball-and-stick representations of water

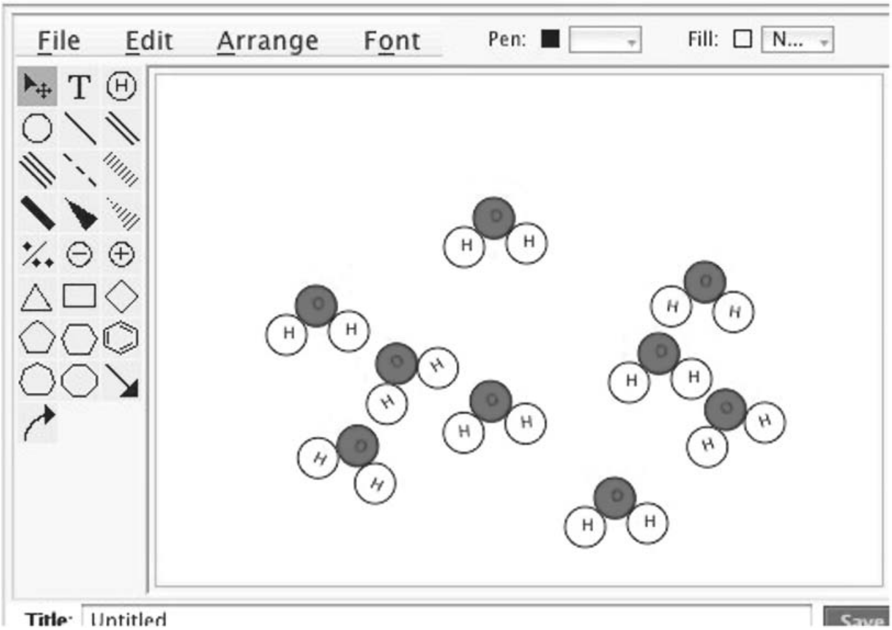


Fig. 11.11 Intermolecular bonding between water molecules

molecules in a plane, it turns out, requires students to make a design decision about the *state* of the H_2O molecules in their representation. There is an inherent meaning in the material act of placing each molecule in a particular place within the spatial plane and in a particular orientation with respect to other molecules. As students create and view their representation, they come to recognize the meaning associated with the placement and orientation of molecules. The design of *ChemSense* supports student learning of the chemical themes in two ways. On the one hand, the *ChemSense* tools force a design decision regarding the state of the molecules and an adequate representation of hydrogen bonding. On the other hand, the tools readily permit the reorientation of molecules drawn by the students, making it possible—and perhaps more likely—that students resituate molecules in their representation to express their understanding more adequately. In both these cases, tool use entails greater engagement with activity that potentially generates understanding of the connectivity and state themes (Hypotheses 1a and 1b).

Episode 4. Chemical Understanding: Attunement to Reaction Mechanisms for Changes in Connectivity. Representational Competence: Use of Expert Representations and the Leveraging of Multiple Representations

While Kimmy and Rebecca reorient the H_2O molecules on the screen to represent liquid as opposed to gaseous water, Danny begins thumbing around in his textbook—an indication that he is working to leverage and coordinate the resources available to him in the classroom—and notices a drawing of NaCl dissolving in water (see Fig. 11.12). Although he does not specify, yet, the mechanism through which this reaction takes place, his comments show that he is using the textbook as a comparison with the students' own representation and a potential model in their efforts to show the way the water and salt molecules behave.

D: Hey, look what I found. Look, this is how it's supposed to look.
K: What?
R: That. [pointing to the picture in the book]
D: And then the water molecules each grab like…
R: Wait, where's the liquid water?
D: The liquid water's the blue stuff.
R: Okay.
D: And the red and the blue thingies
R: That's the water?
D: Yeah, water molecules. And that's the salt crystal, you see how it's like the crystal? Then when it goes in, the water grabs

Danny's notion that the water "grabs" the component elements of salt is the beginning of his representational understanding of hydration and the role of polarized forces within this process, as we shall see later. Here again, we see evidence that the

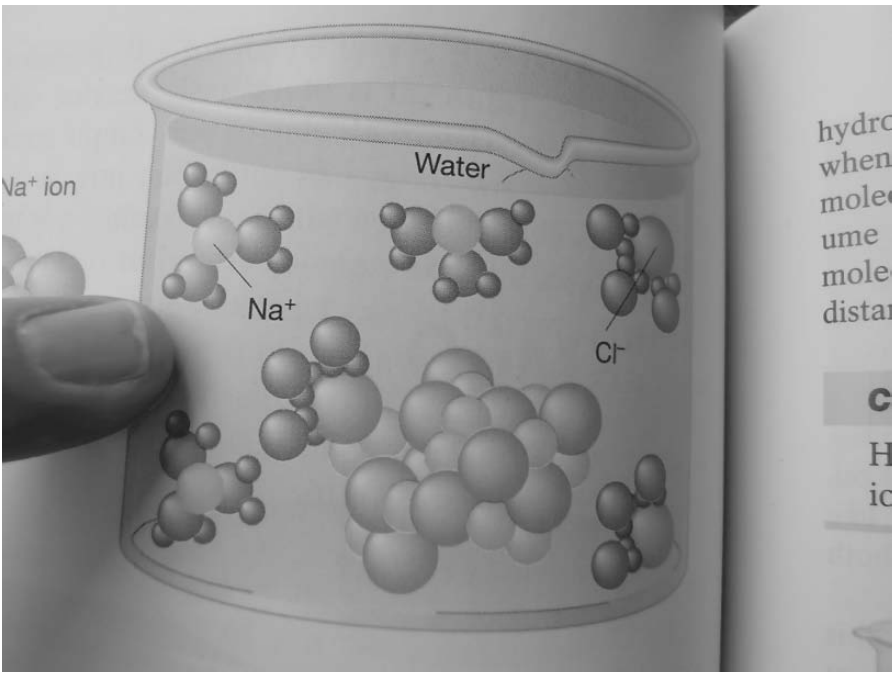


Fig. 11.12 Textbook depiction of NaCl dissolving in H_2O

creation of visual representations using the *ChemSense* tools helps students create symbolic linkages to other visual representations in their social and material environment (Hypothesis 3). In this instance, the linkages are important features of a standard representation from the students' textbook. For Danny, we can argue that as he has used similar representations in *ChemSense*, these types of representations have become more salient in his perception and more meaningful to him. When he looks at his textbook, he finds representational resources that he now has a conceptual and practical framework for integrating in the representation he and his peers are creating. In this sense, he has developed what Greeno (1998) terms new attunements for seeing and meaningfully integrating representations from multiple sources into his classroom activity.

It is important to note in the students' discussion that although the textbook drawing conflates the phenomenological and nanoscopic levels in a hybrid representation, presumably for pedagogical purposes, Danny does not himself independently comment on the physical cup or the blue medium represented in the book when showing features of the molecular depiction to his partners. He seems concerned only with the nanoscopic aspects of the drawing and its relationship to the chemical phenomena the group is trying to represent. When she first sees the depiction, however, Rebecca asks, "Where's the water?" at which point Danny uses both levels of representation in his response, first indicating "the blue stuff" and adding, shortly afterwards, "And the red and the blue thingies" in reference to the molecular depiction. Rebecca asks for further clarification ("That's the water?"), which Danny provides ("Yeah, water molecules."). Although we do not know whether the hybrid feature of the textbook representation originally helped Danny orient to the nanoscopic depiction in this representation, this hybridity plays a role in Danny's explanation of the representation to his partner. Yet, despite this conversational digression, Danny brings the conversation back to his point: showing how the water "grabs" the "salt crystal." Using the textbook representation, which becomes meaningful to the students in the context of their *ChemSense* activity, the students are discursively able to specify and elaborate features of the chemical phenomenon at hand.

A short time later, while the students are animating the dissolving salt crystal, Danny does, in fact, articulate that the polarized molecules bond with one another, pointing out to the others the important features of the textbook representation (Hypothesis 2, representations as a representational resource).

D: Hey, you know what I noticed? Look.
R: What did you notice?
D: In the sodium, sodium has a positive charge, right? So [it] bonded with the oxygen, but then the chlorine bonded with the hydrogen.
R: You're so clever Danny.
D: So clever, yeah. See how the sodium bonds with the oxygen, but then the chlorine bonds with the hydrogen.

This example indicates that use of the representational tools helps students begin to leverage representations off one another as they use them in conversation—much as happened earlier when the students referenced another group's animation in deciding to dispense with their "usual cup." The students' greater capacity to relate the particular features of this textbook representation to their own representation seems to be scaffolded as they work with the tools to create similar particulars within their own representation. This "disciplinary seeing" (Stevens & Hall, 1998) comes about as students work to generate individual atoms of specific types, to bond them at certain angles, to situate them spatially, to orient them with respect to one another, and to do so as part of a larger design process aimed at representing a chemical process that occurs over a period of time. Features of this textbook representation that might have been overlooked instead become useful in students' efforts to imagine how nanoscopic phenomena actually look. In an iterative leveraging process, students' efforts to create their own representations lead to their grasp of features of an expert representation, which in turn is used to improve their own representation.

Episode 5. Bootstrapping Chemical Understanding and Representational Competence: A Chemical Solution to a Representational Problem

When students begin to animate the dissolving of the salt crystal and show the stepwise mechanism of the process, they refer to the textbook drawing again for help. As they start to create the new ionic bonds in accord with the ratio of atoms depicted in their text (see Fig. 11.13), they notice that the numbers of H and O atoms in their own representation do not match up with the Na and Cl atoms. They discuss their mistake, saying that they should have made a smaller salt crystal or more water molecules. Finally, they resign themselves to having just a little lump of salt represented at the end of the animation—an undesired by-product of their representational process.

> R: So how does it happened? Look at the book again?
> D: It shows, like, a couple of water molecules bonding to one.
> R: Three water molecules binding to one; maybe we should have made a smaller little crystal, huh? Maybe we should have made four in the crystal.
> D: Oh, well. No, but then the crystal's still a lump right there [pointing to representation of NaCl crystal].
> R: Oh, it stays lumped?
> D: Yeah, it lumped.
> R: But then eventually it all is done.

The undesired by-product of their representational efforts can be seen as the result of problems coordinating the spatial dimension of generating and arranging the molecules with the temporal dimension of rearranging those molecules. Over time, the molecules must be arranged differently—that is, in such manner as to represent the dissolution of NaCl and the formation of new hydrogen bonds between the water molecules and ions. The animation feature of *ChemSense* requires the stepwise reorganization of molecules within the frame and therefore is the immediate cause of the students' difficulty. However, the difficulty also promotes learning since, over time,

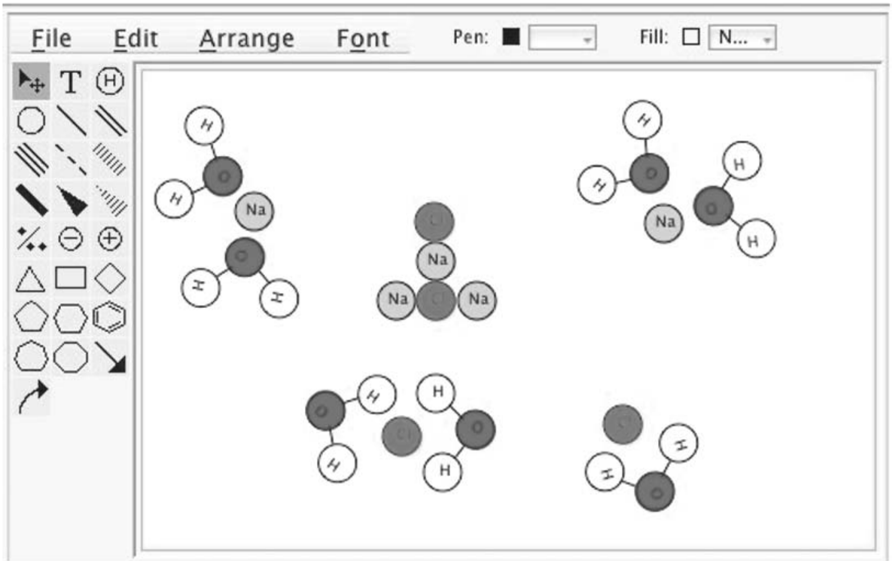


Fig. 11.13 Student depiction of NaCl crystal in aqueous solution

the students map their chemical knowledge onto their representational problem and devise a chemical solution for it (Hypothesis 1c). They declare that what they have represented is a "saturated solution." The students' leftover fragments of representational material become the basis for a chemically elegant solution to their problem. This solution involves the relative proportions of the molecules being represented, which relates to the chemical theme of concentration.

D: That's the leftover, the leftover salt crystal.
R: We haven't made it completely diffuse yet then, so should we finish it? Oh, we didn't make enough hydrogen.
D: Yeah, we didn't make enough water or H_2O for that. Okay, so what do you call this?
K: That's a saturated solution.
D: Yeah, actually that's a saturated solution, so what do you title this?

This episode provides a clear example of how, first, using the tool leads the students to a representational and conceptual predicament, and, second, students use their chemistry knowledge—specifically, of saturation—to retrospectively rationalize the representation they have created. The solution works both ways: they use the chemistry to "fix" the representation, and they use the representation as a trigger to evoke and integrate a particular piece of their chemical understanding into the larger whole of their representational activity. Furthermore, we see that fixing the representation does not involve changing its actual features in any way. Instead, the students label the representation differently ("what do you call this?"), finding a chemical justification that allows them to present or position it in such way that it is responsive to both the assignment and its likely conditions of use in the classroom. In sum, we see here that a representational problem is solved by applying chemical understanding to position or situate the representation rhetorically—that is, within an anticipated context of use.

