JOHN K GILBERT

# CHAPTER 1

# VISUALIZATION: A METACOGNITIVE SKILL IN SCIENCE AND SCIENCE EDUCATION

*Institute of Education, The University of Reading, UK*

Abstract. The range of terminology used in the field of 'visualization' is reviewed and, in the light of evidence that it plays a central role in the conduct of science, it is argued that it should play a correspondingly important role in science education. As all visualization is of, and produces, models, an epistemology and ontology for models as a class of entities is presented. Models can be placed in the public arena by means of a series of 'modes and sub-modes of representation'. Visualization is central to learning, especially in the sciences, for students have to learn to navigate within and between the modes of representation. It is therefore argued that students –science students' especially - must become metacognitive in respect of visualization, that they must show what I term 'metavisual capability'. Without a metavisual capability, students find great difficulty in being able to undertake these demanding tasks. The development of metavisual capability is discussed in both theory and practice. Finally, some approaches to identifying students' metavisual status are outlined and evaluated. It is concluded that much more research and development is needed in respect of visualization in science education if its importance is to be recognised and its potential realised.

## THE NATURE OF VISUALIZATION

The Concise Oxford Dictionary gives the following two definitions for the verb 'visualize:

> '1. form a mental image of; imagine. 2. Make visible to the eye.' (Pearsall, 1999).

The distinction between these definitions in maintained in discussions about the nature of visualization and its role in accounts of the development of understanding. Tufte uses the word 'visualization' to mean the systematic and focused visual display of information in the form of tables, diagrams, and graphs (Tufte, 2001). Other writers are concerned with the reception and processing of that information by the brain. Reisberg, for example, distinguishes between 'visual perception', as meaning that image of an object achieved when and as it is seen, 'visual imagery' as meaning the mental production of an image of an object in its absence, and 'spatial imagery', as meaning the production of a mental representation of an object by tactile means (Reisberg, 1997). The link with brain activity is emphasised by Kosslyn's use of the phrase 'mental imagery' instead of 'visual imagery' (M. S. Kosslyn, 1994). Just to 'muddy the water' still further, 'visualization' is also often used just to cover 'visual imagery' e.g by (NSF, 2001).



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The use of 'visualization' to mean just an array of information (Tufte, 2001) seems to imply a naïve realist view of the world: what is 'out there' must have the same impact on all brains. However, the possibility of a personal construction of knowledge is supported by what is known of how the brain deals with optical phenomena. The close association, if not conflation, of terms associated with brain activity is hardly surprising as there is evidence that visual perception and visual imagery involve similar mental processes and that they are mutually supportive (Reisberg, 1997). Thus they both preserve the spatial layout of an object / image. This is because the speed with which a person is able to scan it (change the focus of attention in the object / image), zoom relative to it (appear closer to or further from it), and rotate it (move it through 360 degrees along any axis), are constant and identical in both cases. Moreover, both provide greater discrimination of detail (i.e. they show greater 'visual acuity') at the centre of the object / image than elsewhere in it. This similarity of processes stops short of them being identical operations, for:

> '(visual) images---have some pictorial properties, but they are of limited capacity and are actively composed' (S. M. Kosslyn, Pinker, Smith, & Shwartz, 1982) (p.133)

It does seem that visual perception is selective, this selectivity being responsible, in part, for the qualitative differences in any subsequently produced visual image. Additionally, differences in the purposes for which and the contexts within which visual perceptions and visual images are produced leads to the latter being active creations that are partial and selective even in respect of the former. In short, 'reality', the products of 'visual perception' and of 'visual imagery', may differ quite a lot.

Whilst the distinctions between 'visual perception' and 'visual imagery' are of great importance to psychologists, they are probably of a lesser importance to practising scientists and science educators. The word 'visualization' may, for convenience, be taken in this book to cover them both.

## VISUALIZATION IN SCIENCE AND SCIENCE EDUCATION

Science seeks to provide explanations for natural phenomena: to describe the causes that lead to those particular effects in which scientists are interested. However, 'phenomena' are not ready – made: we impose our ideas of what might be important on the complexity of the natural world. Scientists then investigate these idealisations, what may be called 'exemplar phenomena', at least at the outset of their enquiries in any given field. Early chemists preferred to work with solutions of pure substances, not with the mixtures found in nature. Early physicists opted for the study of the movement of objects where there was little friction. Early biologists chose systems where tidy crosses of physical characteristics occurred in the initial study of what would become genetics. These exemplar phenomena have one thing in common: they are simplifications chosen to aid the formation of visualizations (visual perceptions) of what was happening at the macro level. Such a descriptions and/or simplification of a complex phenomena is usually called a 'model', this corresponding to the everyday meaning of that word (Rouse & Morris, 1986). As scientific enquiry proceeds in any given field, the complexity of the models of exemplar phenomena that are addressed increases progressively, and the aims of the enquiry become ever more ambitious.

