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FOREWORD

The role of visual representations in the learning and teaching of science: An introduction

John K. GILBERT

Professor Emeritus, The University of Reading
Visiting Professor, King's College London
Editor-in-Chief, International Journal of Science Education

Email: john.k.gilbert@btopenworld.com

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Abstract

Representations are the entities with which all thinking is considered to take place. Hence they are central to the process of learning and consequently to that of teaching. They are therefore important in the conduct and learning of science, given the central commitment of that discipline to providing evidence-based explanations of natural phenomena, in which underlying entities and mechanisms have to be postulated and substantiated on the basis of empirical enquiry. The three generic types of representation and the modes in which they are expressed are presented against the background of an established model of their acquisition, processing and display. The two meanings of 'visualization' are discussed as is the key role played by fluency in them in the attainment of expert status in the processes of science. The nature and origins of students' problems in attaining this 'metavisual competence' are derived from a review of the literature. Good practice in the teaching of the conventions of representation is suggested. Specific research and development is needed if this key aspect of knowledge acquisition and display is to be fully recognised in the varied curricula of formal science education and in the provision of opportunities for the informal communication of science.

The essence of learning and the contribution to it of teaching

Behavioural psychology provided the dominant model of learning and hence the guidance for teaching for many years. This assumed that successful learning involved the mental acquisition of a 'copy' of the information being taught. It was a convincing model for the acquisition of skills where no extensive transfer understanding to other situations was really necessary e.g. in the routine operation of a piece of machinery. However, it proved unable to explain the very varied outcomes of conventional classroom teaching, where the context-transferable understanding of established knowledge is required but which is by no means always attained, 'misconceptions' often being acquired by students(Gilbert and Watts 1983). The suite of psychological theories described as being 'constructivist' has become increasingly influential in both formal and informal educational systems in the last few decades. It assumes that what a person already knows acts severally as a barrier to, a critical filter for, a foundation on which to build, information being received. The major variants of constructivism are the 'personal' variety, where the individual acting alone is the locus of learning (Pope and Keen 1981) and the 'social' variety, where interpersonal interactions are seen to be the locus of learning (Vygotsky 1978).

Underlying all the major theories of learning is the assumption that thinking proceeds by the brain acting on data being received as if that consisted of a stream of 'entities' –that is, as if it had object-like properties. These entities convey specific information about what is being studied by depicting ideas, objects, systems, events, processes, as what may be broadly termed 'representations'. Whilst all thinking employs representations, they are of especial importance in science, and hence in authentic science education. Here the major commitment is to making predictions about the behavior of natural phenomena, based on postulates about the entities of which they consist and on the causal mechanisms operating in them, that are borne out by empirical enquiry. This paper is about the nature of these representations, how they are utilized in the learning of science, and about the implications of this utilization for the design of the science curriculum and for teaching.

Paivio's Dual Coding Theory

These tasks of representation and their use can best be addressed against the background of a model of what happens to all stimuli, whether encountered through formal teaching or in everyday life.

In his 'Dual Coding Theory' (see Figure 1), Paivio proposes that verbal stimuli – those which come in verbal form (as speech) – and non-verbal stimuli (the rest: received through touch, sight, sound, taste) – are processed in different ways by sensory systems that are in common to them both (Paivio 1986). The items of verbal information are stored separately as what he terms 'logogens' which are capable of cross-reference to form 'associative structures'. For example, when a person is studying electricity, they encounter the words 'voltage', 'current', 'resistance', and form them (it is hoped) into a network of ideas on the common theme of 'electricity'. The items of non-verbal information received are also stored separately, here called 'imagens', which are also capable of forming associative structures. For example, a person studying human anatomy will meet a range of diagrams in textbooks with varying degrees of abstraction of the circulatory system. These can be linked together to provide an enriched understanding of that system. Most importantly, the two types of associative structures are capable of 'cross-linking' to form 'referential connections'. Thus, hearing about Mendeleef's Periodic Table and seeing it as a chart will enable the two sources of understanding to reinforce each other. When called upon to do so, an individual will either produce a verbal or a non-verbal output based on the relevant associative structures, or will produce one or both of them based on the referential structures that have been developed. As the presentation of a comprehensive account of verbal stimuli, non-verbal stimuli, their associations and referential connections would be very lengthy, this introductory paper is only concerned with those non-verbal stimuli presented in *visual* form.