Episode 6. Representational Competence: The Social Use of Representations to Express Shared Understanding in the Classroom Setting

After a 15-minute period of struggling to write an equation for the ionic reaction (NaCl dissolving in H_2O), as specified in the *ChemSense* instructions for the day, the students ask the teacher for help. They have tried to follow the directions and finally decided on some possible equations (e.g., "H_2O +NaCl=HCL+NaO"; "H_2O +NaCl→H_2O Na+ H_2O Cl") to represent the phenomena they have just depicted in their animation. They want to know if they have gotten a right answer. After she examines them briefly, the teacher tells them that none of their equations are correct.

R: Let's ask Miss [Astor]. Miss Astor will you help us with something?
D: Miss Astor, we need help.
A: Yeah, what?
D: Does this [equation] look correct?
A: Oh, no.
R: Will you help us? We've been trying for a long time, and we don't understand.
D: We're trying to write this equation of adding salt water into, I mean, adding salt crystals to liquid water.
R: Are either one of these right? Which one's more right?
A: Neither.

When she prompts them to think about what happens in phenomenological terms (rather than thinking about the equation), Danny immediately points to their animation as a model of what actually happens. He also notes that the representation is "ultra-saturated," building on the students' own earlier description of their animation as "saturated."

R: Okay. So can you give us any advice on how to do it?
A: My advice is for you to think what's going to happen to sodium chloride when it goes into the water and not focus on the equation.
D: What happens? Right there. That's what happens [referring to their animation].
R: It breaks apart and binds with the oxygen.
A: Ah, that's nice. But some of it's holding together?
R: We didn't have enough water.
D: It's an ultra-saturated solution.

Although the students failed to represent the iconic reaction with an equation by failing to get a “right answer” to a standard type of chemistry question, they recognized that they had an alternative representation of the same phenomenon. In fact, Danny had earlier described their group’s animation as a “model” of what happens when salt dissolves in water. After the students’ struggles and failure in generating a correct equation in this episode, the teacher validates the visual model (“Ah, that’s nice”) as a socially meaningful embodiment of knowledge and a pedagogically relevant display of understanding, since it directly responds to her advice “to think what’s going to happen to sodium chloride when it goes into the water and not focus on the equation.” In practical terms, this interaction between teacher and student favors the iconic visual representation over the symbolic representation (i.e., the equation), indicating that the former is an important means of displaying shared knowledge in the chemistry classroom and, by extension, in the discipline. Although the students are unable to express the phenomenon at hand in the typical symbolic form (NaCl→[Na+]+[Cl–]), their representation shows their understanding at the molecular level. This example also illustrates that visual representations can serve as tools for informal classroom assessment and as important “talking objects” or reference points for teacher-student and student-student interactions. Although the students had been unable to write an equation for the reaction, their animation seems to serve as a useful intermediary representation (Kozma, 2000b), pictorially embodying students’ developing understanding and probably serving as a basis for their subsequent work with the relevant formal equations.

Discussion

As a design experiment, the purpose of this study was to document the learning that occurred and determine the extent to which the design theories embedded in *ChemSense* contributed to the development of students’ representational competence and chemical understanding. What we learned can contribute to the development of our theoretical framework and to improvements in the design of our software environment.

Representational Competence

Our quantitative findings point to an overall increase in students’ representational competence. Specifically, at pretest, students’ representations tended to focus on depictions of physical observations at the macroscopic level. At posttest, students were much more able to use formal representations to stand for underlying, nanoscopic phenomena. These findings suggest that students developed their representational competence during the sessions in which *ChemSense* was used along with structured laboratory activities, a finding further supported by our analyses of students’ representative practices during laboratory sessions.

From the outset, the students in the group that we closely followed began to show a progressive attunement from depicting the observable features of chemical reactions within their classroom to the use of formal representations of the underlying aspects of the phenomena they were addressing. Their incremental move away from the macroscopic container with the "dots" that they initially contemplated reflects the interrelationship between their developing understanding, the assignment they were given, and the representational resources available to them to complete the assignment—particularly those provided by *ChemSense*. Once they abandoned "their usual cup," Rebecca, Kimmy, and Danny did not revert to representing observable phenomena, and instead created discursive and visual representations that focused on the molecular level, much like the discourse of professional chemists (Kozma et al., 2000).

Although the tools presented the students with particular options—for example, from the periodic table and the symbol palette—for creating iconic representations in space and time, there was much about the ways chemical phenomena could be represented that was not constrained by the tools and was underspecified by the classroom assignment. Therefore, the students had to make a considerable number of independent decisions about the formal features of their representations that, in their estimation, adequately conveyed their understandings regarding the chemical phenomena they were investigating. For example, Rebecca and Kimmy decided against showing intramolecular bonds with lines and, instead, agreed that proximity was an adequate indicator of connectivity. We saw Danny seek out and find visual representations that could help his group develop their own representation. This is evidence that operating in the spatial domain of the *ChemSense* tool promotes consideration of and attunement to using other visual, iconic, and spatial resources that are available in the classroom environment. When the group found that they had too few hydrogen and oxygen atoms (i.e., too few water molecules) to match physically with each of the atoms in their salt crystal, they repositioned the representation in relation to the assignment they were given and vis-à-vis what the students anticipated would be the representation's conditions of use. Such an effort at positioning the representation indicates that the students recognized the differing ways a representation can function rhetorically: with a new name, a "wrong" representation can become the right product created in response to an assignment. Later, when Miss Astor provided them the option to "think what's going to happen to the sodium chloride when it goes into the water" instead of "focus[ing] on the equation," Danny presented their animation as evidence of their understanding and as the basis for the teacher's *in situ* assessment of it. For all the ways in which the *ChemSense* tool promotes thinking and decision-making about chemical concepts as they are embodied in formal features of representations, the communicative and epistemological significance of representations ultimately becomes fully realized as students use them in classroom interaction.

Both the qualitative and quantitative results support our overall contention that the use of *ChemSense* representational resources, within the social and physical contexts of collaborative laboratory investigations, can promote the development of representational competence. These findings, in turn, provide some validation for the conceptual framework and assessment approaches that we use to characterize this construct. However, there was one exception related to level 2, "Early Symbolic Skills." Although many students scored at level 1, "Representation as Depiction," and a handful of students scored at level 2 on the pretest, no students scored at level 2 on the posttest. Rather, students seemed to jump from level 1 to level 3 or 4, much as Kimmy and Rebecca did in Episode 1 when they moved from their "usual cup" to molecular representations. This finding suggests that level 2 may not be a distinct phase that students progress through on their way to higher levels of representational competence. It also suggests that additional research is needed to refine and validate our representational competence conceptual structure, assessments, and rubrics.

As with our analysis of chemical understanding, we believe that these initial findings support the speculation that extended use of *ChemSense* over a semester or a year would result in even greater gains in students' representational practices and measures of representational competence. We believe the recurring use of the *ChemSense* tool set would promote incorporation of the representations that students generate in the software environment into their regular classroom interactions and discourse.

Chemical Understanding

Our quantitative findings also indicate that, after using *ChemSense* along with structured laboratory activities for two weeks, students developed a deeper understanding of the geometry-and connectivity-related aspects of solubility. Specifically, at pretest, few students were able to correctly represent the shape or charge distribution of a water molecule, correctly show the alignment of water molecules with ions and with each other, or adequately discuss relevant connectivity issues. At posttest, students were much more able to show the shape and alignment of water molecules with each other and with dissolved ions, accurately represent correct bonding changes and connections between the macroscopic and nanoscopic levels, and use formal representations to represent the underlying, nanoscopic-level solubility phenomena.

In our qualitative analyses, we see evidence that having a representational tool, such as *ChemSense,* that readily makes iconic representations available to students helps them (1) use these representations meaningfully in their classroom practice, in ways more analogous to those of practicing chemists, and (2) conceptualize chemical phenomena in scientifically valuable ways. Examining the classroom activity of Rebecca, Danny, and Kimmy provides a window on how, by using the representational/semiotic resources provided by the *ChemSense* environment, students are able to engage in complex communication around fundamental principles of chemistry. The two-dimensional space of the computer screen, of course, is in many ways a limited representational environment, but it nonetheless channels students' activity toward constructing molecules with geometric and connective properties that are consistent with knowledge as it is represented and used within the discipline. As Rebecca and Kimmy discuss the number of atoms they need to generate representations of water molecules in Episode 2 or as they discuss the alignment of atoms within the molecule, they are necessarily engaged in consideration of core chemistry concepts regarding the structure and bonds of water molecules. As the students work to orient the molecules appropriately in relation to one another to show liquid water in Episode 3, they are confronted with representational choices that implicate their understanding of the geometric and connective aspects of phases of matter. Participating in making these choices apparent leads Danny in Episode 4 to consider the next step: how should the NaCl crystals and ions be oriented in relation to the H_2O molecules? At this point, Danny proceeds to investigate and coordinate other representational resources in his environment to answer this question, eventually calling the attention of his group members to the way that water molecules "grab" the component elements of salt. Overall, when the three students work to show underlying phenomena in terms of the specific atoms, molecules, and interactions that constitute these phenomena, they are confronted with representational choices that motivate the students to juxtapose, reorganize, and represent the verbal, iconic, and other symbolic elements available as resources in their environment. These joint findings of representational and conceptual development suggest that representational practice and understanding are mutually constitutive.

Although our quantitative results are modest, our qualitative results support the notion that extending the use of *ChemSense* across a longer stretch of students' chemistry coursework would produce even stronger positive outcomes in students' understanding. The study reported here involved the use of *ChemSense* as part of an inquiry-based activity on solution chemistry for only a relatively short time—about two weeks. But the five themes underlying chemical concepts that we develop in this article cut across all of the traditional chemistry topics—e.g., bonding, reaction rates, stoichiometry, gas laws, acid-base reactions. If these themes were developed throughout a series of *ChemSense*-based activities across a whole semester or year, we speculate that students' understanding of the chemical principles captured by these themes would increase. Recurring exploration of the themes through the use of the *ChemSense* tools could provide the basis for a deeper understanding of chemistry than students typically get from the topic-by-topic approach to the field that prevails at the high school level. The design of the *ChemSense* tools, as we have noted, reinforces the five themes by providing students an environment in which the spatial and temporal dimensions of chemical phenomena are salient. The tools put students in the position of actively constructing iconic representations of molecular phenomena in space and time, which we argue, necessarily entails, engagement with the fundamental concepts of the field.

Theoretical Contribution: Representational Constraints, Affordances, and Attunements

On the basis of our findings, we can contribute from a situative perspective to the theoretical discussion of the role of representation in understanding. The specific features of the representational resources both *constrain* and enable or *afford* the representational practices and discourse related to entities and processes that are not otherwise perceptible or available in a situation. As the students in our study become attuned to these constraints and affordances, they talk about the molecular structure of H_2O and its interaction with NaCl, as well as the physical properties of beakers, water, and salt. Consequently, the nature of the conversation becomes more "chemical," and students deepen their understanding of the molecular nature of physical phenomena that have, as a result, become chemical.

But perhaps more important, in their attunement to these representational constraints and affordances in the context of laboratory investigations and social discourse, students come to engage in representational practices that are more like those of chemists. That is, they use the affordances and constraints of the representations to pose questions, reason about answers, and warrant claims. While our observations confirm that the meaning of a specific representation emerged from the discourse around its use, rather than from the representation itself, there were features of the representations that afforded and constrained this discourse in certain ways based on the affordances and constraints that we design into *ChemSense*. For example:

- The interactions between Rebecca and Kimmy as they generated representations of water molecules and positioned them in two-dimensional space during Episodes 2 and 3 support the hypothesis (Hypothesis 1a) that the availability of tools that support the creation and positioning of "balls" of various types promotes the representation and discussion of "molecules," their elemental composition, their structure or geometry, and their connectivity.
- The interaction between Rebecca and Kimmy in Episode 3 about the way to represent intermolecular bonds supports Hypothesis 1b, that the ability to use *ChemSense* to create numbers and proportions of different molecules and position them in certain ways supports an understanding of connectivity and aggregation.
- The use of *ChemSense* tools and other representational resources by the students to show the progression of the reaction in Episode 4 supports Hypothesis 1c, that the ability to animate the position and arrangement of these "balls" over time promotes the representation and discussion of chemical processes.
- Conversely, the lack of tools that directly represent the physical apparatus, substances, and events of the laboratory constrains the discourse and seems to reduce the discussion of such physical objects and events. The fact that Kimmy and Rebecca discontinued their use of physical depictions also seems to support Hypothesis 1, generally.
- All the episodes illustrate and support Hypothesis 2, that the ability to refer indexically to representations of chemical entities and processes that are not otherwise available in the situation increases students' discourse about underlying chemical phenomena and how they are to be represented.
- Danny's use of textbook resources in Episode 4 and his integration of these resources into the generation of the team's representations support Hypothesis 3,

that the *ChemSense* resources increase the likelihood that other representational resources will be used more meaningfully.

- Finally, the conversation between the teacher and the students in Episode 6 that resulted in Danny saying "That's what happens" as he pointed to the animation supports Hypothesis 4, that with use of *ChemSense* over time representations will become increasingly integrated into social practice and central to interactions.