This process of simplification and representation within the scope of human senses with the aid of models becomes of greater importance as, later in a sequence of enquiries, explanations for exemplar phenomenon are sought at the sub-micro level. Models then become vital if the visualization (visual imagery) of entities, relationships, causes, and effects, within exemplar phenomena is to take place. The development of models and representations of them are in crucial in the production of knowledge. A classic example is Kekule's dream about the structure of the benzene molecule being like a snake biting its tail (Rothenberg, 1995). Models also play central roles in the dissemination and acceptance of that knowledge: for example, that of the double helix of DNA has now reached icon status, such that an abbreviated version of it is instantly recognized (Giere, 1988; S. W. Gilbert, 1991; Tomasi, 1988). Models can function as a bridge between scientific theory and the world-as-experienced ('reality') in two ways. They can act, as outlined above, as simplified depictions of a reality-as-observed (exemplar phenomena), produced for specific purposes, to which the abstractions of theory are then applied. They can also be idealisations of a reality-as-imagined, based on the abstractions of theory, produced so that comparisons with reality-as-observed can then be made. In this latter way they are used both to make abstractions visible (Francoeur, 1997), and, crucially, to provide the basis for predictions about, and hence scientific explanations of, phenomena (J. K. Gilbert, Boulter, & Rutherford, 2000).

This wide range of function is made possible because models can depict many different classes of entities, covering both the macro and sub-micro levels of representation. Many models are of objects which are viewed as having either an independent existence (e.g. a drawing of a reaction flask, of an atom) or as being part of a system (e.g. a drawing of a reaction flask in an equipment train, of an atom in a molecule). A model can be smaller than the object that it represents (e.g. of a whale) or larger than it (e.g. of a virus). Some models are representations of abstractions, entities created so that they can be treated as objects (e.g. flows of energy as lines, forces as vectors). Inevitably, a model can include representations both of abstractions and of the material objects on which they act e.g. of the forces thought to act within a structure. A model can be of a system itself, a series of entities in a fixed relation to each other (e.g. of carbon atoms in a crystal of diamond). It can be of an event, a time-limited segment of behaviour of a system (e.g. of the migration of an ion across a semi-permeable membrane). Lastly, it can be of a process, where one or more elements of a system are permanently changed (e.g. of a catalytic converter of hydrocarbons in operation).

Many of the examples given in the paragraph above were drawn from chemistry. This is not surprising – and is evident in the balance of contributions to this book - for the key role of models in the development of chemical knowledge was recognised by the mid-twentieth century (Bailer-Jones, 1999; Francoeur, 1997). Indeed, they have become 'the dominant way of thinking' (Luisi & Thomas, 1990) in chemistry, something that chemists do 'without having to analyse or even be aware of the mechanism of the process' (Suckling, Suckling, & Suckling, 1980). The development and widespread use of computer-based systems for generating and displaying models had its initial impact on chemistry, where visualization is so vital.

However, as later chapters show, this capability is now being fully exploited in physics, biology, and the earth science. Indeed, Martz and Francoeur have produced and regularly update a web-site on the history of the representation of biological macromolecules (Martz & Francoeur, 2004), whilst Martz and Kramer provide a similar service in respect of the teaching resources available (Martz & Kramer, 2004).

If models play important roles in science, it therefore follows that they should play equally important roles in science education. Those students who may become scientists must understand the nature and significance of the models that played key roles in the development of their chosen subject. They must also develop the capacity to produce, test, and evaluate, both exemplar phenomena and explanatory models. Models are equally important in the education of the majority who will need some level of 'scientific literacy' for later life (Laugksch, 2000).

