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Visual and spatial modes in science learning [1][2]

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The paper surveys some major trends from research on visual and spatial thinking coming from cognitive science, developmental psychology, science literacy and science studies. It explores the role of visualisation in creativity, in building mental models and in the communication of scientific ideas, in order to place these findings in the context of science education research and practice.
Keywords: Visual thinking, transformational reasoning, science learning

Motivation for this review

Visual and spatial thinking is an integral part of doing and learning science. The models or idealisations of science are simplifications of complex, real-world phenomena, often expressed in concrete, visual or symbolic modes. Visual imagery and non-verbal, spatial models have been identified in significant discoveries, while in the communication of ideas in science we not only use pictures but also narrations of visual experiences. Visual methods continue to be formulated in pedagogy too, yet a principled and evidence-based basis for these methods is lacking. Although visual thinking is studied in the psychological laboratory and through documentation of the practice of science, this phenomenon has remained elusive for educational research generally and for science education particularly.

Aristotle believed that the faculty of imagination was linked with perception, leading to the production and recall of mental images. Versions of this idea have, barring a few decades in the early twentieth century, remained influential in mainstream philosophy and psychology (Thomas, 2003). Experiences reported by prominent scientists and technologists have been supportive of a strong visual and spatial component in their thinking (Hadamard, 1949; Ferguson, 1977). In developmental psychology, Piaget carried out systematic studies of visual-spatial thinking and of children's drawings (Piaget and Inhelder, 1948 and 1966). Yet, till relatively recently, literature in this area was limited to striking introspective reports, from the psychological laboratory and from real life, and novel pedagogical approaches based on visualisation and drawings.

In the last thirty-five years the situation changed significantly. New experimental techniques were developed in psychology and cognitive science which demonstrated that mental imagery was an

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objective, reproducible phenomenon that could be studied empirically (Shepard and Metzler, 1971; Paivio, 1995), and further, that it had an identifiable neurological basis (Kosslyn and Koenig, 1992). During the same period historians and sociologists of science started to investigate the role of pictures, diagrams and other non-linguistic representations used by scientists in recording and communicating their ideas (Shapin and Schaffer, 1985; Lynch, 1985; Gooding et al., 1989). Philosophers addressed issues raised by visual-spatial and model-based reasoning in science (Giere, 1996; Shank and Cunningham, 1996).

In developmental psychology too there was interest in children's drawings (Goodnow, 1977; Karmiloff-Smith, 1995) and in spatial reasoning abilities (Newcombe and Learmonth, 2005). These developmental studies turn out to have direct implication for learning and pedagogy in school, as they are carried out in more naturalistic contexts than are found in the psychological laboratory.

School education tends to emphasise verbal and algebraic thinking, at the expense of visual and spatial modes (Presmeg, 1986; Trumbo, 2006). Visual methods in pedagogy are formulated usually without reference to cognitive, historical or philosophical considerations. The focus of research in education has been on pictures rather than on mental imagery, and till recently very little of it has addressed topics in school science (Levie, 1987; Mathewson, 1999). Moreover the large number and variety of scientific images in the media have grown, giving rise to a concern that the required visual literacy is not being developed in the population (Trumbo, 2006). In the last decade the emergence of powerful computers, with the possibility of handling dynamic models and simulations, has provided impetus for research on visual thinking in the classroom; one expects that visualisation will become an active field in the near future (Gilbert, 2008; Mathewson, 1999; 2005).

Visual-spatial and diagrammatic reasoning in science is potentially an interesting and exciting area of research. But the literature that bears on it originates from the rather specialised and disparate areas of cognitive science, developmental psychology, science literacy and science studies. An in-depth review of these areas would be a daunting task, more so for one who is not an expert in any of these areas. Coming rather from a background of science education, I review the research selectively and in rather broad strokes, in order to identify some specific themes that seem to me to be relevant for the learning of science and for research in science education.