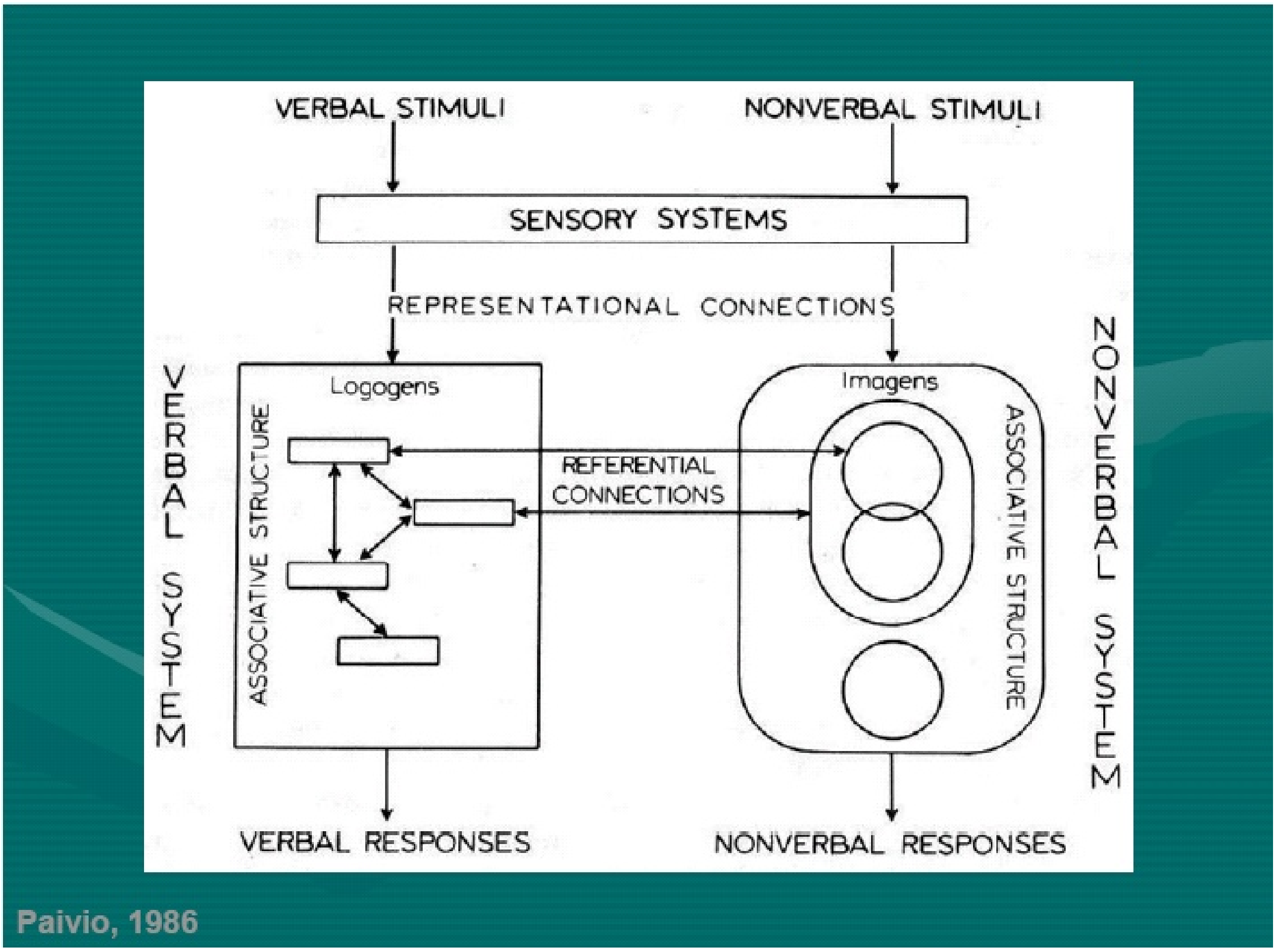

Figure 1: The Dual Coding Theory (Paivio, 1986)

The value of the Dual Coding approach is that, by providing a description of what happens during learning, it enables us to explain, to some extent causally, what happens in the brain. The activity in the brain is 'visualization' and it operates on models.

Modelling, Models, and Visualization

The world-as-experienced is too complex to understand immediately in its entirety. Science 'cuts it up' into phenomena that are considered to be important and which can be comprehended. A typical phenomenon is that of movement. Simplified forms of a particular example of movement are then created that are thought to account for its properties, what it is composed of, and how that composition explains the properties displayed. This is the process of modeling and the outcomes are models. In the case of movement, generic models were produced, for example, in historical sequence by Aristotle, Newton, and Einstein. Representations are how we depict the models that we have created so that the individual concerned can perceive what has been done and can share that with others.

Visual representations exist in two ontological forms. The first of these is as *internal representations* which are the personal mentally constructions of an individual, otherwise known as mental images. The second of these is as *external representations* which are open to inspection by others. The literature, alas, refers to both of these forms as *visualization* (Gilbert 2008). I find it less confusing to use 'external representation' for that which people share and to reserve 'visualization' for internal representation.