Our observations show that the meaning of the students' chemical representations emerges out of their interaction with environmental features such as the *ChemSense* tools, the requirements for the assignment, the informational resources available to them, their own prior experiences, their fellow students, and their teacher. We posit that as these students engage in related wet-lab activities and representational practices in subsequent class sessions, they will be better prepared to make the laboratory phenomena become more "chemical" through the use of representations in a process through which, as Roth (in press) describes, the meaning of the symbolic representation and the physical phenomena are mutually constitutive and reify one another. Visual representations, used side by side with discursive, gestural, and other forms of meaning-making, shape and help students ground their conversation and produce shared understanding to build on one another's contributions to the interactions.

The Design of ChemSense

Our study was a design experiment to both test the theories embedded in our specific design and contribute to the development of sound educational practice. In light of these aims, the study reported here informed the subsequent change of several features of *ChemSense*. Although the qualitative and quantitative data we collected generally validated the design of *ChemSense*, our data also pointed us to refinements we could implement to make our tool even better. In our analysis, we found certain desirable practices that happened less often than expected or that sometimes happened despite a particular *ChemSense* design feature. Both types of occurrences provided opportunities for refinements in our design. The following is a discussion of some of the design changes that we implemented.

In part of Episode 2, Rebecca, Danny, and Kimmy used the knowledge-sharing capacity of *ChemSense* to view an animation by another group. This peer-review activity was part of their assignment and was designed to help facilitate student discourse. Even though they used this part of *ChemSense* for the purpose of peer reviewing other students' work, there was less online interaction than we originally hoped for. We noticed during our observations that there was confusion around the "build-on" metaphor that was used as part of *ChemSense* and that students had trouble understanding where new entries they created would be placed. The students were used to a more familiar "file system" metaphor, used as part of the basic file structure of most computers, rather than the more "threaded discussion" type of metaphor represented by the build-on function. Consequently, we changed the metaphor of the knowledge-sharing tool to that of a file structure to better fit students' experiences and thus make sharing within *ChemSense* as seamless as possible.

In the lab, we observed Danny, Rebecca, and Kimmy using probeware to collect data on conductivity (not reported here). They used PASCO DataStudio to monitor and record input from the sensors and the DataStudio graphing tool to generate graphs of the data. They then exported these graphs as images to be read into *ChemSense*. As mentioned earlier, the use of probeware and data-generated representations is an important resource for connecting student-generated representations to laboratory phenomena. However, these students and others ran into problems when transferring graphs from DataStudio into *ChemSense*, and this difficulty seemed to inhibit the use of these resources. Once transferred, the graphs became nonnative images within *ChemSense* and could not be edited there. Following the study, we created a way for students to import DataStudio data directly into *ChemSense* and then create graphs within the *ChemSense* tool. This change allows students to have more control over the presentation of their data, and it eliminates the need for an external graphing program. This modification is designed to increase the likelihood that these representational resources will be used regularly.

We also documented at the time of the study that students did not have a simple way of creating representations of ions. In Episode 5, Rebecca and Danny worked on creating a representation of sodium chloride dissolving in water. To represent the sodium and chloride ions at the time, Rebecca and Danny had to create the individual atoms and then add "+" or "–" symbols to represent net charge. Although this was only one extra step in the representation process for this particular example, it became apparent that other common but more complex ions, such as sulfate (SO_4^{2-}) or nitrate (NO_3^-), would require multiple steps to represent. Instead of having students step through the process of creating these chemical units by hand, we decided to integrate the most common ions as part of the available periodic table tool within *ChemSense*. With this feature, students can as readily and easily represent ions as they can atoms.

Role of the Teacher

Although *ChemSense* was designed with the collaboration of the classroom teacher in this study, the study was structured to minimize the intervention of the instructor so as to provide more openness for students' constructive use of the *ChemSense* resources. Nonetheless, the teacher in this classroom, Miss Astor, served a pivotal role in legitimizing the value in the classroom of students' visual representations as an index of their conceptual. Although at first she adhered to a "right answerism" mode of addressing the students' questions about their equations, she shifted her role to become more involved in validating the new, alternative mode of representation of chemistry concepts that emerged out of the discourse. In Episode 6, Miss Astor advised students to think about what was happening at a molecular level, rather than think about the syntax of the equation. In response, both the students and the teacher moved from the equation to the animation and began talking about the chemical processes that the equation represented, and they came to a new insight about the state of the solution (i.e., it was an "ultra-saturated" solution).

In this episode, the teacher played an important role in helping students think more deeply about the meaning of the representations that they used. This role was supported by the features of the representational resources. In this regard, our observations are consistent with those reported by Kozma (2000b) in his comparative study of student interactions in the wet lab and computer lab. In that study, because few representational resources were used in the wet lab, both teacher (TA)-to-student and peer-to-peer discussion overwhelmingly focused on the physical apparatus and outcomes with little conceptual talk. However, in the computer lab, students used software that represented the molecular structure of the substance they synthesized in the wet lab. The use of these resources changed the discourse content of both students and TAs, shifting the discussion to chemical concepts such as molecular shape, hydrogen bonding, and nonpolar groups while they used molecular modeling software that included material features corresponding to these concepts. Kozma attributes differences in the amount of conceptual talk in the two settings to differences in their material and symbolic resources.

The role of the teacher is critical in the classroom ecology and can be central not only in the design of the learning activities but also in leveraging the value of the multiple representational forms available to students through strategic discussions. Our interest in the ways in which teachers integrate visualization and modeling tools in their classroom practice has served as part of the impetus for our subsequent research using *ChemSense*. We have since recognized two significant dimensions to teacher use of new tools with their students: (1) developing plans and activities that match the tools and their pedagogical affordances to the mandated curriculum in support of learning objectives, and (2) scaffolding student learning as a result of using these tools in real time through appropriate forms of discourse (questioning, prompting, drawing students' attention to key features, verbally reinforcing the visual and vice versa, etc.). In general, by using and allowing students to use visualizations systematically as core, valid ways of representing chemical phenomena, teachers can significantly augment the traditional representational apparatus of chemistry instruction to leverage understanding at the macroscopic and mathematical levels through representations of chemical phenomena at the nanoscopic level.

Research Implications

Our current research efforts build on our findings and experiences. They focus on the role of the teacher in integrating *ChemSense* into the curriculum and ongoing classroom practice, on the effects of long-term use of *ChemSense* on student learning, and on ways in which the particular features of *ChemSense* can be improved to best support student learning, at both the high school and college levels, where students are using *ChemSense* to depict complex molecules and animate multistep reactions.

Our work with classroom teachers centers on helping them develop and implement standards-based curricular activities to deepen students' understanding of core concepts that can integrate easily with the teachers' existing classroom texts and approaches. Concurrently, we are examining the effects of year-long implementation of these *ChemSense* activities on student learning. Throughout these processes, we are observing both student and teacher use of the tools and are making modifications to the design based on our findings.

The outcomes of our research depend on the successful design of curricula and tools, and also on the ways in which we assess student learning. Assessments that incorporate multiple representations—text and iconic representations—in both the question and the answer, such as those represented by the conceptual test developed by the American Chemical Society (2001), seem likely to be highly sensitive to the effects of participation in *ChemSense.* Similar to our representational competence and chemical understanding rubrics, these measures rely largely on iconic representations of molecular entities and processes in querying students' understanding of both basic and complex chemical phenomena. Since one of our primary assessment concerns is the ways in which *ChemSense* activities themselves function as embedded assessments, providing in clear, digital form views of the "chemical" meanings students make as these meanings are signified through their jointly constructed representations, types of assessment tools such as the ACS conceptual exam could provide interesting ways to triangulate measures of student learning through *ChemSense*.

Finally, our design research was conducted in the context of a particular phase of the design cycle—the early, "open-ended exploration" phase (Shavelson et al., 2003). During this phase, descriptive questions related to "what is happening?" and theory-oriented questions related to "why is it happening?" are appropriate. However, other questions are appropriate for subsequent phases in which the design is refined and further integrated into classroom practice. Within these later phases, questions relate to systematic effects or cause and effect (Shavelson et al., 2003). Small, randomized trials within a classroom might examine which of several well-formulated design alternatives lead to a desired outcome. During the scaling-up phase, the use of experimental studies combined with case studies of implementation can test the generalizability and limits of the effects of a design as it is transported to and tested in other locales. These studies of *ChemSense* are slated for the future.

In terms of instruction, research, and assessment, the potential for visualization tools to improve classroom practice on a broad scale remains largely unexplored. While focusing on the role of the teacher in shifting classroom practice can help us better understand ways in which classroom practice can change, most chemistry teachers have had little experience with visually oriented approaches, especially approaches that systematically incorporate nanoscopic phenomena into their curriculum as representational resources that provide a common ground for students' discourse and experiences. To effect this level of change, the majority of teachers will need to think in new and sophisticated ways about chemistry content: about the quality and uses of representations students encounter; the concepts being built through their assignments; the understandings—including nonscientific conceptions—embodied in student-generated representations; the ways their feedback to students regarding their representations shapes student conceptualizations; and the means of helping students relate depictions of molecular phenomena to chemical equations and lab experiences. The need for research in this area is significant. As a research community, we are still at the beginning stages of understanding in depth and detail the processes through which use of visual representations in classroom practice can contribute to student learning.

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References

American Association for the Advancement of Science. (1993). *Benchmarks for science literacy*. New York: Oxford University Press.

American Chemical Society. (2001). *General chemistry (conceptual) 2001*. Washington, DC: American Chemical Society.

Amman, K., & Knorr Cetina, K. (1990). The fixation of (visual) evidence. In M. Lynch & S. Woolgar (Eds.), *Representation in scientific practice* (pp. 85–122). Cambridge, MA: MIT Press.

Barron, B. (2003). When smart groups fail. *The Journal of the Learning Sciences*, 12(3), 307–359.

Bell, P., & Linn, M. C. (2000). Scientific arguments as learning artifacts: Designing for learning. *International Journal of Science Education, 22*(8), 797–817.

Brown, A. L. (1992). Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings. *The Journal of the Learning Sciences, 2*(2), 141–178.

Brown, A. L., & Campione, J. C. (1996). Guided discovery in a community of learners. In K. McGilly (Ed.), *Classroom Lessons: Integrating cognitive theory and classroom practice*. Cambridge: MIT Press/Bradford Books.

Bunce, D., & Gabel, D. (2002). Differential effects on the achievement of males and females of teaching the particulate nature of chemistry. *Journal of Research in Science Teaching, 39*(10), 911–927.

Chi, M., Feltovich, P., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5*, 121–152.

Clark, H. H. (1996). *Using language*. New York: Cambridge University Press.

Cobb, P., Confrey, J., diSessa, A., Lehrer, R., & Schauble, L. (2003). Design experiments in education research. *Educational Researcher, 32*(1), 9–13.

Collins, A., Joseph, D., & Bielaczyc, K. (2004). Design research: Theoretical and methodological issues. *The Journal of the Learning Sciences, 13*(1), 15–42.

Design-Based Research Collective. (2003). Design-based research: An emerging paradigm for educational inquiry. *Educational Researcher, 32*(1), 5–8.

diSessa, A. A., Hammer, D., Sherin, B., & Kolpakowski, T. (1991). Inventing graphing: Meta-representational expertise in children. *Journal of Mathematical Behavior, 10*, 117–160.

Dori, Y. J., Barak, M., & Adir, N. (2003) A Web-based chemistry course as a means to foster freshmen learning. *Journal of Chemical Education, 80*(9), 1084–1092.

Dunbar, K. (1997). How scientists really reason: Scientific reasoning in real-world laboratories. In R. Sternberg & J. Davidson (Eds.), *The nature of insight* (pp. 365–396). Cambridge, MA: MIT Press.

Gabel, D. (1998). The complexity of chemistry and implications for teaching. In B. J. Fraser & K. G. Tobin (Eds.), *International handbook of science education* (pp. 233–249). Great Britain: Klewer Academic Press.

Goodwin, C. (1995). Seeing in depth. *Social Studies of Science, 25*, 237–274.

Greeno, J. G. (1998). The situativity of knowing, learning, and research. *American Psychologist, 53*(1), 5–26.

Greeno, J. G., & Hall, R. P. (1997). Practicing representation: Learning with and about representational forms. *Phi Delta Kappan, 78*, 361–367.

Hanks, W. F. (1999). Intertexts: Writings on language, utterance and context. Denver: Rowman & Littlefield.

Hinton, M. E., & Nakhleh, M. B. (1999). Students' microscopic, macroscopic, and symbolic representations of chemical reactions. *The Chemical Educator*, 4(5), 1–29.

Hoffmann, R., & Laszlo, R. (1991). Representation in chemistry. *Angewandte Chemie*, 30, 1–16.

Kozma, R. (2000a). *Representation and language: The case for representational competence in the chemistry curriculum.* Paper presented at the 16th Biennial Conference on Chemical Education, Ann Arbor, MI.

Kozma, R. (2000b). Students collaborating with computer models and physical experiments. In J. Roschelle & C. Hoadley (Eds.), *Proceedings of the Conference on Computer-Supported Collaborative Learning 1999.* Mahwah, NJ: Erlbaum.

Kozma, R. (2000c). The use of multiple representations and the social construction of understanding in chemistry. In M. Jacobson & R. Kozma (Eds.), *Innovations in science and mathematics education: Advanced designs for technologies of learning* (pp. 11–45). Mahwah, NJ: Erlbaum.

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. *The Journal of the Learning Sciences, 9*(2), 105–143.

Kozma, R. B., & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching, 34*(9), 949–968.

Krajcik, J. S. (1991). Developing students' understandings of chemical concepts. In S. H. Glynn, R. H. Yeany, & B. K. Britton (Eds.), *The psychology of learning science*. Hillsdale, NJ: Erlbaum.

