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Visualisation in Applied Learning Contexts: A Review

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ABSTRACT

This literature review explores visualisation within the context of learning in design, engineering and technology education. The investigation first defines visualisation, providing examples of activities that utilise visualisation skills within an applied field. Then exploration of the mental mechanisms of visualisation used to engage with those activities is placed within the context of learning in applied fields. The discussion leads to consideration of the role of visualisation in relation to learning abstract technological concepts. The paper concludes that the application of particular visualisation mechanisms is dependent on task and context. Approaches to instruction and the design of learning materials are also considered within the context of visualisation. Finally the review of literature highlights a number of research questions which relate to the individual differences and socio-cultural aspects of learning and using visualisation.

Keywords

Cognition, Visualisation ,Engineering and technology, Technological concepts, Thinking skills

Introduction

This paper explores visualisation within the context of learning in design, engineering and technology education. These fields can be defined as 'applied' learning contexts, as they apply knowledge and understanding in ways that require a physical relationship with a practical, material vehicle providing a focus for learning through doing. Visualisation has been noted as supporting creative thinking (Arnheim, 1970), visual thinking in design education (McKim, 1978) and thinking within science and technology education (Mathewson, 1999). It is suggested that visualisation provides a holistic, "synchronous" (Paivio, 1986, p. 60) approach to thinking, the benefits of which are absent from logical-mathematical and verbal thinking styles (McKim, 1978; Mathewson, 1999). Visualisation ability has been found to indicate the possible future success of students in STEM (Science, Technology, Engineering and Maths) careers (Lohman & Lakin, 2006; Webb, Lubinski & Benbow, 2007) and within the context of further education, has been described as an essential aid to learning about relationships between theory and practise (Haight, 2012). In addition, (Gardner, 1993) has revealed strong individual differences in thinking styles, with some employing largely linguistic methods (e.g., Freud) and others visual-spatial and logical-mathematical means (e.g., Einstein), suggesting that individuals adopt an affinity with certain mental mechanisms in their thinking.

An exploration of KS3 (Key Stage Three in England) students' logical-mathematical, verbal and non-verbal MidYIS (Middle Years Information System) test scores, revealed that spatial ability may be one indicator of high ability within technology education, when compared with performance on subject specific outcome measures at secondary school (Twissell, 2011). Personal experiential evidence suggests that students' ability to visualise and use image based systems of representation promotes improved subject specific thinking and learning through an improved ability to make effective inferences from those representations (Larkin & Simon, 1987). The specific mental mechanisms involved in visualisation would therefore appear to warrant further investigation as to the efficacy of learning and teaching in this mode and the potential benefits to students' learning outcomes.

This investigation first defines visualisation, providing examples of activities that utilise visualisation skills within an applied field. Then exploration of the mental mechanisms of visualisation used to engage with those activities is placed within the context of learning in applied fields. The review of literature is used to identify future research opportunities, emerging patterns, uncertainties and gaps in knowledge (Robson, 2011).

Defining visual-spatial thinking

Visual perception represents a main pathway to the world of experience. Visual information received by the eye is transferred to the occipital cortex and interpreted by the visual association area; here meaning is attached to the received visual stimulus (Martini, Nash & Bartholomew, 2012). Visualisation however is conceived in the literature as a mental process. Hoffler (2010) for example defines visualisation as “any kind of non-verbal illustration (both symbolic, such as graphs, and pictorial, such as realistic diagrams, pictures, or animations)” (p. 246). Lohman (1993) defines “the ability to generate, retain, retrieve, and transform well-structured visual images” (p. 3). Kosslyn (2005) makes a useful distinction between visual perception (viewing a stimulus) and visual mental imagery (an internal process of visualisation drawing on memory in the absence of a stimulus). Van Garderen (2006) posits “visual imagery” (object representation: shape and colour) and “spatial imagery” (spatial relationships between parts of objects, their spatial location and movement) (p. 497). Visual-spatial thinking has been linked with memory as a mechanism to combine perceiving and visualisation processes, which are thought to aid the rapid processing of information (Gegenfurtner, Lehtinen & Saljo, 2011; Mathewson, 1999; Smith, Ritzhaupt & Tjoe, 2010). Thus a distinction emerges between perceiving and processing images, and constructing images as part of a process of cognition in conjunction with memory. In this paper I refer to viewing an external stimulus as *perception* and thinking with images, their spatial relation and transformation, as *visualisation.*