These roles for models in science education are not easy to discharge, for models can attain a wide diversity of epistemological status. A *mental model* is a private and personal representation formed by an individual either alone or in a group. All students of chemistry must have a mental model, of some kind, of an 'atom', all those of physics a mental model of a 'force', all those of biology a mental model of a 'gene', all those of earth science a mental model of a 'tectonic plate'. By its very nature, a mental model is inaccessible to others. However, in order to facilitate communication, a version of that model must be placed in the public domain and can therefore be called an *expressed model*. Any social group, for example a science education class, can agree on an (apparently!) common expressed model that therefore becomes a *consensus model*. Where that social group is of scientists, working in a given subject area, and the consensus model is one in use at the cutting edge of science, it can be termed a *scientific model* e.g. the Schrödinger model of the atom, the Watson - Crick model of DNA. A superseded scientific model can be called an *historical model* e.g. the Bohr model of the atom, the Pauling model of DNA (J. K. Gilbert, Boulter, & Elmer, 2000). Historical models remain in use where they can provide the basis of explanations that are adequate for a given purpose. Historical models also find their final resting place in the science curriculum!

On major aspect of 'learning science' (Hodson, 1992) is the formation of mental models and the production of expressed models by individual students that are as close to scientific or historical models as is possible. To this end, simplified versions of scientific or historical models may be produced as *curricular models* (for example, the widely used dot-and-cross version of the Lewis-Kossel model of the atom) that are then taught. Specially developed *teaching models* are created to support the learning of particular curricular models (for example, the analogy 'the atom as the solar planetary system' used in the lower secondary / junior high school) (J. K. Gilbert, Boulter, & Rutherford, 2000). Sometimes teachers employ curricular models which can be called *hybrid models* because they merge the characteristics of several historical models, this having first been recorded in respect of chemical kinetics (Justi & Gilbert, 1999b). In respect of 'the atom', the dominant model on which school chemistry is based is the Bohr model (an historical model) whilst the dominant model in higher education is based on the Schrödinger 'probability envelope' model (the scientific model).

A further complication for science education is that any version of a model of a phenomenon in the public domain (i.e. an expressed, scientific, historical, curricular, or hybrid, model) is placed there by use of one or more of five *modes of representation*.

- The *concrete (or material) mode* is three-dimensional and made of resistant materials e.g. a plastic ball-and-stick model of an ion lattice, a plaster representation of a section through geological strata.
- The *verbal mode* can consist of a description of the entities and the relationships between them in a representation e.g. of the natures of the balls and sticks in a ball-and-stick representation. It can also consist of an exploration of the metaphors and analogies on which the model is based, e.g. 'covalent bonding involves the *sharing* of electrons' as differently represented by a stick in a ball-and-stick representation and in a space-filling representation. Both versions can be either spoken or written.
- The *symbolic mode* consists of chemical symbols and formula, chemical equations, and mathematical expressions, particularly mathematical equations e.g. the universal gas law, the reaction rate laws.
- The *visual mode* makes use of graphs, diagrams, and animations. Two-dimensional representations of chemical structures ('diagrams') are universal examples. Those pseudo three - dimensional representations produced by computers, that figure so prominently in this book, which may be termed 'virtual models', also fall into this category.
- Lastly, the *gestural mode* makes use movement by the body or its parts e.g. of ions during electrolysis by school pupils moving in counter - flows.

These canonical modes are often combined (Buckley, Boulter, & Gilbert, 1997) e.g. in a verbal presentation of the visual representation of the Krebs' cycle.

In the case of chemistry, and perhaps all the major sciences, the concrete, visual, and symbolic, modes predominate. There are many sub-modes in use within each mode. Taken overall, these modes and sub-modes can be referred to as constituting a 'spatial language' (Balaban, 1999). They occupy the region between the extremes marked by the arbitrary relationship that exists between words and ideas, on the one hand, and the isomorphism that exists between pictures and their referents, on the other (Winn, 1991).

Each of these sub-modes of representation has, to a first approximation, a 'code of interpretation'. This is a series of conventions by means of which those entities and relationships in the model that are capable of effective representation in the sub-mode are depicted. Alas, the problem becomes even more complex. For example, chemical equations, even the two parts to a chemical equation, can be represented in a wide range of ways (sub-sub-modes?) e.g. zinc + hydrochloric acid, Zn + HCl, $Zn_{(s)} + H^{+}_{(aq)} + Cl^{-}_{(aq)}$. Learning these 'codes of representation' is a major task for students: moving between modes is intellectually demanding. Worse still, where the codes are intermingled, as is sometimes the case in textbooks, e.g. $Zn + H^{+}_{(aq)}$, confusion can reign.