In all learning and especially in that of science, individuals form three types of visualizations (internal representations). Building on the ideas of Johnstone and exemplified in the subject of chemistry (Gilbert and Treagust 2009), the first of these is the *macro* type. This depicts the empirical properties of the solid, liquid (including solution), colloid, gaseous, aerosol, phenomena which are of interest to chemists and which can be investigated with the instruments currently available. Macro representations thus permit the production of *descriptive* explanations (Gilbert, Boulter et al. 2000), which include the ascription of terminology to phenomena, a verbal output, and the production of measurements of their properties, which can be presented visually.

The second of these is the *submicro* type which depicts those entities, too small to be seen with an optical microscope (i.e. atoms, ions, molecules, free-radicals) and the bonding within and between them. These enable *interpretative* and *causal* explanations to be produced. That is, of what the model (and, of course, the phenomenon) are considered to consist and the causes of the properties that are measured.

The third of these is the *symbolic* type which depicts submicro entities using letters to represent elements, signs to represent electrical charges, subscripts to indicate the number of atoms in an individual species, subscripts to indicate physical state, and their incorporation into quantitatively balanced chemical equations for the macro phenomena and for any chemical changes that take place within them. As the definition states, the symbolic type of representation enables quantitative explanations to be produced i.e. those showing the amounts of entities involved.

Definitions for the types, whether three in number or more, for biology, physics, earth science, etc, can be produced analogically to the above. The full understanding of any phenomenon that falls within the remit of a science, at any point in the historical development of a field of enquiry, involves being able to produce visualizations of such types and being able to 'move' mentally between them. As we shall see later, this is a major goal of science education and has been found to be a major hurdle for many students.

Whilst visualizations can be produced without overt reference to the external world (this is the act of extreme, or original, creativity), many arise (in the manner sketched by Paivio) from the perception of external representations. The relation between an external representation and a visualization will depend on the purpose for, the focus of, and level of attention to, the stimulus provided. Inevitably, significant differences may arise between an external representation and the resulting visualization. In a similar way, the production of an external representation from a visualization may consequently and subsequently involve changes in what an individual felt was the original. The nature of expressed ideas does seem to depend on the producer's expectations of the particular audience for the external representation and on the response being sought from that audience.

We initially tend to think of something new in terms of something with which we are more familiar. The existence of all visualization thus depends on the operation of metaphor and analogy, ideas that are often conflated.

Metaphor and analogy: the central drives of representation

A metaphor is a relation between two entities (X and Y) of the form 'an X *is* a Y', meaning that the two are identical, for example 'the sun is a furnace'. A metaphor enables entities from different realms to be brought together, so that which is familiar can be used to explain that which is less familiar. Some metaphors seem fairly self-evident (for example , the sun does *look* like a furnace) and are said to involve the *near transfer* of ideas. However, others are far less self-evident (e.g. the 'fishing net' metaphor for space-time) and are said to involve the *far transfer* of ideas (Gentner 1989). While far transfers are often more intellectually productive than near transfers, in that they result in more radical interpretations of new experiences, all metaphors are implicit comparisons that have to be 'unpacked' to reveal the scope and limitations of the insights that they provide. This is done by the means of analogy, where the relationship between X and Y takes the form 'X is *like* Y'.

In general terms, that entity about which an analogy is to be produced is known as the 'target', the entity from which the comparison is drawn is called the 'source', whilst the outcome of ideas 'mapped' from the source to the target is the resulting analogical representation. Hesse produced a useful way of depicting the scope of that mapping (Hess 1966). For her, the *positive* analogy was that which could be usefully drawn because it had an explanatory outcome, the *negative* analogy was that which was not of value because it could not explain anything, whilst the significance of the *neutral* analogy was that for which the status was not clear. The source of the metaphor, the 'distance' of its transfer, the balance of value within the ensuing analogical analysis, all detirmine the explanatory scope of particular modes of representation.

The range of media in which visualizations can possibly be expressed and in which external representations can be constructed may be called the *generic modes* of representation. These generic modes are the gestural, the concrete/material, the visual, the symbolic, the verbal (Gilbert, Boulter et al. 2000). In the course of human intellectual development, each of these modes has acquired a series of specific sub-modes or *forms* which differ from each other in often significant ways. Each of these modes, and hence forms, relates a particular model of a phenomenon to an external representation though a *code of representation* which defines the range of its features that can be successfully depicted.

The scope of the gestural mode of representation

Gesture as a mode of representation is undervalued in science, being commonly considered as of significance only in the arts e.g. ballet. However, watching any teacher at work will provide evidence that gesture, the movement of the body, especially that of the hands and arms, is extensively used in depicting all of the three types of representation (macro, sub-micro, symbolic), most usually as an augmentation to the use of the other modes and forms.