Applying visualisation to design, engineering and technology

Within applied fields, visualisation can be conceived in a number of ways, dependent upon the context of the thinking task. For example producing a conceptual design for a new electronic product requires the designer to imagine the form and features of the product, often without an external visual stimulus. The designer may mentally rotate the design during the exercise, imagining its facets from different viewpoints. Preparation of the concept for manufacture may involve mentally transforming the design from one image type (three dimensional pictorial view) to another (two dimensional plans and elevations), or the designer may imagine a cross section chosen to show hidden detail. Alternatively designing may take the form of technological development and involve visual thinking associated with the application of abstract technological concepts during problem solving. Here concepts may be represented by visual analogy and metaphor, employed to aid the manipulation of, for example, electronic system concepts. Thus a number of visual mechanisms can be identified which aid the designer’s task, including: visual imagination, image rotation, image transformation, visual analogy and visual metaphor. Technology education in particular often draws upon several, if not all, of these mechanisms in the development of product designs and their realisation. In the following section each mechanism is explored in relation to its application to design and the process of learning using these modes of thinking.

Mechanisms of visual thinking

Spatial relation, rotation and transformation

Hoffler’s (2010) meta-analysis identifies two commonly explored factors: spatial visualisation and spatial relation, describing the mental rotation and object relation ability of individuals accordingly. Zacks (2008), exploring neuroimaging, supports the concept of analogue spatial representations, which describe the mental representation and rotation of objects by the brain, as if they were being physically rotated. Correlation between degree of rotation on an experimental task and amount of brain activity is reported to support the use of spatial analogues by the brain to perform these tasks (Zacks, 2008). It has been suggested that these spatial abilities represent innate cognitive processes (Shepard, 1978). However research suggests that the interpretation of visual information is dependent upon early childhood experiences which develop cognitive mechanisms to support that interpretation (Eysenck, 1996). This may include the early play experiences of the child (Vygotsky, 1978) and particularly play with physical objects (Shepard, 1978), in the above analogue representation example (Zacks, 2008).

Gardner (1984) suggests that these abilities represent a separate intelligence, within his multiple intelligence (MI) theory, which draws on experimental psychology and neurology. A range of visualisation abilities are posited which are considered to reinforce one another and work together, such as spatial relation and object rotation. Figure 1 shows a typical spatial relation task which draws on object recognition skills to compare a variety of figures with a target form.

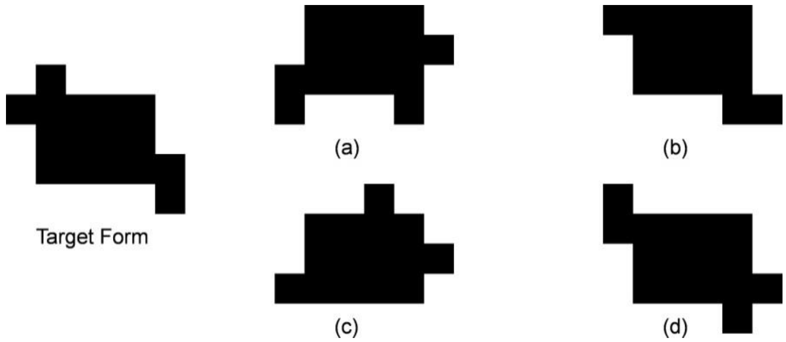


Figure 1. Example pattern matching task (after Gardner, 1984, p. 170)

Shepard and Metzler's (1971) experiment (Figure 2) develops this task, the mental rotation activity introducing the use of imagination to create the new object view when rotated through the picture plane. Participants mentally rotate the object to check whether both items match; thus in 'c' the test items do not match, a conclusion reached following the rotation of the left hand figure and comparing (spatially relating) this mental view with the figure on the right.

