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Learning to Think and Communicate with Diagrams:
14 Questions to Consider

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Abstract

This paper looks at the particular role which diagrammatic representations, and external representations more generally, play within an educational context. In particular, it considers the way in which the demands on diagrammatic representational systems in educational settings differ with respect to other settings (e.g. professional): in some instances, these demands are increased, while in others, the demands are markedly different.

The paper considers three key issues: the question of whether diagrams make certain tasks easier (and whether this is desirable from an educational point of view), the generalisation and transfer of diagrammatic skills once learnt, and the possible problems associated with simultaneously learning domain knowledge and a novel representational system.

The paper then considers a number of sub-issues, and concludes by highlighting areas of particular interest for future AI research.

Keywords: Learning, Diagrammatic Reasoning, Skill Transfer, External Representations

1 Introduction

This paper is written from the perspective of those interested in the roles that diagrams have, or could have, within the context of learning, and within the broader context of education. It is written for those who may wish to apply AI techniques to support learning to think and communicate with diagrams and who also wish to consider the complexities involved. The paper is presented in terms of fourteen questions which require attention.

Viewing "thinking with diagrams" from an educational perspective brings into consideration a number of factors outside those normally considered by persons interested in the formal properties of diagrams. These will be outlined below.

Additionally, however, much of what follows is applicable to the wider issues of "thinking with external representations". The reader can and should consider the issues raised with respect to this broader context.

This relationship is bidirectional: not only can the educational context provide insights which are more widely applicable, but many of the issues found in the literature on the use of external representations are also relevant within an educational context. Thus there is room here for the discussion of issues such as different levels of description, diagrams vs. text, diagram ontologies, linguistics, semiotics, etc.

We have highlighted what we feel are the key issues that are important within educational contexts. However, there are many issues which deserve greater consideration than we are able to give in this paper — for example, the differences between 'animated' and 'non-animated' diagrammatic representational systems[1], and the ways in which diagrams can complement textual explanations. Neither have we provided a full exploration of the ways in which external representation systems differ from diagrammatic representation systems[2].

2 The main issues

Diagrammatic reasoning in educational contexts (and in more general ones too) can be described as depending on the nature of the task, the semantic properties of the diagram, and the person's prior knowledge, including skills, preferences, experiences, etc. (see, for example, (**?**; **?**; **?**)).

A major difference between the educational and general contexts is the emphasis in the former on learning, and therefore greater importance is placed on those characteristics which are expected to promote learning.

In both contexts, an individual might typically want to solve a problem. The process of working through from an informal, ill-defined task to a solution has been described by Cox and Brna in terms of the stages of comprehension, selection of external representation system, construction of external representation, and use (including reading-off results) (**?**). However, it is worth stressing that these different processes interact in very complex ways.

In non-educational (eg. professional) contexts, it is quite common for groups of colleagues to work on a problem together using diagrams both as a vehicle for problem solving and as a means of performing a variety of communicative acts. Thus the diagram may be both an end product and a means to an end.

However, when we start to consider educational contexts in greater detail, there is a complication in this view of reasoning with diagrams (and other external representations). While all uses of diagrams can be viewed in discourse theoretic terms, diagrams play a special part in the ongoing discourse between teacher and student.

The difference in status (power etc) between teacher and students, together with the different expectations present and the ways in which learning is assessed undoubtedly have an effect on the uses to which diagrams are put. The problem here is to outline what is happening. While we will not go into the nature of this discourse in great detail, viewing diagrams as embedded in a discourse may help us understand why the *educational* use of diagrammatic reasoning differs from many other uses. A recent study by Cox and colleagues reports a controlled investigation of 'vicarious' learning outcomes for students who viewed either a) animated diagrams annotated with a previous student's discourse or b) animated diagrams annotated with student-tutor dialogue. Results indicated that both conditions were effective and support was provided for the effectiveness of discourse and dialogue-embedded diagrams as useful learning resources (**?**).

In considering the educational issues, a number of tensions can be identified. First, there is a tension between 'making things easy' and helping students to learn. This tension derives from the assumption that learning comes through doing rather than from some form of passive observation. If learning to utilise diagrams is to be effective, we can expect that practice in utilising diagrams will be important. For example, if we believe that Venn diagrams are an effective method for solving a certain class of problems, then providing a problem together with a range of possible diagrammatic solutions may make it easier for students to solve the problem but give the student no opportunity to practice diagram construction.

Secondly, there is a tension between situated diagram systems and the desire to achieve a degree of generalisation so that the skills and knowledge gleaned from learning one system can more easily be transferred to a new system[3]. This problem strikes at the heart of any attempt to provide a stand-alone curriculum for education in the use of diagrams. Formally, such a curriculum should be possible as other representational systems have their place in the educational system (grammar, algebra, geometry etc). Whether this could, or should, happen is another issue.