Very little research into the use of gesture in science teaching has been published so far. It may be that the specific use of gesture in science is hard to detect against the background 'noise' of complex and continuous bodily movement in busy classrooms and laboratories. But gesture does, for an individual, become more language-like with repetitive use i.e. as a personal repertoire is acquired to express particular meanings. Four usages can be culled from the general literature. First, *deixic* use, that is, pointing to real or virtual objects. For example, a teacher might augment an explanation of the nature and functions of a piece of equipment by pointing to it. Second, *metaphorical* use in which the semantic content, the meaning, of speech is conveyed. For example, the use of hand and arm movements to portray the relative position and movement of the planets in the solar system. Third, for *temporal highlighting,* by means of which emphasis is conveyed. For example, the use of hand movements to emphasise the order of events in the heart as it pumps blood around the body. Fourth, the *social interactivity* use, in which the relationships of ideas to other ideas are conveyed. For example, when displaying the historical sequence of the major paradigms in physics (the Aristotelian, Newtonian, Einsteinian) (Golden-Meadow 2006).

The scope of the concrete/material mode of representation

The major characteristic of this mode is that it retains the three dimensions of that which is being represented. A vast array of sub-modes or forms has come into existence. They can be separated into those than are derived by a simplification and highlighting of perceived aspects of the original macro representation, what Harré calls *homomorphs,* for example cross-sections of a the human body, and those having different source, what Harré calls *paramorphs*, for example the 'ball-and-stick' representation form used in chemistry (Harre 1970).

The ball-and-stick representation uses spheres (the 'balls', often polystyrene) to depict atoms and ions, and thin slithers of wood (the 'sticks') to separate them so spatial distributions can be readily perceived. The scope of this form is determined by the sum of Hessé's positive aspects: for the 'balls', their spherical shape and the availability of a range of sizes and colours with which to differentiate between entities; for the 'sticks', the angles between them and their length, to produce clear angular relationships. The negative aspects are of no representational value but, despite that, of equal importance: for the 'balls', their homogeneous nature, capacity for compression, possible solubility and flammability; for the 'sticks', their thickness. The only neutral aspect of the 'balls' is their rough surface, there are none for the 'sticks'. The sum of these aspects constitutes the code of representation for the form (Gilbert 1993).

The scope of the visual mode of representation

Given the central role of sight *per se* in the repertoire of human senses, it is inevitable that a range of forms and sub-forms have come into existence.

Picture

The sub-forms constitute a continuum from the common meaning of 'picture' i.e that which is recorded by a camera (for example, of the equipment used in a laboratory distillation experiment), through the 'simplified picture' where parts of the original are removed for the benefit of emphasis (for example of distillation equipment with the clamps etc air-brushed out), to the 'sketch', where only simplified depictions of all the core aspects remain (for example that of distillation as a general process). Cartoons may also be included in the picture genre.

All these sub-forms of 'picture' are two-dimensional analogies for three-dimensional objects, depicting not only the entities involved but also their spatial arrangement at any one moment. Animations, a variant of increasing importance in science education, enable changes over time to be represented (Milheim 1993). In summary, the codes of representation for pictures are concerned with the way that the third dimension is presented in two dimensions.

The picture sub-form is used badly in textbooks, very often treated as a decoration adding nothing to the written text, often used to echo textual statements, occasionally explaining ideas in a different way to that given in the text, and very occasionally adding something that cannot be expressed in writing (Pozzer and Roth 2003).

Diagram

The range of sub-forms of 'diagram' is extensive here, from the use of picture-like depictions of objects linked spatially or temporally or causally by arrows or lines, through to examples where the objects have been reduced to symbols and the links have become a grid. There seem to be no conventions on the use of diagrams in textbooks, so that a mixture is often used without justification for the decision that has been taken. This lack of protocol means that students are constantly inventing codes of representation before they can attempt to understand the message contained in a particular diagram. They may consequently acquire misconceptions when the personal code that they use is not that intended by the author of the representation.

Graphic sub-form

Because they enable large amounts of mathematical data to be presented in highly compact forms, there are a wide range of graphical sub-forms e.g. tables, pie charts, block graphs, line graphs, scatter plots. They all enable categorical, relational, spatial, temporal, causal , forms of visual data to be set out abstractly. The codes of representation between the sub-forms differ widely, such that they each have to be learnt separately. This task often falls to mathematics educators. In that case, alas, the transfer of such ideas into a science context is found difficult by many students (Roth, Bowen et al. 1999). Consequently, science teachers often teach the graphical forms themselves: this is effective when it does not conflict with what has been learnt by students in mathematics.

The scope of the symbolic mode of representation

Although the 'symbolic' is undoubtedly one of the major modes of representation, it is not clear whether or not symbols should be classified as visual or non-stimuli. For the sake of completeness of coverage, if for no other strong reason, they are included here and treated as if they were visual stimuli.