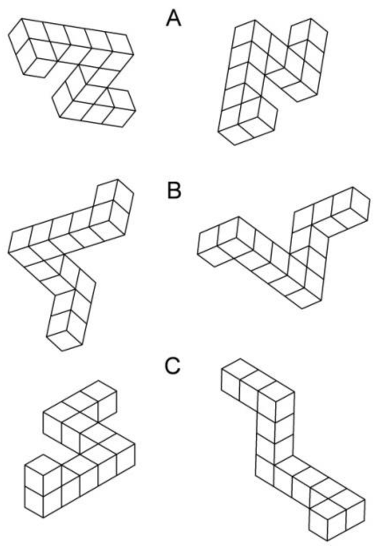


Figure 2. Mental rotation test items (after Shepard and Metzler, 1971, p. 702)

However using neuroimaging to monitor brain activity, Zacks (2008) suggests that this type of study indicates only where brain activity can be observed, rather than an indication of specifically what the brain is doing. Zacks' (2008) discussion supports the assertion that mental rotation is enhanced by corresponding manual rotation performed in the same direction, linking mental and sensori-motor facets of brain activity; and supporting the commonly held belief that seeing and doing combine to enhance individuals' learning experiences.

Within their stage theory of child development, Piaget and Inhelder (1971) believe that the ability to anticipate or imagine a new object view arises only after the child has developed an understanding of object permanence, the gradual discovery of permanence within the environment occurring during the first, sensori-motor stage of development. Piaget and Inhelder (1971) classify imagery in two ways: reproductive images representing events or objects known to the viewer and anticipatory images representing imagined events not yet experienced, but constructed by the viewer. This classification is supported by a framework describing the development of imagery within the distinct age related stages; thus as children advance through the stages, they gradually develop the ability for thought beyond the use of perception and static images (pre-operational stage) and begin to perform (around the beginning of the concrete operations stage) mental transformations and use a developing imaginal ability (anticipation). Thus mentally rotating a figure such as that shown in Figure 2 is only possible following a period of mental maturity. Criticism of this view (Bruner, 1977) however suggests that, although a number of stages can be observed, individual differences and experiences represent a more significant role than stage theorists suggest.

Memory is closely linked with experience and has been posited as an important component of visualisation (Williams, 2012). Memory has also been considered to make a significant contribution to the process of object recognition (Bruner & Postman, 1947) and the creation of new visual imagery in conjunction with stored experiences during child's play (Vygotsky, 1978). Some researchers have reported, however, that KS3 students often fixate on known imagery during the design process (Nicholl & McLellan, 2007), revealing a negative focus in this context. Others (Newcomb, 2007) have found that visualisation strategies (orthographic drawing) improve students' spatial ability and problem solving skills, beyond memory and direct observation. Sibbet (2008), a proponent of visualisation as "process," that is using universal patterns of visual representation in conjunction with experience, describes intelligence as the ability to use memory to draw on these patterns during visualisation and make "inferences" toward an "appropriate action" (p. 124) on the basis of these constructed patterns. Thus mentally rotating an object may facilitate several sequential thought processes, beginning with object recognition, the creation of a mental analogue and its commitment to memory, rotation of the analogue and finally anticipation of the new, unseen object image.

Transformation

Kosslyn's (2005) neuroimaging studies have shown that brain activity responsible for perceiving is also largely responsible for visualisation. Kosslyn's (2005) theory locates visualisation within a connected "visual buffer" (p. 336) which uses multiple areas of the brain to process information related to visual thinking. However as Kosslyn (2005) concedes, it is not clear from results precisely when and how mental images are used to aid cognition. In a related study (Thompson et al., 2009), progress toward this anomaly suggests that two forms of visual mental activity can be identified, on the basis of neuroimaging experiments, including spatial relation processing and spatial transformation processing each undertaken by different parts of the brain. This, it is suggested, has important implications for specific skills training in particular domains, such as "navigating an environment" and "learning surgical techniques," which draw on these two abilities to varying extents (Thompson et al., 2009, p. 1252). In general, researchers agree that "like-modality perception" (i.e., visual, auditory, motor) is strongly connected with visual mental imagery, which in turn is used in conjunction with the body's motor and affective systems (Kosslyn, Ganis & Thompson, 2001, p. 641).