Krajcik, J., Blumenfeld, P., Marx, R., Bass, K., Fredricks, J., & Soloway, E. (1998). Inquiry in project-based classrooms: Initial attempts by middle school students. *Journal of the Learning Sciences, 7*(3&4), 313–351.

Lemke, J. (1990). *Talking science: Language, learning, and values*. Norwood, NJ: Ablex.

Linn, M., Bell, P., & Hsi, S. (1998). Using the Internet to enhance student understanding of science: The Knowledge Integration Environment. *Interactive Learning Environments, 6*(1–2), 4–38.

Nakhleh, M. B. (2002). *Some thoughts about molecular-level representations in conceptual problem solving.* Presented at Problem Solving in Chemistry: An Online CONFCHEM Conference on Chemistry. Available at http://www.chem.vt.edu/confchem/2002/b/nakhleh.html.

Nakhleh, M. B., Lowrey, K. A., & Mitchell, R. C. (1996). Narrowing the gap between concepts and algorithms in freshman chemistry. *Journal of Chemical Education*, 73(8), 758–762.

Council. (1996). *From analysis to action: Undergraduate education in science, mathematics, engineering, and technology*. Washington, DC: National Academy Press.

Pea, R. D. (1992). Augmenting the discourse of learning with computer-based learning environments. In E. de Corte, M. Linn, & L. Verschaffel (Eds.), *Computer-based learning environments and problem-solving* (NATO Series, subseries F: Computer and System Sciences) (pp. 313–343). New York: Springer-Verlag.

Pea, R. D. (1994). Seeing what we build together: Distributed multimedia learning environments for transformative communications. *The Journal of the Learning Sciences, 3*(3), 283–298.

Roth, W.-M. (2004). What is the meaning of meaning? A case study from graphing. *Journal of Mathematical Behavior.*

Roth, W.-M. (2001). Situating cognition. *The Journal of the Learning Sciences, 10* (1&2), 27–61.

Roth, W.-M. (1998). Teaching and learning as everyday activity. In B. Fraser & K. Tobin (Eds.), *International handbook of science education* (pp. 169–181). Dordrecht: Kluwer.

Roth, W.-M. (1995). Affordances of computers in teacher-student interactions: The case of interactive physics. *Journal of Research in Science Teaching, 32*, 329–347.

Roth, W.-M., & Bowen, G. M. (1999). Of cannibals, missionaries, and converts: Graphing competencies from grade 8 to professional science inside (classrooms) and outside (field/laboratory). *Science, Technology, and Human Values, 24*(2), 179–212.

Scardamalia, M., & Bereiter, C. (1994). Computer support for knowledge-building communities. *The Journal of the Learning Sciences, 3*(3), 265–283.

Schank, P., & Kozma, R. (2002). Learning chemistry through the use of a representation-based knowledge-building environment. *Journal of Computers in Mathematics and Science Teaching, 21*(3), 253–279.

Schegloff, E. (1992). Repair after next turn: The last structurally provided defense of intersubjectivity in conversation. *American Journal of Sociology, 97*(5), 1295–1345.

Shavelson, R. J., Phillips, D. C., Towne, L., & Feuer, M. J. (2003). On the science of education design studies. *Educational Researcher, 32*(1), 25–28.

Stevens, R., & Hall, R. (1998). Disciplined perception: Learning to see in technoscience. In M. Lampert & M. L. Blunk (Eds.), *Talking mathematics in school: Studies of teaching and learning*. New York: Cambridge University Press.

Woolgar, S. (1990). Time and documents in researcher interaction: Some ways of making out what is happening in experimental science. In M. Lynch & S. Woolgar (Eds.), *Representation in scientific practice* (pp. 123–152). Cambridge, MA: MIT Press.

Chapter 12
Visualization Without Vision: Students with Visual Impairment

M. Gail Jones and Bethany Broadwell

Abstract Complex science phenomena are often described with visual imagery. Research has shown that visual representations are not only motivating but are also critical in the communication of science concepts (Mathewson, 1999). Yet very little is known about how students with little or no vision learn without access to these representations. This chapter explores how students with visual impairment learn science concepts. Through interviews with students with visual impairments, we explore concepts that are most difficult for these students to learn. The mental representations of science concepts that students with blindness build are discussed as well as the role of passive and active visuospatial processes. In addition, we describe new haptic tools that can be used to design instruction that is accessible to those students that are sighted as well as those that have visual impairments. Finally this chapter outlines the types of future research that are needed to more fully meet the challenge of providing high quality, accessible science instruction to students with visual impairments.

Introduction

Modern science phenomena are often imbedded in visual representations that attempt to capture the complexity of structures, functions, and processes. For many of us, when we think of benzene, the Kreb's cycle, or wavelengths of light, mental images form our conscious memory. Research has shown that visual representations are not only motivating but are also critical in the communication of science concepts (Mathewson, 1999). With increasing frequency science is taught through visual displays in textbooks, powerpoint presentations, and computer-based multimedia materials (Ferk, Vrtacnik, Blejec, & Gril, 2003; van Sommeren, Reimann, Boshuizen, & Jong, 1998). Yet very little is known about how students with little or no vision learn without access to these representations. Parallel to the increase in the use of visualizations in science is a demand for students to have increased spatial skills (National Research Council, 2006). This chapter explores how students with

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visual impairment learn science concepts and the challenges they face in science instruction based on visual imagery. In most of the research discussed, blindness refers to individuals who are congenitally blind or totally blind but it is important to note that many individuals with visual impairment (including some that are legally blind) have some level of sight. This chapter discusses mental representations of science that students with blindness build, as well as the role of passive and active visuospatial processes. In addition, the role of haptics in both perception and as a tool for learning science is discussed.

Visualizing in Science

Imagine trying to learn science without vision. For those of us who are sighted, the task is nearly incomprehensible. Consider being a student in biology and the challenge of trying to accurately understand the phases of mitosis and meiosis, the internal anatomy of a clam, or transcription and translation of DNA. What would it take to learn these topics without visual models? Furthermore, what if your instructor for the class had no special preparation or materials for teaching students with visual impairment? Unfortunately this is the reality for most students with visual impairment.

Mathewson (2005) maintains that there are a series of universally recognized images that are found throughout the sciences including cycles, shadows, color, coils, and webs. He maintains that the ability to visualize in science begins with perceptual experiences and that the individual moves through developmental stages of visualization including didactic, depictions, models, encoded, creative imagery, and finally intuitive discovery. Furthermore, Mathewson (2005) argues that engineers and scientists are typically visual thinkers and that creativity in science is tied to visual abilities. This view of science might suggest that those with visual impairment should steer clear of science and engineering careers. But there are a number of successful scientists with limited or no vision that challenge this perspective. Examples include, William Skawinski a blind chemist who uses laser sterolithography to model 3-dimensional molecules, Larry Hjelmeland, a blind biochemist who studies cell biology, or Geerat Vermeij who researches evolutionary biology (Holden, 1998). Looking more closely at how mental representations are formed shows that although there are some distinct differences in those with and without visual impairment, there are underlying cognitive mechanisms that give rise to accurate scientific understandings.

There is growing evidence that people with total blindness are able to generate and process spatial images and are as successful in some contexts as people with sight. Differences in spatial processing for those with, and without, vision occurs when processing is active, that is when spatial images must be manipulated, transformed, or integrated. When images are encoded in memory without modification (passive processing), there are no significant differences between sighted and blind individuals (Cornoldi & Vecchi, 2000). In this context, Cornoldi and Vecchi define image as the product of a generative process as opposed to traces that result from direct perception. To these researchers traces are sensorial whereas images are more closely tied to perceptual memory. Cornoldi and Vecchi's definition opens the construct of "image" to include representations that are spatial but are not visual in origin. Research has shown that although people who are congenitally blind do not have visual images, they are able to generate mental images from auditory or haptic sensory input. The images that visually impaired people create have the same characteristics as those produced by people with sight (Zimler & Keenan, 1983).

Drawings completed by people with congenital blindness show a remarkable awareness of spatial relationships and perspectives. Kennedy (2003) published a series of drawings by Gaia, a totally blind girl (see Figs. 12.1–12.3).

The drawings that Gaia made represented space using T-junctions for overlap, height in the picture plane, parallel project, and inverse projection. Gaia used the same techniques and included the same features that are seen in sighted students' drawings. Similar results have been reported for drawings by congenitally blind, late-blinded, and low-vision subjects by Heller et al. (2002). Kennedy maintains that haptics provides access to many of the same spatial characteristics as vision (2003).

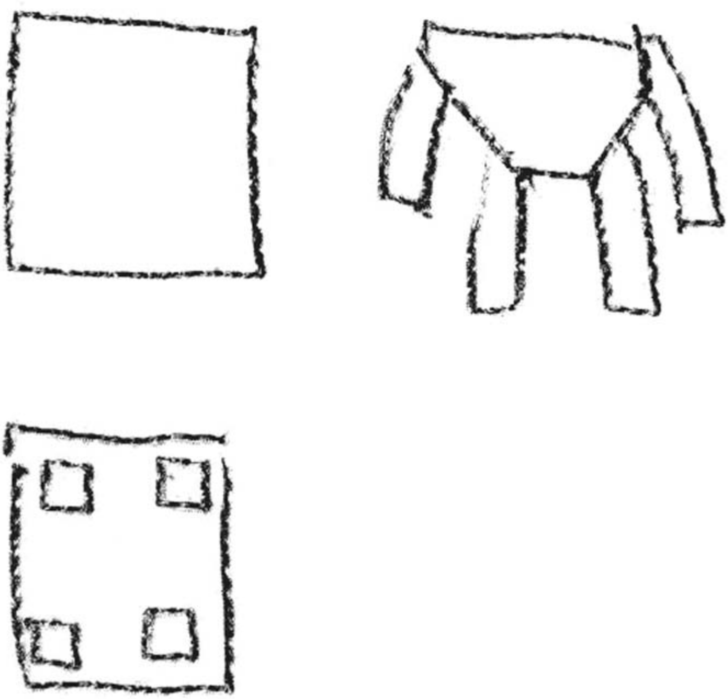

Fig. 12.1 A table from above, from the side, and from underneath. Drawn by Gaia a student with blindness. (Reprinted with permission from Pion Limited, London. From Kennedy, J. (2003). Drawings from Gaia, a blind girl. Perception, 32, 321–340.)

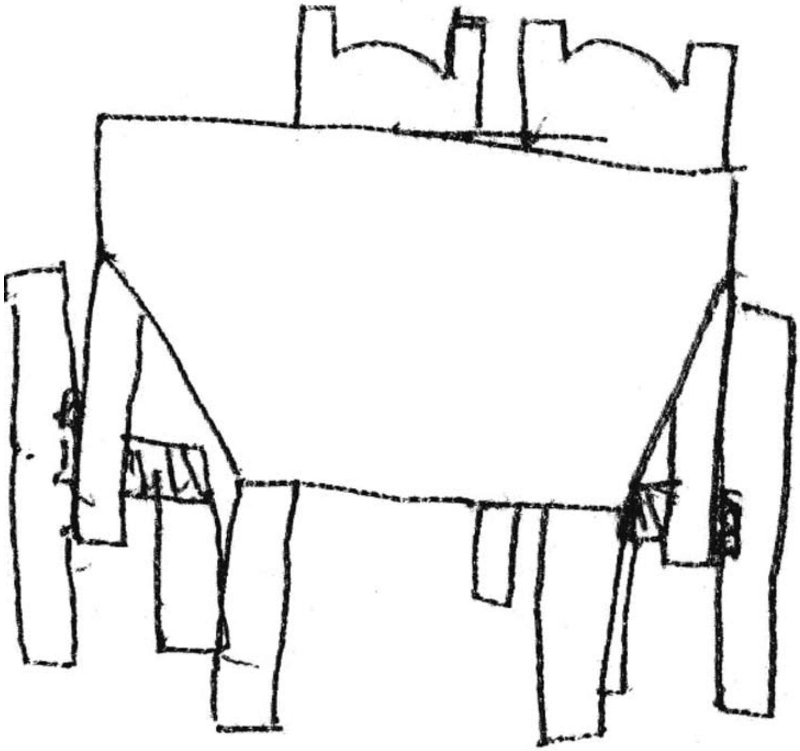

Fig. 12.2 Table and chairs. Drawn by Gaia a student with blindness. (Reprinted with permission from Pion Limited, London. From Kennedy, J. (2003). Drawings from Gaia, a blind girl. Perception, 32, 321–340.)

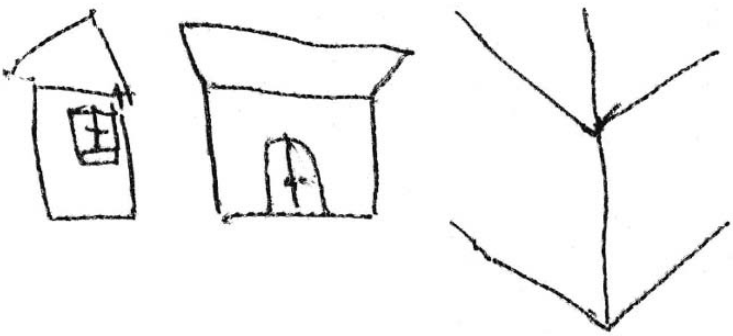

Fig. 12.3 House from gable end, front, and corner-on (incomplete). Drawn by Gaia a student with blindness. (Reprinted with permission from Pion Limited, London. From Kennedy, J. (2003). Drawings from Gaia, a blind girl. Perception, 32, 321–340.)

Furthermore, Kennedy suggests that pictures reproduce properties of objects and scenes available through both touch and vision.