Outline of the review

I begin with the theme of creativity and discovery, going on to the link between imagery and memory and the role of the visual in the communication of ideas in science. I note with some surprise that all these three lines of research have highlighted one common yet unexpected idea. Research on visual thinking, although placed initially in opposition to verbal modes of thinking, has repeatedly encountered a role for language, text and, in general, analytically expressible meaning. Language-based forms of reasoning appear to form an inseparable complement to imagery and diagrammatic reasoning.

It is less surprising, from the viewpoint of science, that model-based reasoning turns out to be a combination of verbal and visual, as well as symbolic and mathematical modes. For science education then we need to find out how best semantic content can be integrated into visual representations, in order to bring about meaningful learning.

A particular strength of visual representations, both internal mental ones and external diagrams and concrete models, is that they are amenable to transformations. I review the evidence for transformational reasoning in science, linking this research with cognitive analyses of mental transformations and use of diagrams for transformational reasoning by children and adults. I identify transformational reasoning as a crucial component in the process of making meaning through visual representations.

Creativity and discovery in science

In self-reports of significant discoveries by scientists a dominant motif has been that of vivid imagery and non-verbal, often spatial models. Paradoxically Francis Galton (1880) found that while people in general society habitually reported instances of mental imagery, the scientists who he spoke with tended to deny any such experience, questioning the very notion of mental imagery. I will re-visit this anomalous observation in "transformational reasoning in science."

Jacques Hadamard (1949) questioned some well-known creative intellectuals of his time. He found that almost all of them claimed to think in vague mental images that were most frequently visual, but also sometimes kinetic and auditory. Visual-spatial conceptualisations in the radical breakthroughs of twentieth century physics were analysed by Miller (1984) and Holton (1986a, 1995). In biology Kierns (1999) documented how visual evidence was critical to the highly original research of Barbara McClintock. Technological designs and visualisations of mechanical inventions over the years were studied by Ferguson (1977).

Though these studies are carefully documented as well as inspiring and persuasive, it is difficult to confirm any general claims based on them regarding imagery, creativity and discovery. Restricting ourselves to the context of science, it is not clear whether observations made with exceptional individuals have strong implications for all scientists or for students of science. Another problem is to arrive at good definitions of creativity and discovery in given contexts, let alone ones that might hold across a range of contexts.

Roger Shepard, a pioneer in the scientific study of imagery, stepped out of the strict experimental tradition of psychology to consider several documented cases of highly creative scientists, technologists, mathematicians, writers, sculptors and others who reported using mental imagery. Shepard (1978, 1988) suggested that imagery and spatial visualisation were essential for creativity and discovery. He also conjectured some reasons to account for the apparent effectiveness of imagery over language in the creative process.

Subsequent research provided indirect support to only some of Shepard's conjectures. A necessary relationship between creativity and imagery has never been found. On the contrary most standardised tests are explicitly designed to tap both visual and verbal creativity. But mental imagery in simple situations has been shown to result in creative responses. In a series of experiments Finke and his collaborators found that subjects could successfully combine and mentally manipulate familiar shapes of letters, numerals and geometrical objects, to discover new forms previously determined by the experimenters. The majority of subjects were able to mentally synthesise such simple, familiar forms in creative ways, into meaningful patterns and entirely new objects, or "preinventive forms" (Finke, 1990).

In other experiments, an expected developmental precedence of imagery over language was supported by observations (Roskos-Ewoldsen et al., 1993; Newcombe and Learmonth, 2005). Finally, a "drive towards symmetry", which is said to have motivated many of the scientists in Shepard's accounts, found a parallel in the imagery responses of laboratory subjects: for example, symmetrical patterns used in experiments were found to cohere easily in the mind and to require less time for processing (Roskos-Ewoldsen et al., 1993).