Mathematical representation of all forms is used widely, becoming increasingly important in science as the sophistication level of the models employed rises e.g. algebraic equations, sets, calculus. This is a separate and extensive branch of knowledge and cannot be addressed here.

However, chemistry has evolved a set of symbols that are widely used across the other sciences. The chemical elements are given symbolic labels, some self-evident e.g. 'H' for Hydrogen, some very evidently derived from Latin e.g. 'Pb' for Lead (after 'Plumbum'). Symbols are given to the particular units of quantity, for example 'mol.', and of concentration , for example '$mol.dm^{-3}$'. For students of chemistry, the most demanding system of symbolic representations is the 'chemical equation', where a number of interlocking conventions apply (Taber 2009). The challenge arises from the many sub-forms that are in use in textbooks. Students are often initially taught chemical equations in a way that is derived from speech e.g.

Sodium hydroxide + hydrochloric acid → sodium chloride + water

However, in the standard IUPAC convention, this reaction should be:

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

which represents a major intellectual leap from the spoken version. Even with the 'spectator' ions left in, this example might be given as:

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

'Molecular equations' (which must lead to misconceptions at the submicro level) are also given:

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

frequently even without the 'state' symbols:

$$NaOH + HCl \rightarrow NaCl + H_2O$$

There seems to be an 'educational consensus' that 'reversibility' symbols are omitted, except in cases where the reaction has a finite equilibrium constant. Even here, the convenient conventions of word processors have lead to a change in the reversibility symbol:

$$N_{2(g)} + 3H_{2(g)} \leftrightarrow 2NH_{3(g)}$$

The indication of precipitation adds a complication in relevant cases

$$Ag^{+}_{(aq)} + Cl^{-}_{(aq)} \rightarrow AgCl_{(s)}\downarrow$$

whilst the addition of thermodynamic information requires additional interpretation

$$CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(l)} \quad \Delta H = -890\ kJmol^{-1}$$

as does the notion of 'electrode potential' in half-cell equations

$$MnO_4^{-}{}_{(aq)} + 8H^{+}_{(aq)} + 5e^{-} \rightarrow Mn^{2+}_{(aq)} + 4H_2O \quad E_{\theta} = +1.52\ V$$

Whilst a complete IUPAC convention set represents a clear code of representation, frequent experience of partial – or even incorrect – systems must cloud students' learning.

Metavisual capability

Importance

All the ultimate explanatory entities in science are too small to be seen with the naked eye. Consequently, a full understanding of a scientific phenomenon -the possession of 'expert scientist' status in it – requires an individual to be able to mentally construct, to move between, the three types of representation: macro, submicro, symbolic. This capability has been described as *metavisualization* and as:

---- involving the ability to acquire, monitor, integrate, and extend from, representations' (Gilbert 2005)

A key issue for science education is how to support students in getting to this level of performance. The first issue is what, in detail, does 'expert performance' involve?

Criteria for the display of metavisualization

Metavisualization is shown by a number of capabilities i.e. that of being able to:

- Demonstrate understanding of all the codes of representation for all the modes of representation and their constituent forms. As has been shown above, these codes are complex and many, perhaps most, have not been coherently expressed in the literature. For example, even those of the form collectively called 'diagrams' are diverse.
- 'Translate' between the various modes for a given model. For example, the school-level model of the 'ideal gas' can be expressed in concrete/material, in diagrammatic, and in mathematical equation, modes and hence forms. A full understanding of the model requires a student to be able to readily access and to appreciate the explanatory scope of each of them.
- Construct a representation of a model for a given purpose. For example, if students wish to show the function of the arterial/venous system, then a 'circuit diagram' is the most appropriate form.
- Use a visualization to make a prediction. The only way that the scope and limitations of a given model of a phenomenon can be established is by making and testing predictions about its behavior. Such predictions are made by imaging possible properties on the basis of a representation.

- Use an existing visualization as the source of an analogy with which to represent an apparently very different phenomenon. For example, the Bohr model of the atom seems to be an analogy based on the heliocentric model of the solar system of planets.

Cognitive psychologists debate whether a full display of visualization - what I have termed *metavisual capability* (Gilbert 2005) - is innate, or the result of suitable experience, or an interaction between the two. This is a manifestation of the 'nature or nurture' debate about human capabilities (Newcombe 2005). It does seem that males are better at visualizing then females and that, although the differences can steeply decline under the impact of suitable training, they never entirely disappear (Halpern 2005). Whatever the causal mechanism behind the development of visualization at any time, there seems little doubt that students do show a range of quality of performance which does impact directly on their performance as scientists.