Thirdly, there is a difficulty that arises in terms of meeting a new diagram system at the same time that new subject-based material is being learned. The tension here is between learning the diagram system versus learning the topic (?).

We therefore organise the first part of this discussion along three lines:

1. The tension between making things easy and helping students to learn
2. The question of how to support the generalisation and transfer of diagrammatic skills.
3. Learning unfamiliar representational systems while learning conceptually new subject matter

3 Making things too easy?

Question 1: What tasks do diagrams make easier?

> Can we consolidate the extensive research on the use of diagrams and other external representations in learning and problem solving to be able to generate useful advice for the instructional designer/teacher?

Question 2: What are the benefits of making tasks easier?

> Does making some task easier imply using multiple representations (?)?

One way to facilitate learning is to 'play to the strengths ' of the student. Thus areas of difficulty are avoided in some way in order to allow students to exploit their strengths or bypass their weaknesses.

Above, we suggested that learning comes through doing rather than from some form of passive observation. The full range of problem solving skills do need practice to attain both competence in performance and comprehension of the (diagrammatic) representational system itself. However, we also accept that it would be a mistake to assume that observation is inevitably passive: an observer may be highly active in constructing, for example, some interpretation of a diagram without necessarily physically manipulating the diagram in any way.

We take it as given that, whatever the form of internal representations, students are actively processing information obtained from the external representation. It is also reasonable to assume a framework along the lines of Rumelhart and Norman's "Accretion, Tuning and Restructuring"

(**?**), and that sometimes new information can lead to extensive internal restructuring (though the current feeling is that such 'radical' change is quite rare).

Salomon has provided a cognitive analysis of the effect of different media on learning (**?**)[4]. He distinguished between learning external and internal symbolic codes, and between 'stationary' and 'transformational' codes. Simplifying for our convenience, stationary is to transformational as problem state is to operator in Newell and Simon's view of problem solving. Stationary and transformational codes are interrelated. For Salomon, a transformational code can be 'short circuited' by providing the stationary code which would have been achieved if the learner had performed the necessary transformations. He argues that short circuiting can save effort but will not lead to the kind of skill internalisation needed for the skill to become a 'mental tool'. This is one of his key concepts for explaining certain effects in the use of media for learning.

Two further valuable concepts are those of activation and supplantation. Activation occurs when the preconditions of a previously learned skill are satisfied, while supplantation is the case where an external transformation has the almost identical effect as the internal transformation that the learner would have applied. Hence supplanting both saves cognitive effort and *models* the transformation explicitly, and more or less accurately. These ideas appear to be fruitful for any analysis that seeks to explain different effects attributable to the external representation systems themselves.

He argues that activation of a cognitive skill is only of benefit if the basic skill is present; short circuiting is useful for saving mental effort but at the cost of failing to provide skill activation. Supplantation is seen as a way in which poor mastery of a skill can be compensated for. However, Salomon does point out that we have no reason to assume that these outline hypotheses work either for all situations or for all students.

As an illustration of supplantation, Salomon (1994) quotes Cronbach and Snow as suggesting that "the high-verbal learner who is weak in visualization might be supplied with extensive diagrams and left to generate his own verbal representations" (**?**, page 70). (Assuming that it is the process of diagram construction that is being supplanted.)

However, Cox, Stenning and Oberlander (1994) have shown that subjects classed as good diagrammatic reasoners perform better than poor diagrammatic reasoners following a graphically taught logic course (**?**). More precisely, since there was also evidence that syntactic teaching produced better outcomes for non-diagrammatic reasoners in a syntactically taught group, the teaching approach matched to reasoning modality preference produced better learning outcomes.

So it remains unclear whether we should compensate for, or teach to cognitive style differences. Even assuming we could identify the relevant individual preferences/aptitudes, we would expect that there will not be a simple either/or decision to take on this.

Cheng has provided a number of examples of Law Encoding Diagrams (LEDs) which capture some implications of physical theories as constraints on the diagram structure (**?**). These diagrams make some aspects of the domain easier to manage, making many problems easier to solve than when using standard algebraic techniques. In order to take advantage of LEDs, a new representational system has to be learned, including how to manipulate it. If students can effectively incorporate LEDs into their problem solving repertoire, then there is still a question as to whether they remain a purely personal 'tool for thought' or a way of communicating problem solving solutions. If the former case holds, then perhaps this is not a useful way of making the task easier since there is then the problem of how the student maps from the LED to the solution required by teachers, examination boards etc. In other words, LEDs need to become acceptable in the classroom.