What is perhaps not supported yet is Shepard's claim that, in creativity, imagery has some special status over language. One clear result from psychological studies is that mental "images" are not purely visual in character; rather they have both depictive and descriptive qualities (Intons-Peterson, 1993), and also abstract elements which are not easily expressible in either of these ways (de Vega et al., 1996). Language and description may either facilitate or interfere with interpretation of visual images (Intons-Peterson, 1993). Further, creativity and discovery in the psychological lab is helped, not by imagery alone, but by the ability to transform information between the verbal and imaginal. Along with mental manipulation of images, activities like doodling or drawing, seeing, hearing and gesturing, when carried out in consonance with the task at hand, enable more creative responses (Roskos-Ewoldsen et al., 1993).

These studies show that, given appropriate task situations, creative responses can be easily elicited from ordinary lay persons. Later we see how historical sources and observations of practising scientists give some insight into the phenomenon of creativity in science. How are these, the lay and expert, kinds of creativity comparable? We leave aside, for the purpose of this discussion, the very different social contexts of the scientific activities. But creative visualisations of scientists are clearly built upon a deep and extensive knowledge of their field. Further, persons who demonstrate exceptional creativity in particular domains might be marked more by their commitment to explore in depth the possibilities suggested by their creations. This is a larger and more extended task, spread over months and years, that must require much more than visual-mental manipulation over milliseconds to minutes, that is tested in the laboratory. This "ninety-nine percent perspiration" aspect of science has direct implications for pedagogy.

From mental images to mental models

The results on creativity show that apparently simple and de-contextualised mental images carry meaning that is not entirely captured by their visual and spatial properties (de Vega and Marschark, 1996; de Vega et al., 1996). The meaning inherent in images may be at least partly expressible in language and other abstract, symbolic notations. Sensory modalities besides the visual may also contribute to these models. Current theories in cognitive science support such multimodal representations of knowledge (Ramachandran and Hubbard, 2001; Barsalou et al., 2003).

What is found true for the kind of simple depictions employed in psychological research (for example, the well-studied duck-rabbit figure), should be even more valid for the much richer images in science. Images in science are not simple perceptual entities. Not just the sophisticated images of high-level science, but the images occuring in school science too, carry a great deal of conceptual, abstract and often mathematical content. Quite unlike images in art, and much less so than images in design and technology, the images in science rarely stand on their own. They need to be supported always by text and other formalisms.

There is limited literature on the understanding of images in semantically rich domains as in science. A broad conceptualisation by Holton (1986b) proposes three closely related forms of imagination in science: visual, metaphoric and thematic. Holton's ideas have found reflection in science education and curriculum theory, though their effect on practice remains to be seen (Matthewson, 1999; 2005). In the more operational terms required for empirical research, specific problem-solving situations in complex domains might call for a combination of propositional knowledge, abstract rules, manipulation of images and mathematical analysis.

In this view a mental image is more like a mental model, not quite a picture in the mind but a scheme for depicting and processing visual, spatial, temporal, causal, or other types of information. Though mental models in principle need not be bound to specific sensory modalities, yet it is conceivable that mental models of blind persons have significant auditory, tactile and kinesthetic components (Gouzman and Kozulin, 1998) while those of sighted persons may have a dominant visual one.

Visual mental models do figure prominently in cases of conceptual change across the sciences (Nersessian, 2002). Though in the creative process there may be no exclusivity to imagery, it is possible that visual and spatial modes facilitate certain operations on mental models. Reasoning with mental models could be described by the umberella term "transformational reasoning", a characterisation that may help integrate visual-spatial with verbal and other modes of reasoning. After reviewing the literature on transformational reasoning I suggest that model-based transformational reasoning is the key to studying the visual and spatial aspects of science learning.