In applied fields spatial relationship and spatial transformation abilities are commonly used in the preparation of manufacturing drawings. This often necessitates the transformation of visual information from one mode of representation such as a three dimensional (3D) external view, to an alternative two dimensional (2D) view of one side of the object, or a cross section showing part of the object as if it were "cut" away. Thus transformation requires an additional ability, beyond object rotation, which draws on imagination to "see" or anticipate the object from a different viewpoint and represent it in a different way. Figure 3 illustrates such a task as a test item, which requires the learner to visualise the cutting plane intersection (right hand image) to allow hidden or otherwise awkward to reveal details to be shown (within the left hand 'Pointed Bracket' model).

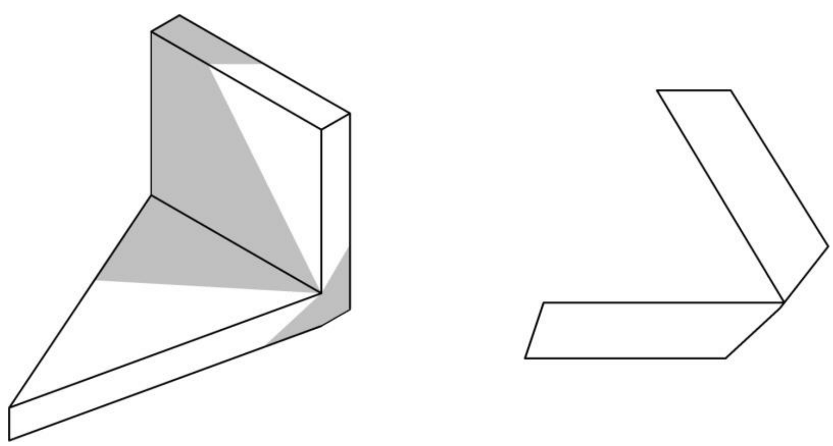


Figure 3. Example spatial relation/transformation exercise ("Pointed Bracket" after Hsi et al., 1997, p. 155)

Piaget and Inhelder's (1971) stage theory would suggest that a series of developmental steps be completed before a learner is able to successfully perform the task in Figure 3. Transformation ability widens the range of representational forms used by the learner, beyond those associated with object recognition and rotation. The sequential relationship between 2D and 3D representations has been explored by Akasah and Alias (2010), within an engineering student skill-development context. Instruction beginning with 3D forms, rather than 2D, was found to accelerate students' visualisation skills due to the existence of a more recognisable referent during mental transformations (Akasah & Alias, 2010). The 3D to 2D visual sequence model has also been found to support students' conceptual learning in physics and mathematics (Basson, 2002). However this approach, the "whole-to-parts" (3D to 2D) rather than "parts-to-whole" (2D to 3D) approach might be predicted to yield accelerated learning, due to its reduced demand on visualisation skills (specifically visual rotation and transformation).

So far visualisation has been conceived as a number of mechanisms which may be an innate part of human physiology, a separate "intelligence," but which have also been shown to involve an element of learning and development (Piaget & Inhelder, 1971). Clearly well-formed visualisation abilities, such as those required for the tasks in Figures 1 and 2, support the designer producing a new product concept. However Gardner (2003) has suggested that the concept of individual intelligences needs revising, on the basis of new genetic and neuroscientific research, which indicates a conception based on wider cognitive interconnectivity. The next section considers the role of verbal reasoning in connection with visualisation as a multi-modal form of cognition.

Verbal and non-verbal processing - dual coding theory

Blakemore and Frith's (2005) overview of neuroimaging and brain functioning, focuses on the connection between visualisation and verbal learning, particularly in support of learning the meaning of concrete and abstract words. Drawing on research using brain injured patients, Blakemore and Frith (2005) support the notion that imagery and language areas of the brain usually conspire, in conjunction with memory, to aid object and image based recognition. Thus neuroscience is suggesting that recognition and recall of concrete words makes use of visualisation, in support of dual coding theory (DCT) (Paivio, 1978). Conversely abstract words draw on alternative language based regions of the brain, which may also include auditory processing (Blakemore and Frith, 2005).

However Arnheim (1970), an opponent of this view, believes visualisation occupies a more prominent role within cognition, which has as its basis perception leading to thought processes grounded in imagery. Arnheim (1970) makes a powerful claim for visual thinking, believing that without it "productive thinking is impossible in any field of endeavour" (p. 3). Verbal language is viewed as a "one dimensional sequence" (Arnheim, 1970, p. 232), not capable of the type of manipulation needed to deal with complex reasoning and problem solving; its origin considered to follow closely perceptual experience. Nevertheless language (both auditory and sign codes) is acknowledged as providing a number of useful functions, including: categorical naming, differing levels of abstractness, thought organisation and the ability to attach a communicable code to an object or event (Arnheim, 1970).