Kennedy's proposition was tested in a study that examined how children with and without blindness recognized raised outline pictures (D'Angiulli, Kennedy, & Heller, 1998). Blind and aged-matched blindfolded sighted children (aged 8–13) were given raised line drawings of common objects and asked to identify them. The blind children could identify many of the pictures and were superior to sighted children in active exploration of the pictures. The researchers maintain that the study supports the premise that similar knowledge of shape of common objects and similar principles of depiction are used by both blind and sighted children when interpreting pictures.

Even color has been accurately conceptualized by individuals who were congenitally blind. Shepard & Cooper (1992) asked congenitally blind, color-blind, and sighted individuals to rate the similarity of colors and analyzed the results with multidimensional scaling. The resulting scalings showed that half of the participants with blindness produced categories that resembled the classical color wheel. One interpretation of this is that the participants with blindness used propositional representations to sort color such as blue is cool or red is hot (Kosslyn, Thompson, & Ganis, 2006).

When individuals with visual impairment were compared to individuals with sight in generating spatial maps or interactive images, those with sight outperformed those without sight. Furthermore, those without sight were slower in completing the tasks (Cornoldi & Vecchi, 2000). When individuals with and without vision were compared on tasks where they were asked to follow and reconstruct pathways on 2-D and 3-D matrices, those without sight had lower performance on 3-D tasks. One interpretation for the lower performance of the visually impaired participants is that detailed mental representations of 3-D patterns require continuous integration of two distinct images in order to visualize the features of the object. It may be that the differences between the performance of those with sight and those without are due to the demands of active cognitive load. Vecchi, Monticelli, & Cornoldi (1995) found that not only did people with visual impairment perform poorer on active tasks, they also showed a selective effect of active load. The load effect was completely absent in sighted but blindfolded individuals.

Kosslyn et al. (2006) argue that individuals with blindness convert shape-based imagery tasks into spatial tasks. Furthermore, they maintain that individuals with blindness do not create visual representations but instead use spatial processing mechanisms to represent imagery tasks. The blind often use information to create spatial representations from a range of activities such as temperature, sound, and tactile sensations such as texture, elasticity, and wetness.

There is growing evidence that even in the absence of visual stimulation people with blindness still use the visual cortex for processing other sensory information (Burton, 2003; Sathian & Zangaladze, 2002). MRI studies showed that when individuals with blindness were asked to read nouns with Braille text as well as when they listened to nouns the visual cortex was activated (Burton et al., 2000a, 2000b). These findings suggest that the visual cortex is really multimodal or a combination of spatial and multimodal. As our understandings of visualization continue to evolve, we may yet find that the differences in the processes used to create mental representations by those with vision and those without are far more similar than different. Perhaps the differences lie more with the language we use to describe the "visualization" process than the presence or absence of sight.

Beyond Visualization: The Role of Haptics

In an effort to measure how different sensory modalities contribute to perception of objects, we conducted a controlled study that compared visual, haptic, and visual plus haptic feedback on the perception and recognition of objects by students with and without visual impairment (Jones, Bokinsky, Tretter, & Negishi, 2005). The groups with haptic feedback used a point probe (the PHANTOM) to feel the objects. The PHANToM® uses a pen-like joystick that permits simulation of fingertip contact with virtual objects. As the student moves a virtual point-probe around in three-dimensional space, the PHANToM® tracks the x, y, and z Cartesian coordinates, as well as the pitch, roll, and yaw. Actuators communicate forces back to the user's fingertips as the probe comes into contact with virtual objects, providing the user with a sense of touching the virtual object (Salisbury, Brock, Massie, Swarup, & Zilles, 1995).

The visual treatment group observed the objects through a small spherical aperture. By reducing the visual field the visual treatment and the haptic treatments were more equivalent. The aperture also forced the visual participants to explore the objects serially, similarly to the haptic group. Each group explored 15 objects (combinations of cubes) with texture, 15 (combinations of cubes) without texture, and 2 complex shapes (torus, sphere). Accuracy, exploration time, and exploration paths were compared for the three treatment groups. Participants included 45 visually normal undergraduate students and 4 blind students. Results showed that for the normally sighted students, the haptic and haptic plus visual groups were slightly slower in their explorations than the visual group. This result supports previous research that has shown that haptic exploration takes more time than visual exploration (Jones et al., 2004). The haptic plus visual group was more accurate in identifying objects than the visual or haptic-only groups. The terms used by the haptic treatment group to describe the objects were qualitatively different from the visual and visual plus haptic groups, suggesting that these modalities may be processed differently. There were no differences across the three groups for long-term memory of the objects. The haptic group was significantly more accurate in identifying the complex objects than the visual or visual plus haptic groups. One possible explanation for this result was that participants tended to allow the point probe to fall off of the cubic shapes at edges whereas the probe tended to stay on the curved shapes. The blind students using haptic feedback were not significantly different from the other haptic treatment group participants for accuracy, exploration pathways, and exploration times. The haptic group of participants spent more time exploring the back half of the virtual objects than the visual or visual plus haptic participants. This finding supports previous research showing that the use of the PHANToM® with haptic feedback tends to support the development of 3-dimensional understandings of objects.

Haptic Technologies and Science Representations

There are a number of new haptic technologies that are proving as useful as tools for students with visual impairment. New force feedback joysticks like the PHANToM® allow students to manipulate and get tactile feedback on three dimensional objects. Early uses for these technologies include flight and medical training (Hayward, Oliver, Cruz-Hernandez, Grant, & Robles-De-La-Torre, 2004) as well as a tool for understanding docking positions for drugs (Brooks, Ouh-Young, Batter, & Kilpatrick, 1990).

In educational settings the PHANToM® has been used to guide a probe in an Atomic Force Microscope. This system, known as the nanoManipulator allows the user to not only image and manipulate objects at the atomic scale, but also provides the user with virtual tactile feedback. In educational settings the nanoManipulator has been used with middle and high school students as they explore properties of adenoviruses and carbon nanotubes remotely from their school to the science laboratory (Jones et al., 2004; Jones, Minogue, Tretter, Negishi, & Taylor, 2006). In this application, the learner can feel objects that cannot normally be visualized except through virtual reality interfaces.

The Haptic Cell

Recently we examined the efficacy of haptic instructional technology for teaching cell morphology and function to middle and high school students with visual impairments (Minogue, Jones, & Broadwell, in press; Jones, Minogue, Oppewal, Cook, & Broadwell, in press). The study examined students' prior experiences learning about the cell and cell functions in classroom instruction, as well as how haptic feedback technology impacted students' awareness of the 3-D nature of an animal cell, the morphology and function of cell organelles, and students' interest in the haptic technology as an instructional tool. Twenty-one students with visual impairment participated in the study. Students explored a tactile model of the cell with the PHANToM® that allowed them to feel the cell and its organelles. Results showed that students made significant gains in their ability to identify cell organelles and found the technology to be highly interesting as an instructional tool. This study showed that there are a number of issues that must be taken into consideration when using the point probe without vision. Students had difficulty locating the cell and the organelles in the 3-D space even though the cell was contained within a virtual box. Organelles were given artificial texture and elasticity to assist students in remembering the organelle morphology but the texture did not appear to be particularly useful to the participants. If the texture and elasticity could be enhanced then it may be more noticeable and useful as a learning tool. Although the pilot showed the haptic software to be of limited value for learning cell parts for students with visual impairment, the students were highly motivated to want to use the tool and were enthusiastic about their interest in seeing the PHANToM® used for other science tasks.

Importance of Visual and Spatial Representations in Science

New technologies have pushed many science fields in new directions that require students to have high spatial and visualization skills. For example, the fields of astronomy, geoscience, and oceanography utilize data rich techniques that require skills in understanding spatial scale, being able to interpret space and time data, as well as the ability to create mental representations (National Research Council, 2006). Areas that have been identified as requiring high levels of spatial literacy include: understanding the size and shape of the earth, the spatial structure of the universe, being able to recognize the shape or pattern amid a cluttered or noisy background, envisioning the motion of objects or materials through space in three dimensions, envisioning the processes by which objects change shape, thinking about time spatially, and analyzing systems with two, three or four dimensional systems where the axes are not distance (such as geospaces) (National Research Council, 2006). While it is recognized that "spatial thinking is integral to the everyday work of scientists and engineers and it has underpinned many scientific and technical breakthroughs" (National Research Council, 2006, p. 230), it is not clear how different science domains utilize and require spatial knowledge and abilities. This question is key for us as we prepare all students for science careers—those with and those without sight.

The Issue: Who will do Science?

There is an ongoing global need for scientists and engineers. Given that many students with visual impairment are equally as capable as their sighted peers, there are many reasons we should make science more accessible for those with visual impairment.

There are approximately 10 million blind and visually impaired people in the United States (American Federation for the Blind, 2003). Of these, approximately 93,600 are visually-impaired students who are served in school special education programs. Visual impairment is defined here as "an impairment in vision that, even with correction, adversely affects a child's educational performance" (See IDEA's Definition of Disabilities at: //www.ed.gov/databases/ERIC_Digests/ed429396.html). A report from the National Science Foundation (2004) shows that in the United

States 10.6% of all undergraduates are students with disabilities. Of this small percentage of students, only 5.0%, 4.5%, 1.0% and 10.7% are majoring in engineering, life sciences, physical sciences, and other technical professions respectively. These statistics are alarmingly low and students with visual impairments make up a small portion of students with disabilities. However, the population of people with visual impairments is growing due to a higher survival rate of premature babies who never fully develop their vision (National Eye Institute, 2006).

Through interviews with students that are mainstreamed into regular education classes we have documented case after case where students tell us that when the class does a lab or other science activity, "I just sit there." Apparently teachers are not able or knowledgeable about how to make accommodations for these students. Students report that for the most part they learn science almost strictly through listening to teachers and through Braille texts. By limiting science instruction to audition, we run the risk of limiting students' knowledge of science as well.

Improving Instruction for Learners with Visual Impairment

There are a number of strategies that teachers can use to provide more effective science instruction to students with visual impairment. Perhaps the most difficult aspect for teachers with mainstreamed students with visual impairment is to think through ahead of time where in the lesson students are likely to need accommodations. Visually complex representations can be made more accessible in a variety of ways from 2-dimensional raised line diagrams, to 3-dimensional rough models, to accurate 3-dimensional models made to scale. The addition of texture and smell to 3-dimensional representations can enhance the student's access to model details as well as reduce the cognitive load needed to process complex constructs.

There are now a number of new technological developments that can also be used to provide students with tactile science experiences. Converting text to Braille is no longer a difficult process and computers can translate text to speech for students with visual impairment. New haptic feedback tools are under development that can be used to provide models and simulations that utilize haptic and auditory stimuli. Probeware can be adapted to provide auditory data rather than visual data for experiments with temperature probes, motion detectors, pH meters, and other sensors. New 3 dimensional printers or rapid prototypers, can be used to produce very accurate scientific models. These 3-D models can provide students with visual impairment the opportunity to feel detailed and accurate representations of proteins, microscopic organisms, or anatomical structures.

At the simplest levels, teachers can take actions that will make a big difference in the accessibility of science instruction. Speaking to the class when entering and leaving, calling a student with visual impairment by name, and using highly descriptive language can orient the student to the learning environment. Safety warnings and the location of safety equipment should be shared with students. Braille labels can be placed on glassware, chemicals, and reagent containers. Tactile maps, diagrams, and graphs can be created with liquid glue or puff paints. Meter sticks and metric rulers can be marked with glue to allow the student with visual impairment to make accurate measurements. Simple chemical reactions conducted in closed zip lock bags allow the student with visual impairment to feel endothermic and exothermic reactions safely. Asking a sighted student volunteer to read directions and guide the student with visual impairment can make a significant difference in the degree to which the student with a disability can participate. Science can be made accessible to students with visual impairment and the greatest challenge left is to get prospective teacher candidates and experienced teachers to begin to make these accommodations a natural part of the lesson planning process.

Areas for Future Research

When people with visual impairments were asked to suggest areas for future research, the participants wanted research that would focus on access to the environment, access to information, as well as research that would examine social and attitudinal factors (Duckett & Pratt, 2001). We recently asked middle and high school students which topics they found difficult to learn in science and they reported difficulty with many of the areas that are traditionally taught with visual representations: layers of the atmosphere, magnetism, invisible fields, volcanoes, electromagnetism, geologic time, equations, topographic maps, phases of cell division, chemistry, DNA, and microbiology. The student voices were united in their request to make instruction accessible for them. The students that we have worked with clearly have the motivation to learn—they just need educators to find better ways to make science available through a modality other than vision. With the significant advances that have been made in technology, there is no reason that we cannot rethink how to represent science to make it accessible. Furthermore, if we liberate the way science is framed it is likely that we can gain great insight into science phenomena by listening more closely to a new group of scientists who utilize new (non-visual) methods of investigating science.

Previous studies of people with visual impairment have provided significant insights into our understandings of the role of visualization in cognition. Even though we have made gains in understanding the teaching-learning process there remain a number of questions to be answered. For example, what do students need to know about spatial thinking to be successful students of science? How do students with and without vision (or with limited vision) develop spatial awareness? What educational experiences contribute to the development of expertise in spatial thinking?

To better understand the creation of mental representations we need to know more about the mechanisms that students with visual impairment use to encode experiences perceived with different modalities. How is encoding and perceiving science different for those with partial blindness than those who are completely blind? Furthermore, we need to know how cognitive development differs for those who are blind from birth compared to those who develop blindness after birth.