Imagery and memory

The unexpected relationship between verbal and visual thinking found in imaginal creativity and discovery, seems quite natural when we look at the role of imagery in memory. From antiquity till today visual imagery has remained popular as a mnemonic for verbal material (Anderson, 1998). Till recently psychological research on memory dealt largely with words and text. Consideration of visual material led to a new conceptualisation of long-term memory (Paivio, 1995) and also working memory (Baddeley, 1992). Working memory, which is involved in temporary storage and processing of information, consists of two complementary subsystems dealing with visual-spatial and verbal information respectively (Baddely, 1992). The classic experiments on imagery (Shepard and Metzler, 1971; Kosslyn and Koenig, 1992) address visual aspects of working memory. Individual differences in imagery tasks are often attributed to limitations of working memory (Hegarty, 2000). Mental models are thought to be constructed through the interaction of the visual and verbal systems in working memory (Schnotz, 2002).

Long-term memory is classified into declarative and procedural memory; the former is further found to comprise of episodic and semantic memory. Visual components in long-term memory are indicated in a study by Kosslyn and Bower (1974), showing that children rely on visual imagery to remember sentences unlike adults who encode sentences more in terms of their meaning. Memory for language materials is found to be dependent on the image-evoking value of words, imagery instructions and imagery strategies (Clark and Paivio, 1991; Paivio, 1995). Consistent with the close interaction between the visual and verbal, mental images are possible to reconstruct based on descriptive information stored in long-term memory (Hyman, 1993).

The research of Paivio and others indicates that imagery may have a role in episodic as well as in semantic memory, in both of which linguistic and imaginal aspects are closely intertwined. Examples from school science too could be recalled. The colours and smells from the chemistry laboratory, a diagram of the digestive system, a schematic ray of light refracted through a cross-section of a slab of glass: these images persist in the memory of adults well past their school years. Laboratory sequences or steps in problem-solving involve remembering of procedures. Research with designers (e.g. Tversky, 2005), shows that imagery may be a component of procedural memory too. Such studies remain to be done in the context of science.

Communication of ideas

The integration between the verbal and the visual needs no justification when we come to the communication of ideas in science. Studies of the practice of science (Butterfield, 1949; Taylor and Blum, 1991; Baigrie, 1996) look at the evolution of scientific illustrations and their role in the creation of scientific knowledge. Phenomena in science are made visible through imagery and drawings. Laboratory scientists in particular make extensive use of diagrammatic devices which further play a key role in scientific argumentation (Lynch, 1985). In the sociology of science even a textual experimental report has been seen as the narration of prior visual experiences - it points to sensory experiences that lie behind the text, and it in turn constitutes a secondary visual source (Shapin and Schaffer, 1985).

Ferguson (1977) and others have attributed the growth and spread of Western technology to the invention of printing, which allowed finely detailed technical drawings to be reproduced and distributed in large numbers. Large-scale printing made illustrated books available to the general population and new discursive and representational styles evolved (Olson, 1994). In science these "literate" linguistic and depictive devices allowed for clarity in reporting of research, enabling separation of the experimental apparatus and conditions from the results, making possible the replication of experiments to produce the accepted facts of science. Ability to make copies of text and diagrams also led to standardisation of equipment which led to further accumulation of results. Thus visual formulation and communication of content contributed significantly to the process of development of science (Shapin and Shaffer, 1985; Subramaniam, 1999).

Research in developmental psychology, inspired by Vygotsky's theory of cognition mediated by the social context of the learner, has focused on the relation between visualisation and communication. Vygotsky emphasises the role of cultural, social and historical artifacts: thus visual images, graphic symbols and models, plans and maps are instrumental in mediating cognition (Vygotsky, 1978). This approach has been used to study science learning in a classroom as it can happen via communication though drawing, speech, writing and model-making (Brooks, 2002). Studies of collaborative learning in adults too have shown how visual information can be shared through drawings and gestures, leading to efficient solution of problems (Heiser et al., 2004). Collaborative learning with diagrams and other shared devices is described by Brooks in this issue. For elucidating students' models in science however, we need to focus on the reasoning process, which we do in the following sections.