The intellectual demand of moving between modes and sub-modes of representation is high, particularly for chemistry, where a full understanding of a chemical phenomenon involves the ability to move fluently between the, confusingly termed, three *levels* of representation of it (Johnstone, 1993; Gabel, 1999; Treagust & Chittleborough, 2001). These are:

- the macroscopic level. This is met directly during observational experience in the laboratory and everyday life, for example colour change or precipitate formation in a chemical reaction, or in pictures of such situations;
- the sub-microscopic level. This is met during the representation of the inferred nature of chemical entities (as atoms, ions, or molecules) and the relationships between them, for example those involved in a chemical reaction. These representations are expressed in the concrete, visual, or verbal, modes;
- the symbolic level. This is the representation of the identities of entities (atoms, ions, or molecules), for example those involved in a chemical reaction (producing a 'chemical equation') or of the quantitative relationships between them (producing a 'mathematical equation', for example in calculating equilibrium constants).

Transitions between these levels of representation are found difficult by students to make, as is born out by research. Undergraduate chemists have been found able to identify both the macroscopic manifestations of chemical phenomena and to produce symbolic level representations for what they interpreted as happening in those phenomena, whilst having a poor understanding of them at the sub-microscopic level (Hinton & Nakhleh, 1999). In short, they were not able to move into and between the modes of representation with the fluency that is expected of them. Expert chemists, by definition, do achieve this fluency (Kosma, 2003; Kosma, Chin, Russell, & Marx, 2000; Kosma & Russell, 1997).

All expert scientists - chemists, physicists, biologists, earth scientists - must be readily able to visualize a model when it is met in any one of the modes, or sub-modes, of representation and at any level of representation. As one might expect, there is a correlation between the level of what might be termed the 'visuospatial skill' that a person displays and the capacity to solve problems requiring an overt component of visualization. What is, however, very unexpected is that there is also a correlation with success in respect of problems - at least in chemistry - that *do not* require visualization (Bodner & McMillen, 1986). In an excellent review of the overall field of visualization in the learning of chemistry, Wu and Shah put forward a range of explanations for the latter. The most likely explanation is that 'non-spatial requirement' problems are more effectively addressed by the insertion of the skill of visualization, especially where diagrams are physically drawn to help the student in the process of finding a solution (Wu & Shah, 2004). There is a steadily growing body of research that suggests that student achievement in science is generally supported by direct access to multi-media modes of representation e.g.(Ardac & Akaygun, 2004).

## METACOGNITION IN VISUALIZATION

The processes of visualization are, as we have seen, widely used throughout science and science education. Their attainment and fluent use must, I suggest, entail 'metacognition': the ability to 'think about ones thinking' (P. S. Adey & Shayer, 1994). In formal terms

> 'Metacognition is probably best conceptualised as a set of interrelated constructs pertaining to cognition about cognition' (Hertzog & Dixon, 1994)

whilst, in more accessible terms:

> 'A metacognitive learner is one who understands the tasks of monitoring, integrating, and extending, their own learning' (Gunstone, 1994)

Why should metacognition in respect of visualization exist? First, because the existence of modern technology has provided so many important images that they cannot easily be learnt separately by an individual. Yet most people are able to navigate through these shoals. Second, because, from that range of images, there is no way for a person to know which one(s) will be of importance in the future (after (Kluwe, 1987)). We cannot safely learn to interpret just a few such types of image. In view of the opinion of Favell that many aspects of cognition may attain 'meta-' status (Flavell, 1987), I suggest that 'metacognition in respect of visualization' be referred to as 'metavisualization'.

What evidence is there that metavisualization can exist? There are three sources of evidence. First, a general 'spatial intelligence' does seem to exist i.e. one that applies across all fields of knowledge. If it is of universal applicability, then a fluency of competence – of metacognition - must be capable of acquisition. Second, a general model of memory exists that is capable of application to visualization and which represents the development of metacognitive competence. Third, there is evidence that visualization is central in the processes of thinking, in which memory is inevitably employed, and which must therefore be acquired by all. Taking these in turn:

### *General spatial intelligence*

Gardner (1983) suggests that the mind consists of a series of distinctive 'intelligences'. The indicators for the existence of a given intelligence are that:

- it resides in a mental faculty, located in a specific area of the brain, that can be damaged and even destroyed;
- it has traceable evolutionary antecedents. It should be possible to infer how the intelligence has come about, to deduce the consequences of that process, and to gain evidence of its consequences over time;
- a particular set of operations are employed to process input and to encode that which is learnt. A given class of stimulae are treated in an identifiable and distinctive way;
- there is an identifiable developmental trajectory for individuals in respect of the intelligence. It should therefore be possible to say

where a person is in the development of the intelligence by their identifying current performance;

- specific tests can be developed to identify how and to what extent it operates;