Students' problems: their nature and origin

Students' metavisual capabilities have been mainly investigated in the field of chemistry(Wu 2004), perhaps because it is there that visualization has the most readily obvious saliency as a determinant of attainment. Several general problems have been identified. First, the conventions of representation for the submicro and symbolic types are often not understood (Kosma 1997). This seems hardly surprising, given that all the codes are not systematically taught. Second, students find the interpretation of a phenomenon presented in the symbolic type difficult to interpret into the corresponding submicro type (Krajcik 1991). Perhaps the complexity of navigating through the intricacies of the symbolic type provides too great a cognitive load and requires too much working memory for this 'translation' to be readily achieved. Even where a particular mode can be focused on, moving between the sub-forms of representation are found problematic (Keig 1993). Lastly, when all these problems are absent, whilst representations of the macro type can be both understood and produced, linking a given macro representation to the corresponding submicro and symbolic types is found difficult (Ben-Zvi 1988).

The problems suggest that specific teaching interventions are needed if 'expert chemist' status is even to be approximately approached.

Supporting the attainment /use of metavisual capability

The task and its attainment

As a set of mental operations, metavisual capability consists of the fluent deployment of three complimentary skills, those of:

> '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 (this is 'rotation')
>
> 3. Spatial Relations: The ability to visualize the effects of the operations of reflection and inversion)' (N.Barnea 2000)

A step-wise scale which shows the progressive development and display of representational competence has been suggested for university students of chemistry (Kosma 2005). However, it is not yet clear whether such a scale has widespread applicability across different age groups or across the sciences. However, this does suggest that systematically addressing these skills in teaching should yield an improved realization of, or the development of metavisualization.

The direct teaching of the codes of representation

The conventions of symbolic representations are taught, for mathematical equations in mathematics education and for chemical equations in chemical education. However, there is no general and systematic address to the codes of the modes and forms, as well as their interpretation, in the context of science education as a whole. A start was made many years ago in chemical education (Tuckey 1993), but the development of a comprehensive corpus of teaching materials does seem well overdue.

The use of multimodal presentations

The ability to 'translate' between visual representations and to integrate them with them with verbal presentations can be enhanced by the use of *multimodal* teaching. This is the use of several relevant modes and forms when teaching a particular idea (Mayer 2005). Principles for good practice in the deployment of multimodal approaches have been proposed by Mayer (2005) on the basis of considerable experience with animations. These are the:

- Multimedia principle. It is better to use words and pictures rather than just words
- Contiguity principle. Words and pictures should be presented at the same time, rather than successively,
- Modality principle. When associated with an animation, words should be presented orally rather than in print form on the screen.
- Redundancy principle. The simultaneous verbal and visual presentation of words is to be avoided.
- Personalization principle. Words are better presented in a conversational style rather than a formal, didactic, style
- Interactivity principle. Learners should be able to control the rate at which the presentation is made
- Signaling principle. Key steps in a narrative should be verbally signaled.

These ideas augment those of Paivio (1986) (discussed earlier) in that they promote the formation of associative and referential connections. This will take place in response to either visual or non-visual stimuli as well as in response to those produced between them.

Good pedagogic practice

A number of general pedagogic techniques for the promotion of the skills of visualization have emerged in recent years, not least through the Cams Hill Science Consortium (Newberry 2010). This extended action research project has developed as series of successful teaching strategies for use with students throughout the age range of 5 to 16 years. These are to:

- Have students work in a project mode on problems that they find interesting. This has enhanced student engagement and lead to sustained learning
- Arrange classes so that students work in small teams. The value of peer teaching has become apparent
- Encourage student to evaluate their personal attainment and to set their own future learning goals. A sense of ‘ownership of education’ was widely observed
- Require students to manage their own work and hence learning

This project mode requires students to explicitly engage in modelling, the skills of which need to be taught them.

Teaching of modeling

A 'model of modelling' has been developed: a diagram which identifies all the mental activities and phases involved in conducting a project (see Figure 2) (Justi 2002). An early activity in the conduct of any project is the development of a personal mental model or visualization of the core phenomenon. This 'model of modelling' has been tried out in a school chemical education course for 15-16 year on the topic of 'ionic bonding'. It has been found to actively engage students in developing and testing their own visualization of the formation, nature , and explanatory value, of ionic bonds (Gilbert 2010).