Transformational reasoning in science

Mental manipulations and transformations of images are a recurrent theme in the reports of imagery by scientists. Psychological research indicates that visual-spatial images are easily susceptible to transformations: in the mind, or externally via concrete models, or on paper. Further, images can hold powerful metaphorical connotations which suggest relations and concepts extending beyond their concrete physical form (Arnheim, 1969; Tversky, 2005). Perhaps, beginning with perceptual images, it may be possible to work up to abstract theoretical concepts and frameworks. This is not to propose an empiricist view in which knowledge is derived from sense experience, but rather to emphasise the theory-ladenness of the images themselves (eg. Topper, 1996) which makes them amenable to model-based transformations.

Historical studies lend credence to this notion. Biology began with visual images recorded as drawings by herbalists, naturalists and explorers. Over time the depictions of individual specimens were transformed into idealised representations of types, ideals or species (Topper, 1996). Generalisations then drawn from these visual images were codified and elaborated in the form of taxonomy. These judgements of morphological similarity and differences must also have required an intuitive kind of transformational reasoning. Such reasoning became more explicit in the work of Georges Cuvier (1769-1832), a pioneer in comparative anatomy. Later, in 1917, D'Arcy Thompson developed a theory of transformation in which he viewed morphology, growth and evolution in terms of mathematical transformations involving the whole organism (Thompson, 1961). To take an example from geology, the study of landform structures involves transformation of observational data via imaginal structural models into parameters that could be fitted into a mathematical or computer model.

A remarkably similar transformation from observational drawings to idealised diagrams is seen in Faraday's rendering of lines of force (Gooding, 1989) leading up to Maxwell's equations of electromagnetism. For Faraday and Maxwell images were heuristic devices guiding their discoveries (Wise, 1979; Nersessian, 1995). Faraday's diagrammatic representations, deriving directly from experiment, corresponded to a concrete physical conception of lines of force. Maxwell, who built on Faraday's work, developed diagrammatic representations that were more abstract, serving to visualise the relationships between fields rather than the fields themselves. Maxwell's visualisations led more explicitly to his mathematical formulations (Nersessian, 1995). Transformational reasoning, in the sense indicated by these examples, goes well beyond mental manipulations of simple figures. It is a challenge to characterise such reasoning in reasonably clear terms and to find ways of studying it.

Contemporary physics, chemistry, physiology, molecular biology, pharmacology, geology and metereology, offer numerous examples of problems that are formulated visually and solved through visual-spatial transformations. These transformational techniques, through continuous usage, get codified into systems of symbols that can be manipulated using a set of rules. Once the problems have been formulated visually, analytical tools can take over and independently lead to further progress without reference to the original visualisations.

For instance, after Maxwell formulated his mathematical relationships his visual models became redundant (Nersessian, 1995). Today scientists routinely use Maxwell's equations without needing to recreate his visualisations. Similarly Feynmann diagrams, created by an exceptionally visual physicist, are now a standard calculation tool of quantum field theory. Stepping back to the nineteenth century, it is perhaps significant that Galton's (1880) observations, cited in the section on "creativity and discovery", were made at a time when the physical sciences appeared to have reached a culmination in their development. Classical physics had been established on firm theoretical and mathematical basis and further new discoveries seemed unlikely. This notion was soon to be overturned, and we find that in the new mathematics and physics of the early 20th Century there was a resurgence of interest in mental imagery (Hadamard, 1949; Miller, 1984).

Cognitive analyses of transformational reasoning

Piaget and Inhelder (1966) were perhaps the first to study mental visual transformations carried out by children. They proposed that early childhood imagery is "reproductive" in nature; the development from reproductive mental imagery to transformational reasoning with images becomes possible with the emergence of mental operations. This theoretical stance was however tempered by their observation that there are large individual differences in such transformational reasoning in the adult population. Piaget and Inhelder's suggestions were, to identify such typologies early and study them longitudinally, and to study people with extraordinary visual achievements, for example earth scientists, and also those with psychopathological disruptions of visual imagery as in hallucinations (Piaget and Inhelder, 1966).