Are there ways we can represent science differently—rather than expecting those without sight to adapt to visual representations? We know little about how science concepts are cognitively structured and whether or not there is a hierarchy to best promote learning. Is there a hierarchy to different attentional stimuli? Within individuals or groups of individuals that share particular characteristics, are there developmental differences that can predict when spatial and other types of focused learning experiences are more or less effective?

At the most basic levels of education we know little about which topics are the most difficult for students with visual impairment to learn. If we could identify the topics that are problematic for students with visual impairment, we could systematically research the characteristics that make these topics difficult as well as more effective ways to teach them.

One of the goals of this chapter is to encourage other researchers and educators to think deeply about how we can better teach students with visual impairment. We stand to learn a great deal about science, science education, and the teaching-learning process. But more importantly, there are large numbers of students who need access to high quality science instruction and we need these students as part of our science workforce for tomorrow.

References

American Federation for the Blind. (2003). Blindness statistics. Retrieved August 15, 2006 from: www.afb.gov.

Brooks, F. P., Ouh-Young, M., Batter, J. J., & Kilpatrick, P. J. (1990). Project GROPE-Haptic displays for scientific visualization. *ACM Computer Graphics, 24*, 177–185.

Burton, H., Snyder, A., Conturo, T., Akbudak, E., Ollinger, J., & Raichle, M. (2002a) Adaptive changes in early and late blind: a fMRI study of Braille reading. *Journal of Neurophysiology, 87*, 589–611. Retrived from http://jn.physiology.org.

Burton, H., Snyder, A., Diamond, J., Raichle, M. (2002b) Adaptive changes in early and late blind: a fMRI study of verb generation to heard nouns. *Journal of Neurophysiology, 88*, 3359–3371. Retrived from http://jn.physiology.org.

Burton, H. (2003). Visual cortex activity in early and late blind people. *The Journal of Neuroscience, 23*(10), 4005–4011.

Cornoldi, C., & Vecchi, T. (2000). Mental imagery in blind people: The role of passive and active visuo-spatial processes. In M. Heller (Ed.), *Touch, representation, and blindness* (pp. 143–181). Oxford: Oxford University Press.

D'Angiulli, A., Kennedy, J. M., & Heller, M. A. (1998). Blind children recognizing tactile pictures respond like sighted children given guidance in exploration. *Scandanavian Journal of Psychology, 39*, 187–190.

Duckett, P., & Pratt, R. (2001). The Researched Opinions on Research: visually impaired people and visual impairment research. *Disability and Society, 16*(6), 815–835.

Ferk, V., Vrtacnik, M., Blejec, A., & Gril, A. (2003). Students' understanding of molecular structure representations. *International Journal of Science Education, 25*(10), 1227–1245.

Hayward, V., Oliver, R. A., Cruz-Hernandez, M., Grant, D., & Robles-De-La-Torre, G. (2004). Haptic interfaces and devices. *Sensor Review, 24*, 16–29.

Heller, M., Brackett, D., Scroggs, E., Steffen, H., Heatherly, K., & Salik, S. (2002). Tangible pictures: Viewpoint effects and linear perspective in visually impaired people. *Perception, 31*, 747–769.

Holden, C. (1998). Leveling the playing field for scientists with disabilities. *Science, 282*, 36–37.

Jones, M. G., Andre, T., Kubsko, D., Bokinsky, A., Tretter, T., Negishi, A., et al. (2004). Remote Atomic Force Microscopy of microscopic organisms: Technological innovations for hands-on science with middle and high school students. *Science Education, 88*, 55–70.

Jones, M., Bokinsky, A., Tretter, T., & Negishi, A. (2005, May 2). A comparison of learning with haptic and visual modalities. *Haptics-e The Electronic Journal of Haptics Research [Online], 3*(5). Retrieved on Augusts 14, 2006 from: http://albion.ee.washington.edu/he/ojs/viewarticle.php?id=44.

Jones, M. G., Minogue, J., Tretter, T., Negishi, A., & Taylor, R. (2006). Haptic augmentation of science instruction: Does touch matter? *Science Education, 90*, 111–123.

Jones, M. G., Minogue, J., Oppewal, T., Cook, M., & Broadwell, B. (2006). Visualizing without vision at the microscale: Students with visual impairment explore cells with touch. *Journal of Science Education and Technology* 15, 1573–1589.

Kennedy, J. (2003). Drawings from Gaia, a blind girl. *Perception, 32*, 321–340.

Kosslyn, S., Thompson, W., & Ganis, G. (2006). *The case for mental imagery*. Oxford: Oxford University Press.

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

Mathewson, J. (2005). The visual core of science: Definition and applications to education. *International Journal of Science Education, 27*, 529–548.

Minogue, J., Jones, M. G., & Broadwell, J. (2006). Exploring cells from inside out: New tools for the classroom. *Science Scope*, 29(6), 28–32.

National Eye Institute. (2006). A Report of the National Advisory Council: *Report of the Visual Impairment and its Rehabilitation Panel.* Retrieved August 15, 2006, from http://www.nei.nih.gov/strategicplans/neiplan/

National Research Council. (2006). *Learning to think spatially*. Washington, DC: National Academies Press.

National Science Foundation. (2004). *Women, minorities, and persons with disabilities in science and engineering* (NSF 04–317).

Salisbury, K., Brock, D., Massie, T., Swarup, N., & Zilles, C. (1995). Haptic rendering: Programming touch interaction with virtual objects. Proc. *Symposium on Interactive 3D Graphics*, ACM. pp. 123–130.

Sathian, K., & Zangaladze, A. (2002). Feeling with the mind's eye: Contribution of visual cortex to tactile perception. *Behavior Brain Research, 135*, 127–132.

Shepard, R., & Cooper, L. (1992). Representation of colors in the blind, color-blind, and normally sighted. *Psychological Science, 3*, 97–104.

van Sommeren, M., Reimann, P., Boshuizen, H., & Jong, T. D. (Eds.). (1998). *Learning with multiple representations*. Amsterdam: Permagon.

Vecchi, T., Monticelli, M., & Cornoldi, C. (1995). Visuo-spatial working memory: Structures and variables affecting a capacity measure. *Neuropsuchologia, 33*, 1549–1564.

Zimler, J., & Keenan, J. (1983). Imagery in the congenitally blind: How visual are visual images? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 9*, 269–282.

Chapter 13
When an Image Turns into Knowledge: The Role of Visualization in Thought Experimentation

Miriam Reiner and John Gilbert

Abstract This chapter will suggest that experiments carried out in thought are a valid and powerful tool for the construction of insight into the behavior of the world. Thought experiments (TEs) include five components, the central of which is visualization. We suggest that the bounded yet structured visualization of imaginary worlds, integrated with logical and conceptual derivations from them, provide a powerful cognitive mechanism for 'knowing'. We define kinds of visualization in a TE by analyzing well known historical thought experiments in science and students' TEs. We suggest that the structures of these imaginary worlds are based on a kind of 'instinctive knowledge' which is frequently tacit.

The Problem

How is a picture turned into knowledge about it? One person may look at the following picture (see Fig. 13.1) and see a hill, whilst another will look and see a graphical representation of a potential wall in physics.

Both are valid. Actually, this picture was obtained in a study of students' learning of fields of force in a virtual world in which they 'felt' the force exerted on the virtual particle. They did so through a force-feedback interface. The interface, a 'smart' joystick, was held by subjects. Moving the joystick moved the particle. Forces exerted on the particle were exerted by the joystick on the hand. The subjects in this study (Reiner, 1999a) were describing a static representation of their perceptions of the distribution of the intensity of forces acting in the virtual space. But one can think of a picture such as this differently: how is the behavior of the particle different at the 'top' vs. the bottom? How is motion affected by the changes in forces? The first view, of a hill, a field or a landscape, is more of a static interpretation of the picture. The latter is more of a dynamic interpretation. In this paper we suggest that specific, dynamic, views of pictures are provided by TEs. Our opening question

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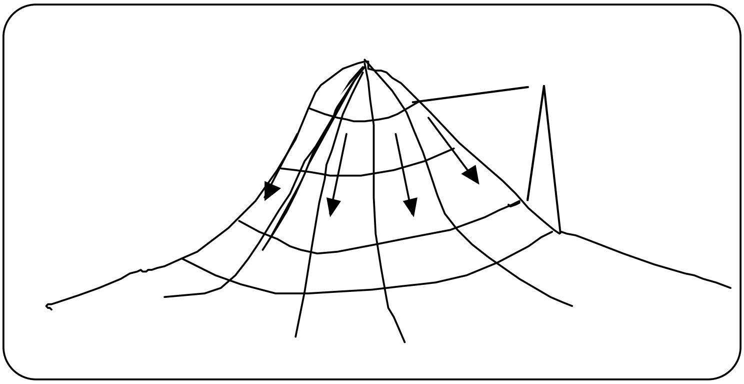

Fig. 13.1 The static interpretation of a picture

now becomes: How can a TE turn a picture into knowledge? We will show that TE's integrate the dynamic manipulation of visual images with conceptual and logical derivations to generate new ideas.

This chapter describes the cognitive nature of TEs by providing examples from both physics and from students' thought experiment that are used to generate knowledge. We focus on the role of visualization and its integration into a cognitive whole through the use of logical derivation rules to provide conceptual knowledge. For us, the scope of visualization extends beyond that of mere static images and includes that of objects, trajectories, and interactions, all subject to well structured rules. Thus

Fig. 13.2 'Welcome to the edge of the Universe' (Illustration from the Stanford Encyclopedia)

imagination is bounded and structured according to a-priori defined rules. Where do these rules come from? Are these rules arbitrary, a product of creative imagination only? We show that they rules are a valid reflection of the behavior of objects in the physical world, translated into precise forms and elegantly packaged so that they can to be inserted into imaginary worlds on which experiments are carried out, results are observed, and conclusions drawn.

An Introduction to TEs

Thought experiments are devices of the imagination used to investigate the nature of things (Stanford Encyclopedia . (http://plato.stanford.edu/entries/thought-experiment/#ExaThoExp) (see Fig. 13.2). How then is it possible to produce valid knowledge about the world based on imagination only?

One vital piece of evidence is that TEs are heavily used in widely accepted scientific reasoning, are in major physics papers, and have thus been considered an indispensable tool for physicists (Sorenson, 1992). Maxwell's 'Demon', Einstein's 'Elevator', Heisenberg's 'Gamma-Ray Microscope', Schrödinger's 'Cat', Stevin's 'Rolling Chains', are just a few examples that illustrate the major impact of TE's on the sciences. TEs have been reported through history down to our own time, where the creation of quantum mechanics and relativity would have been highly unlikely without the crucial role played by TEs (for a review, see Reiner and Burko, 2003; Gilbert and Reiner, 2000). An early example of a TE is in Lucretius, *De Rerum Natura* (Brown, 2004 also in the Stanford Encylopedia at http://plato.stanford.edu/entries/thought-experiment/#ExaThoExp). It shows that space is infinite:

> If there is a purported boundary to the universe, we can toss a spear at it. If the spear flies through, it isn't a boundary after all; if the spear bounces back, then there must be something beyond the supposed edge of space, a cosmic wall that stopped the spear, a wall that is itself in space. Either way, there is no edge of the universe; neither is there a boundary. Space is infinite and unbounded.

This example includes three components common to TE's: visualizing a situation; carrying out an operation, frequently an experiment; and observing what happens then, i.e what the outcomes of the operation are – the results. All three components require internal visualization which relies on bounded imagery.

Visualization, experimentation, and observation, can be viewed as analogous to laboratory experiments, with the exception of the nature of the world involved. In a TE the world is imaginary and relies on the thinker's past experience and knowledge, while in the laboratory the world is external and is independent of the thinker's past. This also illustrates the weaknesses of TEs – the thinker is bounded by personal rationality, past experience and personal knowledge. Nevertheless, the frequent use and immense influence of TE's on the sciences suggests that TE's are efficient tools for argumentation and the construction of worthwhile knowledge. For instance, mentally 'walking' through the 'edge of the world' TE, is an educational experience: the learners conceptualizes 'the world' as infinite, and unbounded. The learner further practices logical derivation and utilizes past experience of moving objects. Several studies have shown that students perform TEs in science learning (Reiner, 1998, 1999a, 2006; Reiner and Burko, 2003; Reiner and Gilbert, 2000; Klassen, 2006). Students' TEs do not mimic the content or high conceptual coherency and logical elegance of scientists' TEs, yet they consist of the same building blocks (Reiner and Burko, 2003).

TEs as Tools for Collaborative Problem Solving

In spite of being rooted in personal experience, TEs can go beyond personal reasoning, and be used as tools for the collaborative construction of knowledge, i.e. in constructing arguments in a scientific discourse. Norton (2004) claims that TE's are mere arguments, but Gendler, (1998, 2004, 2005) and Bishop (1999) take the opposite view: their stand is that TE's include components of tacit knowledge and intuition. Mach suggested that we possess a store of 'instinctive knowledge' constructed through recurring experience, either actual experience or inherited through the evolutionary process (Mach, 1960, 1976; Laymon, 1991). This knowledge is not necessarily articulated at all, but is triggered by factors in a situations that we encounter. This instinctive knowledge is an *umwelt* – it constitutes an inner mental world that includes mental models of the behavior of physical objects in the world.