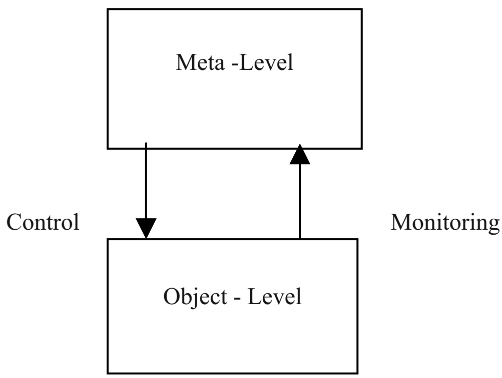
Applying these criteria, Gardner concludes that there is a specific 'spatial intelligence' such that:

> 'Central to spatial intelligence are the capabilities to perceive the visual world accurately, to perform transformations and modifications upon one's visual experience, even in the absence of physical stimulation' (Gardner, 1983) (p.173)

The majority opinion amongst psychologists is that the capacity to visualize is derived from the right-hemisphere of the brain e.g. (McGee, 1979) although some believe that the left-hemisphere is involved in some operations (S. M. Kosslyn, 1987). There is evidence of the evolution of sight and of the capacity for visual imagery (Morris, 1998) (p. 8). The issues of a developmental trajectory and of the use of specific tests to identify it are dealt with later in this chapter. How it operates is the second piece of evidence.

*General model of memory*

A model for the operation of memory and hence for the performance of metacognition (Nelson & Narens, 1994) can be represented as:




Visual perception monitors events taking place at the object – level, providing information that causes a model of the perceived object to be initially attained, and then either retained or amended, at the meta-level in the brain. Control, exerted by the meta-level, causes either the unchanged retention of, or changes in, what is perceived at the object-level. Monitoring and control are assumed to act simultaneously.

The Nelson & Narens model of the operation of memory – here we are concerned with the retention of an image – has three stages: acquisition, retention, and retrieval. In the development of metavisualization – what might helpfully be called the development of 'metavisual capability' – the learner becomes increasingly aware of *monitoring* what image is being learnt, of how to retain that image, and how to retrieve it. I suggest that a fourth stage might be added to this model:

*amendment*, the production of a version of the stored image that is retrieved for a specific purpose: a visual image. In acquiring metavisual capability, the learner:

- in respect of the acquisition stage, becomes increasingly able to make 'ease -of -learning judgements i.e. to be able to state what has been learnt and to predict the difficulty of and likely success in future learning. It becomes progressively easier to say, with certainty, what images are known and how difficult it will be to successfully acquire other specified images;
- in respect of the retention stage, becomes increasingly consciously able to mentally rehearse the acquired memory. It becomes progressively easier to retain specific images in memory;
- in respect of the retrieval stage, becomes increasingly convinced both that what has been learnt will be remembered in the future and that knowledge is held accurately. It becomes increasingly easy to retrieve accurate images;
- in respect of the proposed amendment stage, becomes increasingly able to consciously amend retrieved information for particular purposes. It becomes progressively easier to make changes to a retrieved image in order to meet any specific demands made of it and so produce a visual image.

*Visualization and thinking*

The third piece of evidence is based on the four categories of relationship that visualization has to thinking (Peterson, 1994). Thus:

- Reasoning. One form of reasoning involves the generation of new images by recombining elements of existing images. This is the basis of visual analogy. For example, the perception of waves on water led historically first to the development of the wave model of light and later to the wave model of sound.
- Learning a physical skill. In learning a skill, a person first produces a visual perception that defines the nature of the physical movement entailed in the exercise of the skill. This is done by observing an expert demonstrating the skill. This model is used by the learner to guide the personal development of the physical movement until, when perfected (an ideal situation!), the original visual perception is matched by the visual image that has evolved. For example, this is done in learning to use a pipette, to dissect a carcass, to tune a radio circuit.
- Comprehending verbal descriptions. Visual memory is distinct from linguistic memory (Haber, 1970). However, visualizations can be generated from a series of propositional statements, a process that, for many, makes an understanding of the relationships between the latter easier to acquire. For example, the structure of a crystalline substance can be understood by producing a mental image after reading a description of it. As will be argued implicitly throughout

this book, the availability of virtual representations may be making this process obsolescent, for 'visual understanding' will be acquired directly.