DCT (Paivio, 1978) on the other hand posits a strong psychological relationship between verbal and nonverbal processes, which are considered to be separate, but associated functions of thinking which aid memory in encoding information in different ways. DCT conceptualises the representation and processing of information in two ways (Paivio, 1978; Paivio, 1986; Clark & Paivio, 1991). Firstly words (sequentially processed arbitrary symbols) and images (synchronously processed visual imagery) are represented as codes which form associative networks; that is, they associate through the referential process of naming images and representing words with images (Clark & Paivio, 1991). Secondly associative connections make links within the coding representations, such as connecting words with other associated words (or events or emotions) and images with other visual imagery related to the image, object, sound, smell or previous experience.

Two key features of DCT emerge. First, and importantly for the student/designer who may be working with physical models, is the acknowledgement of wide ranging sensory input (visual, auditory, tactile and kinaesthetic) and the role of emotion during the thinking process. Clark and Paivio (1991) describe a process of arousal which affects the prominence of any representation and its subsequent associative potential. This also includes the influence of past experience, representing a constructivist perspective for the theory which indicates that individual experiences can affect the processing and storage of the same sensory input among individuals who may recall these experiences in different ways. An example may include different individuals learning or performing a task in different environments, who may consequently attach different emotions to the task and its recall. Second is the facility for imagery to represent multi object perspectives, which can aid memory and their potential for "dynamic spatial transformations," providing the facility for imaginary thinking not possible with words alone (Clark & Paivio, 1991, p. 152). This personalised approach to thinking and the application of images and words is illustrated by Piaget and Inhelder (1971) with their number sequence representations and Hoffler's (2010) counting strategy example.

However Randhawa (1978) questions the efficacy of DCT to adequately explain specifically how verbal or nonverbal systems relate to cognition. Shepard (1978) questions verbal means of cognition as an adequate mode of representation for, or thought about, complex ideas during the learning process suggesting that it maintains "established ideas and entrenched traditions" (p. 156). In addition Steiner (1974), using multiple ordering tasks, found that training using an "ikonic" (p. 892) medium (wooden blocks of varying sizes and colour), as opposed to a symbolic medium (words representing the blocks: "grey," "tiny" (Steiner, 1974, p. 897)), significantly improved performance, possibly due to the clarity of the visual material which avoided the need for interpretation through reading and verbalisation. Nevertheless a recent study by Griffin and Robinson (2005), claims support for DCT, on the basis of an exploration into "visuality" and "spatiality" (p. 24). Their study found that icons (visual representations) were more effective at encouraging recall of textual features, when compared with recall based upon spatial positioning (spatiality). Consequently Griffin and Robinson (2005) conclude that text recall makes most effective use of visually iconic (mimetic) information, rather than spatially related information and thus support the concept of DCT, within the context of Geography education.

Symbols, codes and multimodal thinking

The use of recognisable referents in the form of symbol systems has been suggested as important to spatial ability; for example allowing the child who, able to negotiate the environment using well-formed spatial skills during school age years, finds it very difficult to apply symbol systems to recreate or communicate that environment (Gardner, 1984; Vygotsky, 1978). This indicates a link between learning and the development of linguistic and symbolised modes of thinking in relation to the use of spatial skills; thus support for multimodal thinking. Relatedly Piaget and Inhelder (1971) propose a "system of imaginal symbols" (p. 381); for thought to occur, be internally processed and communicated, personal images (imaginal symbols) are created to represent the child's words. These symbols are then used as referents to replace verbal means when memorising, evoking and thinking about a perception or event. In applied learning contexts recognisable referents often take the form of symbols and codes in addition to those used verbally. For example learning about technological concepts, such as the electronics example in Figure 4, involves understanding meaning represented by electronic component symbols, which are in turn used to aid spatial understanding about current flow.