Thought Experiments in Other Domains

Although this chapter focuses on TE's and visualization in the sciences, it is important to recognize that TEs are a general cognitive mechanism and their use is thus not limited to the sciences. For instance, Searle's 'Chinese Room' TE was devised to establish that no computer, just by running a program, can *understand* the Chinese language. Searle maintains that computers can only *simulate* thought and his argument is one of the most widely credited counters to claims of the possibility of artificial intelligence. The Stanford Encyclopedia entry on TEs shows that 'much of ethics, philosophy of language, and philosophy of mind, are based firmly on the results of thought experiments': Putnam's 'Twin Earth', Parfit's 'People Who Divide Like An Amoeba' are just a few examples drawn from the same source . TEs are also used in the social sciences too, for example in existing legislative systems when new laws are invented because a case before the court has no precedent. Similarly, TEs are utilized when legislative committees have to invent a law *in anticipation* of events that might occur in the future (Wilkes, 1988). Works of science fiction can be viewed as extended series of TEs. Social negotiation continuously requires that participants imagine the state of mind of opponents in order to design the next move. Interestingly, some research shows that young children, before the age of two and half to three years, are not capable of imagining the mind of another person, and thus have not yet developed a 'theory of mind'.

The Importance of TE's as Cognitive Mechanisms

This importance is rooted in two different frameworks. The first is the nature of science and, whilst this will be illustrated mainly in physics, it is relevant for all scientific domains of knowledge. The second is rooted in how we think.

Contemporary research in physics, which involves experimental regimes that are unreachable even by current instrumental technologies, such as Planck-scale physics or the interiors of black-holes, require the construction of 'what if' imaginary worlds, TEs. Through such experiments in thought, all such situations are cognitively reachable. The second concerns the human natural cognitive routines used for generating knowledge. Images of 'what if' situations, such as predictions of paths of moving objects, a player's ability to clearly see in the mind's eye whether a ball that is thrown will reach a target, simulating a colleague's response to heavy criticism, are all inherent to everyday thinking, and are kinds of experiments run in thought. Such experimentation in thought involves, seeing with the mind's eye, i.e. engaging in imagery. Thus TE's include mental visualization processes, as part of construction of knowledge. Yet, TEs, being the fruits of not only of physical phenomena, but also of our imagination and prejudices, are prone to errors, just like any other cognitive process. Visualization in itself goes beyond 'seeing' of pictures. It is the attachment of meaning to pictorial representations. Thus visualization is a process that integrates non-symbolic representations (such as graphical and pictorial representations) with semantics. A line on a piece of paper, for instance, has no meaning in itself. However, if it is associated with temperature values during a day it becomes meaningful. Once such a line becomes meaningful, we can use it for prediction or for the analysis of events, using a mechanisms such as TEs.

What are the Components of a Thought Experiment?

It is difficult to produce a precise definition of a TE (Brown, 2004), but we can define the features that will help us recognize one when we see one. Just like physical experiments, TEs are used in an attempt to understand something about the behaviour of objects. Sorenson (1992) creates a parallelism between real and thought experiments: TEs are considered to be heuristics for problem solving, experiments that have never been performed other than in the mind, events that occur in thought, observed only with the mind's eye (Ibid). Sorenson's definition hints at the necessity of visualization, in addition to conceptual and logical derivation (Bunzl, 1996). Generally, TE's can partitioned into five stages (Reiner, 1998). First, the research question and general assumptions, such as the physical theory, to be used. Second, the features of the world as imagined by the physicist, i.e., what the (relevant) system looks like. This, of course, determines – in conjunction with the assumptions – the formulation of the TE and the choice of the physical model to be used. Third, the carrying out of the TE itself, which is usually a series of formal deductions from the preceding two stages. Fourth, the extraction of the results from the carrying out of the experiment, and, fifth, the drawing of the conclusions about its meaning (for additional details, see Reiner and Burko, 2003).

Visualization in a TE

Imaginary worlds are a central feature of TEs. Without the visualization part, no thought experiment can be performed (Gendler, 2004, 2005). The imaginary world is the visual mental expression of the experiment, shaped analogously to a physical experiment.

Imagination is, in general, seen as the power or process of producing mental images and ideas. The term describes the process of accessing memory – reviving in the mind percepts of objects constructed formally through experience (Rebber, 1992). This process is also termed imaging or imagery and refers to reproductive as opposed to productive or constructive imagination (Allard, 1993). Imagined events, such as the trajectory of a falling object or the motion and impact of a piston in an engine, are seen with the mind's eye – they all draw on sensory experience.

What are the features of visualization in a TE? How is visualization triggered and turned into knowledge? In the following we analyze several famous TEs, as well as drawing on research on children's TEs, in order to identify the process of converting an image into knowing through a TE.

Riding on a Ray of Light

A famous example of the interweaved of visualization and logical-conceptual processes is in one of Einstein's first TEs, as described in his autographical notes. He describes the central function of a TE. The nature of it and its significance are described as:

> *...a paradox upon which I had already hit at the age of sixteen: If I pursue a beam of light with the velocity c (velocity of light in a vacuum), I should observe such a beam of light as an electromagnetic field at rest though spatially oscillating. There seems to be no such thing, however, neither on the basis of experience nor according to Maxwell's equations. From the very beginning it appeared to me intuitively clear that, judged from the standpoint of such an observer, everything would have to happen according to the same laws as for an observer who, relative to the earth, was at rest. For how should the first observer know or be able to determine, that he is in a state of fast uniform motion? One sees in this paradox the germ of the special relativity theory is already contained.*
>
> (For more details, see Sections 5–6 of 'Einstein's Investigations of Galilean Covariant Electrodynamics prior to 1905,' *Archive for History of Exact Sciences*, **59** (2004), pp. 45–105.)

The five components are easily visible in this TE: a questions is set concerning the nature of the electromagnetic field; There is an assumption – that electromagnetic fields cannot be static (derived from Maxwell's equations and from Einstein's experience); An imaginary world is constructed – the features and state of objects are defined (i.e. the field is oscillating, the ray travels at the speed of light, the oscillating field travels at speed of light) and rules for behavior of the objects are defined. An experiment is carried out: both the traveler of the ray of light and the field are traveling. The observer observes the wavefront of the field. And the result is that the field seems static, which is impossible. Where does the knowledge that the field is relatively static come from? It is so obvious that nobody ever opposed this. The knowledge is so easily accepted because it is rooted in everyday sensory experience, shared by all. Frequently we experience relative motion, for example driving a car at a given velocity and observing another car coming in the same direction at the same velocity: both are at rest relative to each other. This precise experience was put to work in the above experiment: Within the imagined world of riding on a ray of light, and looking at the wave-front of an electromagnetic wave, one concludes, with no logical support, based only the on sensory experience of everyday life, that the wave-front is at rest. One needs to imagine the situation in order to 'know' that 'the wave-front seems at rest'.

This is an example of what Mach termed 'instinctive knowledge'. Using Stevin's 'Rolling Chain' TE, Mach showed how instinctive knowledge is used to generate knowledge:

In Stevin's TE, one visualizes a chain that is draped over a bent frictionless plane, as in Fig. 13.3(a). The question is: will it move and, if so, how? Extend the chain by adding a few links. Now connect them together so they become a close loop, as in Fig. 13.3(b). Will the chain rotate towards the left? No, since this will create perpetual motion, mobile, an infinitely rotating system with no input of energy, a engine that consumes no energy. Will it rotate to the right? No, for the same reasons as before. The chain on the bent frictionless planes must have been in static equilibrium. Otherwise, we would have a perpetual motion machine; and according to our experience-based 'instinctive knowledge', says Mach (1976), this is impossible. The five components of the thought experiment are obvious – a question (where will this move?) an imaginary world in which actions are taken (e.g. add links, connect ends of the chain.) an experiment, and a conclusion (no motion).

If so, if indeed our instinctive knowledge is so powerful – how come our instinctive knowledge is not sufficient to answer the question from the start? We suggest that the cognitive dynamic part of looking at a picture, manipulating the world rather

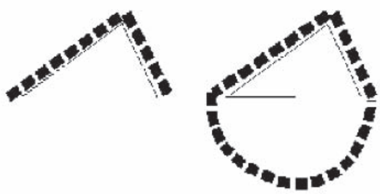

Fig. 13.3 How will the chain move?

(a) (b)

than the more static way of looking at a pictorial representation, i.e. conducting a TE, is a necessary and sufficient approach. That is, the experiment, the logical and conceptual derivations that structure the world, and the instinctive knowledge that tells us what is acceptable and what is not (perpetual motion), are crucial in reaching an answer.

There are three conjoint sources for the production and use of the bounded and structured imagination involved in these examples: an individual's instinctive knowledge, already-possessed conceptual structures, and the application of logic. If this has been found for scientists' TE's, will it be the same for students' TE's? Are students at all capable of producing such a complex and sophisticated cognitive mechanism as a TE? Obviously there is a major difference between scientists' 'instinctive knowledge' as compared with 'students' instinctive knowledge. How will this affect students TE's?

The Role of Embodied Knowledge, Logics and Visualization in Students' TE's

There are numerous papers that show that students indeed perform TE's (Gilbert and Reiner, 2000; Klassen, 2006; Reiner, 1998, 2006; Reiner and Gilbert, 2004). Although both scientists and students have a-priori commitments, beliefs and practices, these are different, and hence may affect the structure and bounding rules of an imaginary world.

Do students' have different views of the nature of 'substance' from scientists? Do students' problem solving heuristics have the structure of a TE? A fine-grained analysis of students' problem solving heuristics investigated these questions (Reiner, Slotta, Chi, & Resnick, 2000). The results suggested positive answers to both questions: students' problem solving heuristics reflect a structure of a TE, yet students; students' have different views of the nature of 'substance' than scientists. Yet, much more became apparent than a mere answer to the research questions.

The following is a very brief description of the experimental design and results. Students, 15 to 16 years old, were separated into four groups and presented with a task designed to provide opportunities for imagining situations related to physics-based conceptual thinking. The task was stated as follows:

> You are one of the participants in a bike race in a rocky desert. You need to carry water. The organizers provide you with four uncovered buckets full of water up to about 3 cm from the rim, each of about 30 N. Two dust roads are open for your choice. The first is relatively short, narrow, rocky, very steep, and almost a straight line. The second is winding, long, moderate slope, and smooth. The winner is the one who arrives first. You cannot afford losing the water. What road would you choose and how would you arrange the buckets so your chances to win are optimal?

Students participating in the study had no background in physics, other than a limited background on elementary fluid mechanics, but were all experienced cyclists.

A fine-grained analysis of students' talk-loud and discourse analysis of the collaborative solving of this problem showed a consistent ability to structure imaginary worlds, discussed and analyzed from a *dynamic* perspective, following precisely the structure and components of a TE. What kind of instinctive knowledge was used by the students to construct and 'observe' results in their imaginary world? What are the three sources of structuring and bounding of the imaginary world, that were previously identified in the scientific TE's? i.e. what are the constraining factors acting on students' visualization that stem from the use of logic, from existing conceptual constructs, and from the individual's instinctive knowledge? The results showed that students' structuring as well as instinctive knowledge arose from bodily-sensory knowing, or *embodied knowledge* (Johnson, 1987; Lakoff, 1987). Embodied knowledge originates in sensory memories related to bodily dynamics and kinematics, such as memories of impact, forces, and orbits, and is stored as *image schemata.* Students applied consistent bodily-image schemata, that is, the consistent application of a system of beliefs that can be roughly categorized as a *'balance schemata'* (three types) and '*symmetry schemata'* (four types). They frequently appear together in the sense that bodily force considerations are related to symmetry considerations of the physical system (for additional details, please see Reiner, 2000). An interesting referential strategy was employed by students. They imagined not only how the water would behave under changing conditions, but they also imagine themselves as being in the place of the water in order to imagine the feel of the forces acting. This strategy for visualization suggests that students employ imagination of different kinds, not only visual but also images of forces and motion– their own body substitutes for the water in order to predict the impact of the acting forces. Predictive capability was attainable only if students engage within the context of reproductive imagination. In sum: students' instinctive knowledge was rooted in image schemata, in systems of a-priory assumptions and beliefs, in their sensory memories and conceptual commitments.

What is Being Visualized? Beyond Simple Objects – Generic Objects and Rules of Interaction

Unlike the everyday visualization of objects such as seeing in the mind's eye one's child's face, or beautiful scenery, or even a mathematical graph, visualization in a context of a TE includes worlds that are beyond a mere collection of objects. The objects are mentally accompanied by rules of behavior and interaction with other objects in the world, constrained by the bounding and structuring rules of instinctive knowledge – different types of image schemata, sensory memories, frames of conceptual and logical commitments and assumptions.

The Generic Nature of Visualized Objects in a TE

In a sense, the objects used in TEs are not entire: they frequently consist only of lines, heaviness and colour are not present, whilst surface texture, precise size or shape, often do not seem to be important. The ray of light in Einstaein's experiment could be a line or a propagating BXE wave, or a concentric propagating circle. The conclusion of the TE is not affected. The objects in Stevin's experiment need not to be of a particular shape. Circularity would be appropriate (actually, in many of the illustrations in references to this TE, the chain is made of spherical objects), the bucket in the students imagination has no particular color, as is the shape of the rock in Galileo's experiment (for an analysis of students use of the free fall TE by Galileo, please see, Reiner, 1998). Only prototypical features are used to represent the objects. The precise nature of the protoypical descriptions of an object that are sufficient for mental representational manipulation and generally for thought must be the subject of a future study. For the purposes of this paper, it suffices to say that objects are minimally represented in a TE, with no extra details, unless relevant to the TE.

Directionality and Relationships to Real-world Situations

The relationship between the three vital components – instinctive knowledge, conceptual frameworks, and the application of rules of logic – are changed during the course of a TE, being not unidirectional but rather in a 'to and fro' relationship as portrayed in Fig. 13.4.