- Creativity. This can take place either by the reinterpretation of the meaning of an existing image or by a change in the frame of reference within which an image is set (Reisberg, 1997). The literature of the history of science is replete with examples of how major scientific advances have been made in these ways e.g. by Faraday, Maxwell, Tesla, Feynman, and, as has already been said, Kekule (Shepard, 1988).

## THE CONSEQUENCES FOR LEARNING OF NOT HAVING A METAVISUAL CAPABILITY

If visualization is an important aspect of learning – especially in the sciences, where the world-as-perceived is the main focus of interest – then not possessing, having failed to develop, metavisual competence will have serious consequences.

Although many of the studies into the consequences of poor metavisual skills have taken place with secondary (high) school students, it does seem likely that similar problems will be faced by some university students. Wu identify several classes of problems in the field of chemistry (Wu & Shah, 2004), of which the most significant are:

- that whilst chemical phenomena can be represented at the macroscopic level, students find it difficult to do so for the same phenomena at the sub-micro and symbolic levels (Ben-Zvi, Eylon, & Silberstein, 1988);
- that students find difficulty in understanding the concepts represented in a given sub-mode at the sub-micro and symbolic levels (Kosma & Russell, 1997). In particular, they find difficulty with the interpretation at the sub-micro level of a reaction represented at the symbolic level (Krajcik, 1991);
- moving between the modes and sub-modes of representation a given molecule, what Siegel delightfully refers to as 'transmediation' (Siegel, 1995), is found problematic (Keig & Rubba, 1993).

Thus developing the skills of visualization is important if progress is to be made in learning science.

## DEVELOPING METAVISUALIZATION CAPABILITY

A person with metavisual capability in the area of science will have a range of knowledge and skills in respect of the specific conventions associated with the modes and sub-modes of representation used there, together with more general skills of visualization *per se*.

These 'codes of representation' can best be discussed with use of the idea of semiotics – the study of signs and their meaning (Buchler, 1940). A consensus model has an identified relationship to that which it represents (the referent) such that there is societal agreement on the meaning that it conveys (the 'mental model 1' is evoked)

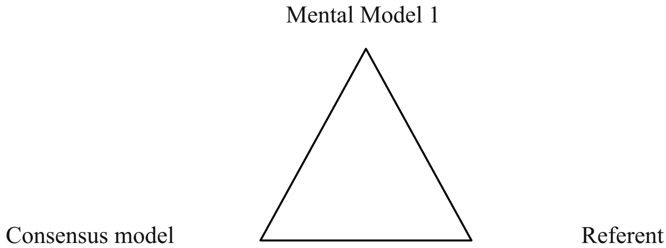
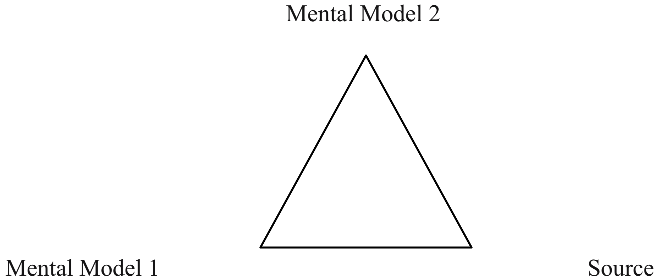



*Figure 1: The semiotic triangle for a model*

As we have seen, the relationship between the referent and the model is governed by the nature of the simplifications made to the former and the purposes and assumptions embodied in the creation of the latter.

A given consensus model is represented (i.e. produced into the public arena as an expressed model) through the use of a particular mode of representation. A mode of representation is produced by the operation of analogy on a source that is a commonly experienced phenomenon. A given mode of representation is useful in that it has a clear relationship to the model that it represents (now 'mental model 1') and to the source from which it is drawn such that there is agreement on the meaning that it conveys (the 'mental model 2').




The ideal representation, given above, would include all aspects of Mental Model 1 in Mental Model 2. In reality, this is not achievable because each mode of representation has a specific scope and limitation, so that several modes of representation are usually used, each conveying specific aspects of Mental Model 1.

Representation is made more complicated by the fact that the drawing of any analogy with a source (e.g. of the referent in respect of Mental Model 1, and of Mental Model 1 in respect of Mental Model 2) is itself a complex business. Hesse (1966) argued that all analogies consist of three components. The 'positive analog' is those aspects of the source that are thought to be similar to aspects of that-which-is-to-be-represented. The 'negative analog' is those aspects of the source that are known to have no similarity to that - which - is - to - be -represented. The 'neutral analog' is those aspects of the source whose similarity status to that - which - is - to - be - represented is unknown.