Tests of spatial ability call for simple imaginal transformations like mental rotation, reflection, cutting, folding and perspective-change (Sorby, this issue). In a survey of individual differences in spatial ability Hegarty and Waller (2005) looked at factor-analytic studies of psychometric data. In a result reminescent of Piaget's classification of imagery, at least two distinct cognitive processes were found to underlie performance on tests of spatial ability: one corresponding to the construction of an image and the other to its transformation in memory. In simple tasks involving construction of a mental image, individual differences are observed only when a speed limit is placed on the task. If enough time is provided for complex tasks then individual differences are seen in the complexity of transformations that a person is capable of carrying out in memory. There is evidence that spatial ability assessed through such relatively content-free tasks is correlated with success in mechanical occupations, mathematics, physics and medical professions (references cited in Hegarty and Waller, 2005; Tversky, 2005).

A distinction between visual and spatial is seen in neuropsychological studies. Visual processing in the brain is found to involve a ventral pathway leading to the inferior temporal cortex, which processes object features, and a dorsal pathway leading to the parietal cortex, which processes information on spatial location and relationships (Kosslyn and Koenig, 1992).

The research of Shepard and of Kosslyn concerned mental rotations, mental scanning and zooming, in which mental transformations were found to be linked to perceptual processes. Studies of more complex visuospatial reasoning indicate that the order of performing the transformations may be tied to motor processes, like the act of drawing or constructing a figure (Tversky, 2005) or the order of actions involved in carrying out a physical process (Schwartz and Black, 1996; Hegarty, 2004a). Mental representations of simple mechanical systems (pulleys and gears) are thought to encode, not the visually observed motion of components of the system, but rather the causally understood chain of events. Under different conditions students use either mental imagery or abstract causal rules to solve problems related to such systems (Schwartz and Black, 1996; Hegarty, 2004a).

Shepard and Metzler's (1971) classic experiments showed that people rely on mental rotation for comparison of generic three-dimensional objects. But when structurally similar objects rich in information are used, such as molecules in stereochemistry, students are likely to apply rules involving planes of symmetry. Only when they are forced to treat the molecules as generic objects, do students resort to visualisation and mental rotation strategies (Stieff et al., 2005). Thus in moderately complex contexts, transformations on internal or external representations may require not only a perceptual and a motor basis, but also a conceptual basis.

The research described above uses drawings, which are considered as external representations that facilitate operations on internal mental representations. Ways of analysing the conceptual basis of such images, and further developing a pedagogy for them, are indicated by research specifically on drawings and diagrams, which we consider next.

Transformational reasoning through drawings

Consider first the case of children's drawings. We observe that children's early drawings have both expressive and depictive functions. The expressive aspects of their drawings are likely to have significant bearing on our understanding of visual thought as a tool for creativity and the conception of ideas. Yet these aspects have been relatively less encouraged in school; expressive drawings have been studied mostly in contexts like the psychology of art, emotional development, psychoanalysis and therapeutic use for trauma victims. The use of expressive drawings in more "cognitive" tasks remains to be explored.

By necessity then we restrict the discussion to the case of depictive drawings and ask, what is the relationship between children's external depictions and their mental representations? A common and long-standing observation from children's drawings over the years has been an apparent transition, from a schematic stage, when children draw "what they know", to a stage of visual realism, when they start drawing "what they see" (Wales, 1990; Carvalho et al., 2004). In reality, a host of other factors affect children's depictions, from physical constraints to cultural symbolism to individual styles to value judgements (Wales, 1990, Goodnow, 1990). As for diagrams in science, which carry significant conceptual content, it seems that another transition might be needed, from "what one sees" to "what one knows (or has learnt)". We mentioned parallels in the history of science with instances of exact depictions giving way to idealised, theory-laden ones (Gooding, 1989; Topper, 1996). Such studies are yet to be done in science learning. Another conclusion from the developmental studies is that external depictions are not related in a staightforward way to internal mental representations. We will return to this point.