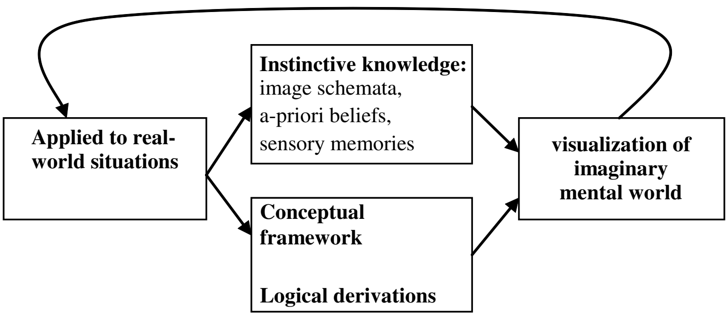

Fig. 13.4 The Interrelationships between instinctive knowledge, concepts and logical derivations in TEs

Furthermore, if the TE as a whole is applied to understand real-world situations, it sometimes preceding a real experiment, hence is changed as a results of observations in the real world.

With a Grain of Salt: When is a TE Wrong?

TE's being the product of imagination and instinctive knowledge – our personal 'umwelt' – are prone to errors. Furthermore, one of the underlying assumptions in this chapter is that perceptual experience is the grounds for visualizing situations in a TE, and personal image schemata are the materials for making predictions. This raises some doubts concerning the validity of a TE: Duhem (1954), a historian of physic, claims that a TE is no substitute for a real experiment, and should be forbidden in science. In view of the massive use of TE's in science, not too much sympathy has been expressed with this view. Dennett (1991) refers to the central role of naïve concepts in TE's: since TE's are based on folk concepts (i.e. naïve scientific ideas) TE's may lead not only to errors but they are inevitably conservative. The latter statement is reflected in the research literature: for instance and Reiner and Burko (2003) show that not only is the structure of a TE is shared by scientists and children, but sources of error are also shared. Yet the type of errors differs. Three cognitive processes were found to possibly lead to the erroneous conclusion in a TE's (Reiner and Burko, 2003):

1. Intuition may override the conventional theoretical framework. For example, intuitive judgment and past general experience, rather than theoretical constructs, led Schwarzschild, a prominent astrophysicist, to erroneously assume that a star can be taken as being static, as nothing in his past experience may have suggested otherwise. Indeed, one of Einstein's better known aphorisms is that 'commonsense is a deposit of prejudice laid down in the mind before the age of eighteen'. Students' too tend to ignore theory when intuition is more accessible. The most famous example is the overriding of Aristotelian intuitions over Newtonian intuitions by many, if not all, younger students (McClosky, Caramazza, & Green, 1980). Another example is the overriding of a materialistic assumption over energetic and field assumptions (Reiner et al., 2000). Too many to cite here, such examples are reported in the science education literature in different domains of science.
2. Incompleteness of the set of assumptions concerning the imaginary world of a TE. Reiner and Burko (2003) analyzed Landau's TE to show that he ignored hydrostatic equilibrium, Einstein ignored the gravitational red-shift effect in his analysis of the 'clock-in-the-box' TE, and Maxwell included kinetic theory but not quantum mechanics (which was as yet unknown). Similarly, in analyzing a series of students' TE's, they showed that students use fragmented pieces of a theory, applied inconsistently to different situations (see also DiSessa, 1992).
3. Irrelevancy of assumptions that were included in the features of the imaginary world in the TE. For example, Einstein assumed extra symmetry in his toy model of cluster of particles, i.e., a set of stationary configurations assuming a symmetry which is not inherent in the phenomenon.

In short, the above may be considered as the three I's: Intuition, Incompleteness and Irrelevancy, which we abbreviate is abbreviated to I3. These three provide a typology of cognitive erring-mechanisms that can be used for predicting classes of errors in TEs, analyzing naive learning processes, and developing learning environments. The analysis of TEs carried out by experts suggests that these cognitive mechanisms are embedded in physics thought, and hence a step in construction in physics, further suggesting that 'to err' is 'to learn'.

Overview

We have shown that visualization is a central component in TEs, the central component in a list of five: stating a question, visualizing an imaginary world, visualizing an experiment in the imaginary world, visualizing results, and constructing a scientific conclusion. Three components depend on visualization. We suggested that visualization of imaginary worlds in a TE is not arbitrary, subject to creative, open imagery, but rather is bound and structured according by the individual's conceptual framework and logical derivation practices, and is based on Mach's 'instinctive knowledge'. Instinctive knowledge, if put in more updated terminology, consists of a series of sensory memories and image schemata which are not necessarily verbal (Johnson, 1998; Lakoff 1987) for students' image schemata see Reiner, 1999; Reiner, 2004).

Visualization in a TE, rooted in imaginary processes, are also prone to err, resulting in erroneous conclusions. We showed that there are three types of mistakes resulting from such visualization processes, termed the three I's: Intuition, Incompleteness and Irrelevancy. Yet the power of such errors is in its recognition. The process or erring becomes a process of learning.

We suggest that the importance of visualization in a TEs, beyond that of being an elegant mental manoevre, is that, in that the process of using a TE, students can experience the role – supportive or destructive – of physical intuitions, incompleteness, and the importance of relevancy. We suggest that the importance of including TEs in the teaching process is threefold. The first is obvious: TEs are inherent to scientific thought and learning science also means becoming familiar with the scientific culture – deductions based on observation, experimentation in the laboratory and experimentation in thought. The second is that TEs force a learner to access tacit intuitions, explicit and implicit knowledge, and logical derivation strategies, and integrate these into one working thought process. The third is that, just as in the scientific community, through social discussions of TEs, conclusions and thought processes are negotiated, leading to conceptual refinement and the construction of reliable knowledge.

Quality in Student Thought Experimentation

The evidence presented above strongly suggests that the structure of students' TEs is, even without any special educational input, similar to that of scientists. So what needs to be done to improve the quality i.e. the educational value of students' TEs? They need enhanced opportunities to: raise questions that will either/both promote concept development and facilitate the transfer of ideas between contexts of scientific interest; create imaginary worlds and design TEs; carry out those TEs; obtain the results of their TEs, evaluate the outcomes and draw conclusions.

The research reviewed above suggests that four problems have also to be addressed:

a. Students use unproductive intuitions in designing TEs. This is because they have had inappropriate experiences on which to construct their intuitions;
b. the detailed mechanism used by students in the construction of imagined worlds is faulty. This arises severally from weaknesses in: the mental construction of objects to be used in TEs; the dynamic relations assumed to take place between those objects; the rules assumed to control the behaviour of the objects used;
c. students' use of fragmented conceptual knowledge, perhaps especially the employment of 'alternative conceptions' or 'misconceptions';
d. that during the construction of a TE, students let their intuition over-ride their conceptual knowledge.

Raising the Quality of Students' Thought Experimentation

How the can the quality of students' TEs be raised? How can the problems with 'uneducated' TEs be addressed? Mostly, importantly of all, what part do representations and their visualization play in the above two questions? Detailed answers to these questions would require a programme of research and development. However, some general strategies can be suggested.

Three changes of emphasis in pedagogy seem called for:

1. Greater use of interactive questioning, both teacher-led and student-led, in classes. General approaches to this have been widely discussed e.g. (Bennett, 2003) (pp. 146–173) and (Monk and Osborne, 2000) (pp. 88–103).
2. A more explicit address in student- and teacher-conducted practical work concerned with 'providing insights into the nature of scientific methodology' (Hodson, 1990).
3. Mentorship by the teacher in the design and conduct of TEs, associated with both practical work and paper-based problem solving. Perhaps this could be done not only for whole TEs but also for each of the component parts. This will require a high level of teacher 'subject knowledge' and 'pedagogical content knowledge' (Shulman, 1987).

Specific address corresponding to the four problems in student use of TEs can be made by:

a. providing students with practical work that 'motivates {them} to learn by providing them with enjoyment and stimulating their interest'(Hodson, 1990). In practice, this means providing them phenomena that pose conundra and puzzles in their solution and which depend on acute observation for their description. 'Open work' (Simon and Jones, 1992), that is, practical work in which students play a major role in deciding what is to be done, how it should be done, conducting the practical work, and reporting its outcomes, will be important here.

b. Requiring students to explicitly contruct mental objects, describe the behaviour of those objects, and to discuss the rules that govern this behaviour.
c. Ensuring that students have an ‘acceptably scientific’ rather than an ‘alternative’ understanding of prerequisite concepts. In short, relevant ‘conceptual development’ must be facilitated Posner, Strike, Hewson, & Gertzog (1982).
d. Demonstrating the primacy of conceptual knowledge over experiential knowledge during the mentorship mentioned above.

The visualization of ‘external 3D representation at the sub-micro level’ and of ‘internal representations’ will be needed at ‘meta level’ (see Chapter 1) in order for the quality of student TEs to be raised.

References

Allard, F. (1993). Cognitive Expertise, and Motor Performance. In Starkes J.L., and Allard F. (Ed.), *Cognitive Issues in Motor Expertise* (North Holland: Elsevier Science Publishers B.V.) 17–33.
Bennett, J. (2003). *Teaching and learning science:A guide to recent research and its applications*. London: Continuum Press.
Bishop, M. (1999). Why thought experiments are not arguments. *Philosophy of Science, 66*, 534–41.
Brown, J. R. (2004). Peeking into Plato’s Heaven. *Philosophy of Science, 71*, 1126–1138.
Bunzl, M. (1996). The logic of thought experiments. *Synthese, 106/2*(Fall), 227–240.
Dennett, D. (1991). *Consciousness explained*. New York: Little Brown
DiSessa, A. (1992). Designing Newton’s law: Pattern of Social and Representational feedback in a learning task, In R.J. Beun, M Reiner, (eds.), *Natural Dialogue and Interactive Students Modeling*, NATO publication.
Duhem, P. (1954). *Aim and structure of physical theory*. Princeton: Princeton University Press.
Gendler, T. S. (1998). Galileo and the indispensability of scientific thought experiment. *The British Journal for the Philosophy of Science, 49/3*(Sept), 397–424.
Gendler, T. S. (2004). Thought experiments rethought — and reperceived. *Philosophy of Science, 71*, 1152–1164.
Gendler, T. S. (2005). Thought experiments in science. *Encyclopedia of Philosophy*. New York: MacMillan
Gilbert, J., & Reiner, M. (2000). Thought experiments in science education. *International Journal of Science Education, 22*(3), 265–283.
Hodson, D. (1990). A critical look at practial work in school science. *School Science Review, 71*(256), 33–40.
Johnson, M. (1987) *The body in the mind:* Chicago, The University of Chicago Press.
Klassen, S. (2006). The science thought experiment: How might it be used profitably in the classroom? *Interchange, 37(1)*: 77–96.
Lakoff, G. (1987). *Women, fire and dangerous things: What categories reveal about the mind.* Chicago: University of Chicago Press.
Laymon, R. (1991). Thought experiments of Stevin, Mach and Gouy: Thought experiments as ideal limits and as semantic domains. In Horowitz & Massey eds. *Thought Experiments in Science and Philosophy*, pp. 167–192.
Mach, E. (1960). *The science of mechanics* (Trans. J. McCormack, 6th ed.). LaSalle Illinois: Open Court
Mach, E. (1976). On thought experiments. In J. McCormack (Trans.), *Knowledge and error* (pp. 134–147). Dordrecht: Reidel,

McClosky, M., Caramazza, A., & Green, B. (1980). Curvelinear motion in the absence of external forces: naive beliefs about motion of objects. *Science*, *210*, 1139–1141.

Monk, M., & Osborne, J. (Eds.). (2000). *Good practice in science teaching: What research as to say*. Buckingham: Open University Press.

Norton, J. (2004). On thought experiments: Is there more to the argument? *Proceedings of the 2002 Biennial Meeting of the Philosophy of Science Association, Philosophy of Science, 71*, 1139–1151. [Preprint available online].

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accomodation of a scientific conception: towards a theory of conceptual change. *Science Education, 66*, 211–227.

Reber, A. S. (1992). Implicit learning and tacit knowledge. An essay on the cognitive unconscious, Oxford Psychology Series, 19 (Oxford: Oxford University Press).

Reiner, M. (1998). Thought experiments and collaborative learning in physics. *International Journal of Science Education, 20*(9), 1043–1059.

Reiner M. (1999a). Conceptual construction of fields with a tactile interface, *Interactive Learning Environments, 6*(X), 1–25.

Reiner, M., Slotta, J., Chi, M. T., & Resnick, L. (2000). An underlying materialistic commitment in naive thought. *Cognition and Instruction, 18*(1), 1–35.

Reiner, M., & Gilbert, J. (2000). Epistemological resources for thought experimentation in science learning. *International Journal of Science Education, 22*(5), 489–506.

Reiner M., & Burko, L. (2003). On the limitations of thought experiments in physics and implications for physics learning. *Science and Education, 12*, 365–385.

Reiner M., & Gilbert J. (2004). The symbiotic roles of empirical experimentation and thought experimentation in the learning of physics. *International Journal of Science Education, 26*(15), 1819–1834.

Reiner, M. (2006). The context of thought experiments in physics learning. *Interchange, 37*(1), 99–117.

Shulman, L. (1987). Knowledge and teaching: foundations of the new reforms. *Harvard Educational Review, 57*(1), 1–22.

Simon, S. A., & Jones, A. T. (1992). *Open work in science: A review of existing practice*. London: King's College, University of London.

Sorensen, R. A. (1992). Thought Experiments, Oxford University Press, Oxford.

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