Take, as a very simple example, the simplest material sub-mode of representation used to express atoms / ions at school level. It uses polystyrene balls to represent them in the commonly used 'ball-and-stick' mode (J.K.Gilbert, 1993) (p.16) (see Fig 1).

| **Feature of Polystyrene balls** | **Positive analog** | **Negative analog** | **Neutral analog** |
|---|---|---|---|
| Variable colour | * | | |
| Finite size | * | | |
| Variable size | * | | |
| Spherical shape | * | | |
| Solid surface | | | * |
| Rough surface | | | * |
| Low density | | * | |
| Homogeneous | | * | |
| Aerated texture | | * | |
| Compressible | | * | |
| Can be pierced | | * | |
| Soluble | | * | |
| Flammable | | * | |

*Figure 2: The analog status of polystyrene balls*

If a student incorrectly assumed that a negative analog (e.g 'homogeneous nature') was in fact a positive analog (i.e. that an atom/ion is of a uniform composition), then a misunderstanding, a misconception, would be generated.

The 'diagram', the most commonly used form of two-dimensional visualization, is equally demanding of students. A diagram can, in the most general terms, be described as a series of nodes connected by lines. The nodes can be of a wide range of types, from pictures, to sketches, to icons, to symbols. The connections between them can be lines or surfaces, indicating spatial, temporal, or propositional, relationships. There seem to be no generic forms of diagram, with textbooks often conflating different types (Unsworth, 2001). In the case of the 'virtual mode' of visual representation, heavily used within this book e.g. IsisDraw, RasWin,ChemDraw,Chime, each of the several trademarked systems all seem to have its own convention.

A necessary condition for students to understand a diagram i.e. be able to interpret specific aspects of a model from it, is that the convention of representation should be both stated and adhered to by the producer of the diagram, e.g. a textbook writer. This is not always done. A sufficient condition for students to understand a diagram is that they have explicitly learned these conventions. Again, this is apparently not currently done in any systematic way. Drawing an analogy to work on the learning of the 'nature of science' (Abd-El-Khalick & Lederman, 2000), I suggest that this could be done by a mixture of direct instruction and ample opportunity to use the conventions in practice.

In summary, in order to become metacognitively capable in respect of visualization, students should:

- know the conventions of representation, both for the modes and major sub-modes of representation that they are likely to encounter;
- know the scope and limitations of each mode and sub-mode i.e. what aspects of a given model each can and cannot represent;

According to Barnea (2000), there are three complementary skills associated with what I now call a metavisual capability i.e.

> '1. Spatial visualization: the ability to understand three-dimensional objects from two-dimensional representations of them (and vice versa). ;
>
> 2. Spatial orientation: the ability to imagine what a three-dimensional representation will look like from a different perspective (rotation);
>
> 3. Spatial relations: the ability to visualize the effects of the operations of reflection and inversion'

Perhaps, in the light of what has been said earlier, 'spatial visualization' might now be called 'spatial interpretation' to avoid confusion.

These three skills respectively entail:

- being able to 'translate' (transmediate) between modes or sub-modes e.g to be able to move fluently between two-dimensional and three-dimensional representations of a given model, that is, to be able to produce a material mode presentation from a virtual mode representation, and vice versa ;
- being able to mentally change the perspective from which a given three-dimensional representation is viewed;
- being able to operate on the representation itself, particularly in terms of taking mirror images of it.

The development of a full range of metacognitive skills is considered so important that there has been a strong advocacy for the reformulation of the school curriculum in general into the 'thinking curriculum' (Fisher, 1998). In the area of metavisualization, the systematic cultivation of these specific skills, within a broad envelope of 'visual literacy skills', has been suggested by Christopherson (1997). But how can this be done? One approach is by general good practice in the use of representations by teachers and in textbooks, whilst the other is by the specific cultivation of the skills involved. The 'general good practice' approach involves (Hearnshaw, 1994):

- 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. . This might even be preceded by

teaching students the ‘master images’ used in representations (Christopherson, 1997);

- 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 specific development of the skills of visualization in the subject of chemistry has been reviewed by Tuckey & Selvaratnam (1993). They identified three approaches, respectively using:

- stereodiagrams. These consist of pairs of drawings or photographs, one giving the view of a model 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, 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.

Evidence exists from of specific studies to show that each of these approaches can be successful (Tuckey & Selvaratnam, 1993). It should be noted that all the studies were completed before the widespread advent of the personal computer. This must surely have made the task easier, if only because of the 24/7 availability of any teaching material.