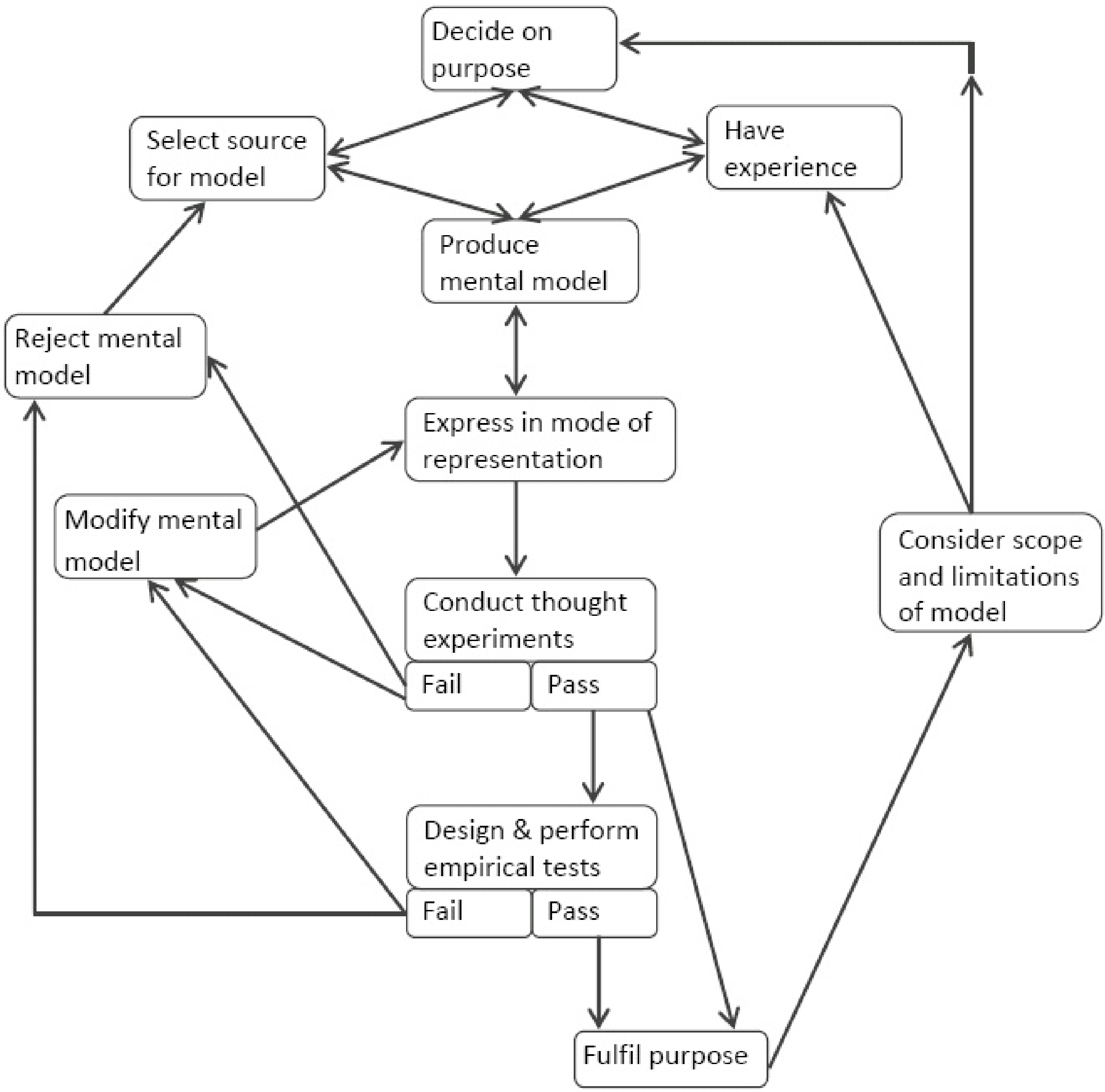

Figure 2: A model of modeling (Justi & Gilbert, 2002)

A way forward: Research and development needed

The field of research into visualization has, perhaps quite naturally, been dominated by cognitive psychologists. Their collective address to the complex issues involved has been to conduct tightly designed 'control' experiments based on the manipulation of specific 'variables' and often to use undergraduate psychology students as the subjects for these experiments. In particular, the assessment instruments that have been developed are only available under the supervision of a qualified psychologist, which fatally restricts their use in everyday classrooms.

The outcome of these circumstances has been the acquisition of 'knowledge' that is not transferable to an understanding of the messy world of the everyday learning of established knowledge by science students. As a consequence, there has been little if any development work into ways of improving the deployment or development (dependent on where one stands on the nature v. nurture issue) of metavisual capability in ordinary science classrooms. The opportunities for major research and development work in respect of established knowledge and ordinary science education are legion. Here are a few of the most pressing questions that must be addressed:

1. What are the codes of interpretation for all the major modes and forms of representation?
2. What do these codes tell us about the explanatory scope and limitations of these mode s and form?
3. how might the modes/forms best be combined in the teaching of key issues and skills in science?
4. how might students' metavisual capabilities be efficiently and effectively developed?
5. how can students' progress in displaying/developing metavisual competence be validly assessed by science teachers in the course of their work?
6. What implications do the answers to these questions have for the design and conduct of both science teaching and the conduct of science teacher education?