Hoffman (2012) describes learning generally as "the development of cognitive systems [which] depend on signs and representations as mediators" (p. 185) and which in turn are facilitators of communicable knowledge, personal to the individual. Signs and representations have been considered to evolve, from signals to symbols, and through socio-cultural complexity, to complex grammar and language (Sinha, 2004). Therefore visual thinking within this view is closely associated with the socio-cultural practises of communication structures and the construction of personal knowledge, concurring with Piaget and Inhelder (1971). Bruner's (1977) conception of learning specifically links the use of media symbols (ikonic and symbolic) with cognitive processing as a means to construct and facilitate new knowledge. Hoffman's (2012) discussion makes a persuasive case for the tactile engagement with "concrete objects and representations" (p. 193) in the development of cognitive ability, within a mathematics learning context, reinforcing the use of concrete symbols to aid cognition. Thus this perspective closely interlinks perception, visual thinking using symbols and learning through the manipulation of the symbols (Bruner, 1977), imagery and connected verbal representations. Continuing the example in Figure 4, this equates to recognition of the symbols, the use of the symbols to mediate the behaviour of the electronic circuit and the use of spatial ability to visualise the relationship between the system's input, process and output.

Developing a technological understanding, particularly in electronics, often necessitates an understanding about mathematics, which uses its own taxonomy of codes and symbols accompanying their verbal counterparts. Developing mathematical competency begins with the child's understanding of object permanence, evolving into the use of complex symbols to enable reasoning with abstract concepts (Eysenck, 1996; Gardner, 1984). Research in this field has considered object recognition, perceptual organisation and structural representation, identifying student difficulties with movement between these phases and beyond object recognition, when problem solving (Gal & Linchevski, 2010). Assel et al. (2003) found that children's early experience with visual-spatial problem solving through play enhances later mathematical ability. Bobis (2008) describes the use of "subitising," (p. 6) that is the recognition of spatial structure (features and relationships) utilising visual means to calculate the number of items within an object arrangement, thereby reducing the need for a mental calculation. Here verbal codes are also suggested as supporting the child's construction of "pattern-name associations" (*ibid*) which increase the speed of cognitive processing. Thus this line of reasoning would suggest that visualisation is a means to link quantity with instruction directing its manipulation, within a system of symbolic representations.

van Garderen's (2006) and Edens and Potter's (2008) studies make a distinction between pictorial and schematic imagery within mathematics education. The studies found that high mathematical achievers held a preference for using schematic imagery (spatial relationships encoded within the imagery), while low ability achievers preferred pictorial imagery (visual appearance encoded within the imagery). Thus visualisers focused on either the appearance of the objects within the problem situation (pictorial) or the spatial relation and overall concepts within the problem (schematic). Positive correlation was identified between the use of schematic imagery and successful mathematics problem solving. Within electronics education Chen et al. (2011) exploit these alternative symbols, using both external representations (pictorial) and concept models (schematic) and conclude that combining these into one simulated visualisation enhances the learning of abstract concepts as the learner can more easily "verify and clarify the existing knowledge" (p. 269) using both familiar referents and symbolic representations.

In summary the use of codes and symbols appears to improve the speed of cognitive processing, beyond that which may be possible with words and images alone. They may be applied to allow thought about complex and abstract concepts and their communication to others. The choice of code or symbol may depend upon context and the type of knowledge being manipulated. In many cases, such diagrammatic illustrations, symbolised forms of representation are quicker to recall and explain (Larkin & Simon, 1987).

Analogy and metaphor

Abstract technological concepts, such as that shown in Figure 4, form an integral part of the work of designers in many applied fields. Thought about these concepts is enhanced with the use of visual analogy (Petrucci, 2011), which allows a visual likeness or explanation in combination with verbal means to represent the complex abstract concept; verbal means alone often not allowing adequate engagement with concepts or facilitating the correction of misunderstandings. Figure 4 represents an analogy which depicts the behaviour of an electronic capacitor using hydraulics. Interpretation requires an understanding of the symbols used, draws on both spatial relation and transformation ability, but crucially offers an explanation difficult to provide verbally.