It does seem that skills of visualization improve with age during childhood and adolescence, with relevant experience playing a major role in that development. With the use of the 'Cognitive Acceleration in Science Education' programme, Adey et al (Adey, Robertson, & Venville, 2002) were able to develop metacognitive skills in general in UK school pupils aged 5-6 years. Studies of the relationship between gender and metavisual capability seem inconclusive: any possible initial advantages for boys can readily be nullified by providing suitable experience for all from which girls seem to benefit most (Tuckey & Selvaratnam, 1993).

Attention has recently been paid to ‘intentional conceptual change’: the bringing about of learning by an individual internally initiating thought, by then acting in a goal-directed manner, whilst exerting conscious control on both throughout. Hennessey has argued that developing a capacity to undertake intentional conceptual change is intertwined with the development of metacognitive capabilities generally (Hennessey, 2003). By extension, this work suggests that, where the learning involves 3D structures, e.g. of molecules, it will be mutually supportive of the development of metavisual capability.

## EVALUATING THE ATTAINMENT OF METAVISUALIZATION

Assessing an individual's performance on visualization tasks, the necessary first step to the evaluation of their status in respect of metavisualization, is difficult for two reasons. First, for any particular skill of visualization that is becoming metacognitive, the person concerned is undertaking a process of which there may already be an inner awareness but which is not yet evident in overt behaviour. Second, that individual may not be aware that these processes are taking place. Three general ways of obtaining insight into a person's status in respect of any metacognitive skill have been suggested (Garner & Alexander, 1989): asking them about it; having them think out loud whilst doing a task thought to involve the skill; asking them to teach another person a way of successfully tackling such a task. These approaches do assume that the person has the verbal skills necessary to explain what they are doing and that they are not too bound up in the immediacy of the task.

The task of the assessment of competence in visualization may be made easier by the suggestion that there are two 'levels' of metavisualization. At the lower level, an individual is:

> 'capable of reflecting about many features of the world in the sense of considering an comparing them in her (sic) mind, and of reflecting upon her means of coping with familiar contexts. However--she is unlikely to be capable of reflecting about herself as the intentional subject of her own actions' (Von Wright, 1992) (p.60-61) (quoted in Georghiades, 2004)

whilst at the upper level:

> ‘Reflecting about one's own knowledge or intentions involves an element which is absent from reflections about the surrounding world. Self-reflection presupposes, in the language of mental models, a 'metamodel': in order to reason about how I reason, I need to access to a model of my reasoning performance’ (Von Wright, 1992) (p.61)(quoted in Georghiades, 2004).

There are a series of general tests available for assessing competence in some of the key aspects of visualization at the lower level of metavisualization. These are in respect of three spatial ability factors (Carroll, 1993):

- ‘spatial visualization’. Defined by Carroll as tests that ‘reflect processes of apprehending, coding, and mentally manipulating spatial forms’ (Carroll, 1993), one well-known example is the ‘Purdue Visualization of Rotation’ test (Bodner & McMillen, 1986);
- ‘closure flexibility’. This is concerned with the speed with which a person identifies and retains a visual pattern in the presence of distractions. One such scheme is the ‘Find-a-Shape-Puzzle’ (Pribyl & Bodner, 1987);
- ‘spatial relations’. This is concerned with a person’s ability to judge which figure is the same as a target figure. On example of such a test is the ‘card rotation’ task (Barnea & Dori, 1999).

These tests have been used in the field of chemistry, for which additional specialised paper-and-pencil tests are also available. These are for an understanding of and capability to use:

* the conventions for representing 3D structures in 2D, the use of 'depth cues'(Tuckey & Selvaratnam, 1993)(p.101-102);
* the relationship between diagrams (2D) and material models(Tuckey & Selvaratnam, 1993)(p.104);
* the operations of rotation, reflection, and inversion (Tuckey & Selvaratnam, 1993)(p.104-108). Ferk has produced computer-based versions of tests of these skills that relate to the 'virtual' mode of representation (Ferk, 2003).

Assessment of performance at the upper level of metavisual competence could be made by interview as these tasks are being completed.

## CONCLUSION

A case has been made out for the existence of ‘metavisualization’ or ‘metavisual capability’. For this to be substantiated, there is a need for a systematic programme of research into the role that visualization plays in learning, into the scope and limitations of the various sub-modes of representation, into the ways that the learner navigates between the three levels of representation. It is only then that we can embark on an informed programme of curriculum development and teacher education to maximize the attainment of metavisual capability by all students of science.

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