A fruitful line of research in developmental psychology has adopted, not a "declarative", but a "procedural" view of drawings. A child's first drawing is regarded, not as a simple "printout" of a perceptual input but as a conceptual schemata constructed through activity, reflection and the influence of culture (Olson, 1970). Thus the drawing does not so much indicate what the child sees or even knows. Rather it shows how (s)he goes about solving a problem and developing a set of conventions, strategies and organising principles that work for the task (Freeman, 1975; Goodnow, 1977). Drawing skills are represented, at a procedural level, as a sequence of steps (Goodnow, 1977; Karmiloff-Smith, 1995). Though significant changes in these procedures may be initiated through encounter with novel problem situations, developmental change is believed to be a largely internal, endogenously driven process (Karmiloff-Smith, 1995).

From the perspective of science learning one is interested in changes that occur due to exposure to new concepts and materials. Research on scientific diagrams too, like the developmental research cited above, supports a procedural view of drawing. Diagrams aid thinking and problem-solving by exploiting certain capabilities of the visual system: like detecting spatial and geometrical relations, efficiently encoding such information and going beyond it to form generalisations (Larkin and Simon, 1987; Pylyshyn, 2003). We thus begin to see how diagrams support transformational reasoning.

Diagrams facilitate mental operations by using space to convey abstract concepts, in that process placing conceptually related information in spatial contiguity (Tversky, 2001). Apart from their external referential meaning which may have to do with a complex reality, diagrams have their own internal meaning. Reasoning with diagrams tends to be focused on the inscription, i.e. the internal meaning, rather than on the external referential meaning (Döerfler, 2004). The rules for transformation that might have applied in the complex situation thus get traded for simpler rules that apply to the diagram. Efficient and successful diagrammatic reasoning needs extensive experience with manipulating diagrams (Döerfler, 2004).

How experts use transformations

In the use of diagrams in complex knowledge domains there are clear differences between novices and experts. Experts' internal representations encode a fair amount of subject knowledge, while novices may encode mostly surface features of external representations (Hegarty, 2004b; Trumbo, 2006). Studies of practising scientists using external visualisations (Trafton et al., 2005; Trickett and Trafton, 2006) show that spatial transformations are the key to connecting external with internal representations. In analysing photographic and diagrammatic data as well as in interpretation of graphical displays, the scientists (astronomers, physicists and metereologists) in these studies frequently compared several (external) images on the computer screen with each other, and also with their own internal representations, mentally transforming them so as to bring about a match between the internal and external representations.

In another instance of transformational reasoning, experts did well in using diagrams to restructure a problem situation. In a study of figure combination and restructuring it was found that while mental imagery facilitates combination of given objects, radical restructuring happens only with the help of a sketch. Experts in design and engineering are particularly good at solving problems in this way (Verstijnen et al., 1998; Subramaniam and Padalkar, this issue).

The transformational reasoning afforded by diagrams results in a facilitation of the imaged mental process. The most compelling arguments to support this "external-internal facilitation" view come from use of drawings in design (Tversky, 1999). In design, the conceptual content lies almost entirely in the drawings: the design is created as a drawing and is also communicated as a drawing. In science the conceptual content may reside in a combination of text, drawings or diagrams and other symbolic devices; thus more specialised rules of transformation would apply which might be characteristic of the domain.

The conceptual component of mental models may derive from a combination of their visuo-spatial, auditory, haptic and motor properties. Spatial cognition in childhood develops through an interaction between tactile, visual and motor learning (Diamond, 1991; Newcombe and Learmonth, 2005). Later in adulthood, for professions that call for fine or large motor co-ordination, like mechanical assembly, surgery, sculpture and gymnastics, the training consists largely of visual and aural inputs. These may involve observing and listening to a master teacher, or analysing diagrams. Thus in specific situations adults may continue to develop mental models with properties that are visual as well as haptic and auditory, possibly also including other modalities (Barsalou et al., 2003).