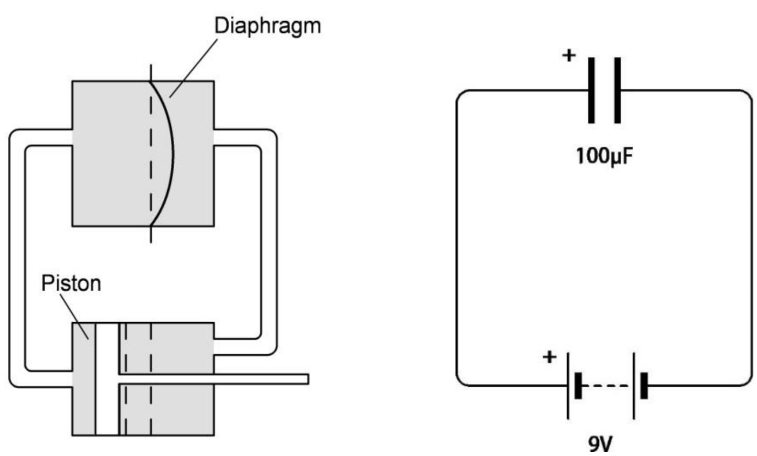


Figure 4. Example visual analogy using hydraulics (after Hughes and Smith, 1995, p. 90)

Similarly Mathewson (1999), exploring visualisation within a scientific and technical context, suggests “higher-order visual spatial thinking is inherently analogic” (p. 38) and relies on mental representations and comparisons which often arouse visual metaphors to enhance their potential. Thus in the hydraulic analogy (Figure 4) the metaphor ‘pressure’ might be used to replace ‘current flow’ to explain more successfully how an electronic capacitor charges and discharges. In another way, Figure 4, a “graphic” metaphor, allows the learner to connect with “foundation” metaphors (Sibbet, 2008, p. 122); early experiences which are used for future interpretations, in this case the early experience of the behaviour of liquids.

Geake (2008) captures the essence of the discussion around cognitive functioning in research on “fluid analogizing” (p. 187) in relation to the presentation of new visual stimuli. While recognising the role of perception in analogy generation, Geake (2008) supports the concept of fluid analogizing which describes the brain’s ability to draw upon “myriad functional modules,” (p. 191) with working memory acting as a “dynamic workspace” (*ibid*) for communication between modules, leading to divergent thinking beyond concrete solutions to problems.

Visualisation in applied learning contexts

Research within applied learning contexts has focused on the trainability of visualisation, often within engineering as a means to improve 3D spatial awareness (Potter et al., 2009). Improved interaction and personal learning of abstract engineering concepts has been reported, through ICT facilitated graphics (Nguyen & Khoo, 2010). Hsi, Linn and Bell (1997) report the use of specific problem solving strategies by students, which relate to domain specific instruments (orthographic projection, isometric views and section drawings) and parallel Mathewson’s (1999) visualisation strategies. Pulé and McCardle (2010) suggest the use of strategy can be linked with a preferred learning style (visualisation method preference) and memory, on the basis of research within the context of electronics education and the use of symbol systems. Chen et al. (2011), also exploring learning within electronics, believe a visualisation based learning model which incorporates ICT facilitated graphic manipulation and a reflective stage enhances conceptual learning and achieves a “higher level of cognition” (p. 269) on the basis of verification and clarification of existing knowledge. Conjointly these studies support the notion that visualisation skills can be acquired, honed and developed, and are not “fixed or culturally exclusive abilities, but respond to instruction and mediation” (Potter et al., 2009, p. 109).

Discussion

Researchers have highlighted the significance of perception and memory in the child’s early years of cognitive development (Piaget & Inhelder, 1971), but the existence of distinct stages has been questioned with an alternative, individualistic viewpoint proposed on the basis of environmental influences and differing methods of representation used by children to develop their thinking (Bruner, 1977). The socio-cultural context of these processes has been considered, emphasising a link between an individual’s learning and the context of the learning (Vygotsky, 2004) and the interactions made between the participants within the learning context (Fleer & Richardson, 2008). Consequently here a constructivist, socio-cultural perspective is accepted as underpinning the development of visualisation and its application to learning.