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References

Ben-Zvi, R., Eylon,B., Silberstein,J. (1988). "Theories, principles and laws." Education in Chemistry: 89-92.

Gentner, D. (1989). The mechanism of analogical learning. Similarity and analogical reasoning. Cambridge, Cambridge University Press: 199-241.

Gilbert, J. K. (1993). Models and Modelling in Science Education. Hatfiield,Herts, Association for Science Education

Gilbert, J. K. (2005). Visualization: A metacognitive skill in science and science education. Visualization in Science Education. Dordrecht, Springer: 3-24.

Gilbert, J. K. (2008). Visualization:An emergent field of practice and enquiry in science education. Visualization: Theory and practice in science education. Dordrecht, Springer: 3-24.

Gilbert, J. K., C. J. Boulter, et al. (2000). Positioning models in science education & in design and technology education. Developing Models in Science Education. Dordrecht, Kluwer: 193-208.

Gilbert, J. K., C. J. Boulter, et al. (2000). Explanations with models in science education. Developing Models in Science Education. Dordrecht, Kluwer: 193-208.

Gilbert, J. K., Justi,R.J., Quieroz,A.S. (2010). The use of a model of modelling during the learning of ionic bonding. Contemporary Science Education Research: Volume 3 (International Perspectives), Istanbul, European Science Education Research Association.

Gilbert, J. K. and D. F. Treagust (2009). Macro, submicro and symolic representations and the relationships between them: Key models in chemical education. Multiple Representations in Chemical Education. Dordrecht, Springer: 1-8.

Gilbert, J. K. and D. M. Watts (1983). "Concepts, misconceptions and alternative conceptions: Changing perspectives in science education." Studies in Science Education: 61-98.

Golden-Meadow, S. (2006). Non-verbal communication:The hand's role in talking and thinking. Handbook of Child Psychology (Volume 2)(6th Ed.). London, John Wiley: 336-369.

Halpern, D. F., Collaer,M.L. (2005). Sex differences in visuospatial abilities: More then meets the eye. The Cambridge Handbook of Visuospatial Thinking. Cambridge, Cambridge University Press: 170-212.

Harre, R. (1970). The Principles of Scientific Thinking. London, MacMillan.

Hesse, M. (1966). Models and Analogies in Science. London, Sheen & Ward.

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: 369-387.

Keig, P. F., Rubba,P.A. (1993). "Translations of representations of the structure of matter and its relationship to reasoning, gender,spatial reasoning,and specific priuor knowledge." Journal of Research in Science Teaching: 883-903.

Kosma, R., Russell,J. (1997). "Multimedia and understanding: expert and novice responses to different reponses of chemical phenomena." Journal of Research in Science Teaching: 949-968.

Kosma, R., Russell,J. (2005). Modelling students becoming chemists: Developing representational competence. Visualization in Science Education. Dordrecht, pringer: 121-146.

Krajcik, J. S. (1991). Developing students' understanding of chemical concepts. The Psychology of Learning Science:International perspectives on the psychological foundations of technology-related learning environments. Hillsdale,NJ, Erlbaum: 117-145.

Mayer, R. (2005). Multimedia learning: Guiding visuospatial thinking with instructional animation. The Cambridge Handbook of Visuospatial thinking. Cambridge, Cambridge University Press: 477-508.

Milheim, W. D. (1993). "How to use animation in computer assisted learning." British Journal of Educational Technology: 171-178.

N.Barnea (2000). Teaching and learning about chemistry and modelling with a computer-managed modelling system. Developing models in science education. J. K. Gilbert. Dordrecht, Kluwer: 307-324.

Newberry, M. (2010). The Thinking Frame. Cams Hill Science Consortium.

Newcombe, N. S., Learmonth,A.E. (2005). Development of spatial competence. The Cambridge Handbook of Visuospatial Thinking. Cambridge, Cambridge University Press: 213-256.

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

Pope, M. and T. Keen (1981). Personal Construct Psychology in Education. London, Academic Press.

Pozzer, L. and M. Roth (2003). "Prevalence, function and structure of photographs in high school biology textbooks." Journal of Research in Science Teaching: 1089-1114.

Roth, W.-M., G. Bowen, et al. (1999). "Differences in graph-related practices between high school biology textbooks and scientific ecology journals." Journal of Research in Science Teaching: 977-1019.

Taber, K. (2009). Learning at the symbolic level. Multiple representations in chemical education. Dordrecht, Springer: 75-108.

Tuckey, H., Selvaratnam,A. (1993). "Studies involving three-dimensional visualization skills in chemistry." Studies in Science Education: 99-121.

Vygotsky, L. S. (1978). Mind in Society:The development of higher psychological processes. Cambridge,MA, Harvard University Press.

Wu, H. K., Shah,P. (2004). "Exploring visuospatial thinking in chemistry learning." Science Education: 465-492.