Transformational reasoning in the learning of science

The powerful concept of transformational reasoning helps integrate the visual-spatial with the semantic component of mental models. Going beyond the classic and purely visual-spatial sense of mental rotations and other manipulations of objects, we have considered transformations of complex mental representations and of their schematic and symbolic externalisations in the form of diagrams and other notations.

Transformational reasoning has perhaps been more studied in mathematics education, and more recently, in design and technology, than in science education. Central to this notion is the ability to envision, not a static state, but a dynamic process by which a new state or a continuum of states are generated (Simon, 1996). In mathematics (Simon, 1996; Douek, 1998) the objects and the operations on them can be defined with some clarity while in science this is more difficult to do. Nonetheless the heuristics of operations in science may bear similarities with that in mathematics and engineering. Douek (1998) for example points out a close relationship between metaphors and transformational reasoning, considering metaphors as particular outcomes of transformational reasoning. This kind of reasoning is more intuitive than inductive or deductive, appearing to involve a series of leaps into the unknown. Some authors consider it to be a case of abduction (Douek, 1998; Shank and Cunningham, 1996; Magnani, 2001).

A classic sequence in inquiry-based science first introduces a natural phenomenon and then goes through a cycle of observation, description, prediction and explanation. Transformational reasoning is essential to this cycle. For example, problem-solving in optics requires conversion of real or imagined situations into schematic diagrams. In study of 13-14 year old students' conceptions in optics, Ramadas and Driver (1989) found that diagrams as opposed to verbal descriptions enabled students to work within an abstracted context consisting of light sources, rays and geometrical projections. This conversion into diagrams allowed for the introduction of conceptual elements into a perceptual description of the situations.

The data in this study was analysed by Ramadas and Shayer (1993) in terms of the descriptive-explanatory dimension in students' responses. Scores along this dimension were dependent on the demands of the problem and also on the mode of its presentation. Presenting the problem in the form of a diagram rather than as pure text led to more responses of the explanatory type. Interestingly the opportunity to set up the situation in the laboratory did not afford additional help.

We saw that developmental change in children's drawings comes about through the invention or discovery of new procedures. In the context of science learning such development is likely to be driven by classroom experience and conceptual change. In a study of 3rd-5th graders' drawings of motion Ramadas (1990) found that younger children spontaneously used rich contextual, though non-causal, cues to depict motion. Older children tended to use more causal cues and pictorial conventions inspired by animations. The choice between contextual cues and pictorial conventions in older students seemed driven by the type of problem situation: by posing a more demanding task of depicting velocity, the choice was tilted in favour of pictorial conventions and, within these, there was a preference for abstract symbolic rather than simple photographic conventions. Here we see an interaction between age / experience and task demand, and evidence that changes in procedure could be brought about exogeneously through learning experience on the task.

In the now standard terminology of conceptual change (Posner et al., 1982) I have argued that the notion of transformational reasoning may be "intelligible" and "plausible", at an intuitive level. Is it a "fruitful" concept for science education research and practice? Mathai and Ramadas (this issue) use transformations to define visualisation of human body systems. In elementary astronomy, earth-based perceptual data need to be reconciled with the learnt model of the solar system, for which diagrams can help (Subramaniam and Padalkar, this issue). Our pedagogy for the round earth has used tools found to be effective in developing spatial reasoning: 3-d models and manipulative tasks, body gestures and schematic diagrams. In this case body gestures serve to simulate a dynamic situation and to facilitate transformation between a situation or model and a diagram (Padalkar and Ramadas, 2008).

Visual and spatial studies in science education have to map a space between the content-lean research of cognitive psychology and the rich conceptual domains traversed by historical and sociological studies of science. Inquiry learning approaches in particular are yet to solve the problem of inductive generalisations from first-hand experience. Language-based methods offer a way, but they must be supported by visual and spatial modes. We need studies of children learning science to examine the mediating role played by 3-d models, diagrams, gestures and other visual-spatial modes.

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