The review reveals a number of mechanisms which aid visual cognition and a number of more general learning concepts. The overlapping nature of some of the terms and concepts is particularly notable, perhaps reflecting the contextual relationship between mental mechanisms and use of terminology. The wide range of visualisation conceptions may also indicate a relationship between concept and learning context. Thus spatial relation and mental rotation ability are clearly of benefit to students of engineering, while analogy and metaphor and the use of icons and symbols, may enhance the understanding of technological concepts. Figure 5 provides an example of an abstract concept represented in three ways, taken from electronics education. Each symbol system has its own method of representation and consequently involves different modes of thinking in its understanding of an electronic logic system. Further exploration may explain how individuals construct an understanding of such a concept in this context, how imagery is used across the three symbol systems and the relative use of different modes such as verbal language, icons and symbols within each coded system of representation; the translation from one mode to another perhaps reinforcing conceptual connections through reinterpretation (Suh & Moyer-Packenham, 2007). This type of visualisation ability appears to link with individual learning and the construction of personal knowledge systems, where it has been shown that preferences include pictorial, animated or schematic representations for thinking about complex abstract concepts (van Garderen, 2006; Edens & Potter, 2008).

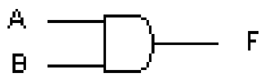
Circuit Symbol	Truth Table			Boolean Algebra
	A	**B**	**F**	
	0	0	0	F = A.B
	0	1	0	
	1	0	0	
	1	1	1	

Figure 5. AND gate represented by three symbol systems

DCT provides a model for thinking about how individuals achieve the interaction between verbal and visual means, including the utility of iconic and symbolic imagery, to aid the construction of personal knowledge, analogy and metaphor. Further exploration may develop an understanding of the relative relationship between concreteness, abstraction and imagery outlined by Clark and Paivio (1991), which may be explained with greater clarity on the basis of empirical evidence from applied field contexts.

Conclusions and further research

Two key areas have been discussed: the mechanisms of visual thinking and their application to learning in applied fields. These have emerged from a body of research which in general posits the positive role of visualisation as a means to enhance learning, problem solve, memorise and recall information, represent and communicate. These skills can be fostered (Potter et al., 2009) and the design of instruction in visualisation should aim to reinforce the mechanisms which support the process of visual thinking. Wu, Krajcik and Soloway (2001) offer a useful framework for thinking about instruction, based around three levels of representation. These include macroscopic (observable-including engagement through practical action), microscopic (atoms, particles-abstract and invisible elements) and symbolic (symbols, numbers, formulas and equations) representations providing an approach to the design of instruction which, when each level is satisfied, may contribute to increased understanding through the development of a “higher-order” visual metaphor (Mathewson, 1999, p. 38). In addition, offering opportunities for students to translate between representations has been shown to reinforce conceptual development (Suh & Moyer-Packenham, 2007). Similarly the design of instructional materials may also benefit from an approach which includes multi-modal representations, encouraging engagement with and translation between knowledge presented in different forms, particularly in light of research which suggests multiple representations are of benefit to students’ conceptual understanding (Ainsworth, 2006) and the importance of visualisation as a processing mechanism (Wu et al., 2001). This review also reveals the significance of practical application i.e., sensori-motor engagement, to learning using visualisation which has been shown to enhance visualisation processes (Kosslyn et al., 2001; Shepard, 1978; Vygotsky, 1978; Zacks, 2008).

A number of research questions emerge from the review, which may be of importance to educators in improving subject specific thinking and learning. For example how specifically do students construct their understanding of abstract technological concepts using the visual means available to them? What is the relative use of icon, symbol, code, analogy and metaphor when constructing these concepts? How do individuals construct these concepts differently?

Developing Paivio’s (1978) associative networks and associative connections concepts, four specific research questions emerge in relation to each, within applied learning contexts:

- How does image attachment vary among individuals when thinking and learning about abstract technological concepts?
- What is the nature of any connected foundation metaphor?
- What visual links do individuals make while translating between the elements of abstract technological concepts when developing their understanding of these?
- How do individuals construct their personal understanding, using additional means such as verbal and sensori-motor modes, within applied learning contexts?

A significant gap in the literature relates to the individual and social context of learning using visualisation. Drawing on Bruner (1977) and Vygotsky (1978) respectively, these two themes warrant further investigation in relation to individual differences and the influence of environmental factors on learning, including the effects of socio-cultural interactions (Fleer & Richardson, 2008). Answers to these questions may support the development of curriculum materials and approaches to learning which better support individuals during their learning of complex technological concepts.

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