Finally, there is the issue of multiple representations. Given that particular representations necessarily highlight some types of information at the expense of others, this property of selective highlighting could potentially be exploited so as to help students focus on the information which is relevant to their current stage in the problem solving process[5]. However, there is some evidence that students cannot always cope effectively with multiple coordinated representations. Ainsworth *et al* demonstrate that simply providing coordinated representations does not by itself guarantee success (**?**). Indeed, under certain circumstances, it would seem that these representations could 'act against' each other. Schwarz and Dreyfus constructed several measures of information integration from multiple representations (**?**). These are candidates for further work in developing methods for evaluating information integration in systems such as the ones Ainsworth describes.

Cox and Brna have provided a detailed study of the use of SwitchER, a system designed to encourage users to solve problems using multiple serial representation construction (**?**). Their results indicate that representation selection depends on subjects examining the task requirements carefully. SwitchERII, an intelligent learning environment developed by Cox, features a variety of ways in which the subject is supported in his/her attempt to solve a certain class of word problems (analytical reasoning problems) (**?**). These include an ability to reorder the question's premises, recognition of possible unfamiliarity with a representational system, and recognition of some problem with a specific diagram. However, subjects were often unable to report their awareness of any specific advice given by the system, probably due to the high cognitive load of problem comprehension and external representation construction. Certainly subjects could not avoid noting an intervention since no further progress was possible until they clicked on the appropriate button. There were cases of students who went on to make an error despite a warning about their representation. In this case, SwitchERII made the task easier but the interface did not fully ensure the assistance was recognised. SwitchERII has been used to investigate the relationship between errors made in diagram interpretation and errors made subsequently (by the same subjects) in diagram construction. It was found that errors in representation interpretation do not necessarily predict errors of representation construction – the two tasks differ significantly in terms of cognitive load and in the degree of engagement with the task that they engender (**?**; **?**).

4 Generalising and transferring diagrammatic reasoning skills?

Question 3: Can we provide a convincing account of how learners gain a high level of competence at operating with relatively unfamiliar external representation systems?

What are the alternative models for generalisation? What is the most convincing explanation?

Question 4: How important is translation skill?

Can we accept that one measure of proficiency is the ability to move gracefully between external representation systems? Are there alternative measures?

As mentioned above, learning to use a diagrammatic method for performing a task always occurs in a specific context, and depends to a great extent on the task, the student's prior knowledge, diagrammatic reasoning system's characteristics and the physical and social context. Many of the problems in becoming an effective 'diagrammatic reasoner' can be viewed in terms of how to generalise from experience and transfer skills learned in one context to another.

In seeking to explain transfer, Lowe has argued for the existence of *diagram genres* which enable those familiar with domain dependent, highly specific representations to be highly proficient with superficially very different diagrammatic systems in different domains of use (**?**).

There are models of learning to use representations embedded in a computer interface. These are models of exploratory learning often set in the context of learning to use an unfamiliar software application. However, for the most part, this approach has tended to examine skill learning rather than conceptual learning. For example, Rieman, Young and Howes have provided a fine-grain model of exploratory learning (IDXL) which depends on scanning the interface and internal comprehension strategies (**?**). Kitajima and Polson provide a more abstract comprehension-based model (The LInked model of Comprehension-based Action planning and Instruction taking — LICAI) of exploration of an interface (?; ?) based on Kintsch's construction-integration theory of text comprehension (?). These models take some steps that may eventually lead to models of exploration-based diagrammatic reasoning in unfamiliar domains as they seek to explain exploration driven by a combination of the situation, prior knowledge and the task. So far, they do not address the problems of using computer applications to learn conceptually difficult material at the same time.

Van der Pal has tried to confront some aspects of learning formal reasoning from a situated action perspective (cf (?)) while seeking to respect the need to explain the process of generalisation/decontextualisation (?). However, it is not just the circumstances surrounding the use of diagrammatic systems which lead to problems connected with generalisation: to an extent, it is connected with the semantic and cognitive properties of the representation systems themselves.

Stenning and Oberlander have argued that a diagrammatic representation system gains some of its cognitive tractability from the limitations on its power of expression (?). Their argument depends in part on the difficulty of representing alternative possibilities using diagrams. This problem arises in the Hyperproof system (?). This system features a fairly standard natural deduction proof system with a limited set of predicate relationships available. The novel feature is a chess board and blocks of different shapes, sizes and positions and some simple mechanisms for allowing for indeterminate representations — hiding position, shape and size. The axioms and goal to be proved are all cast in terms of the blocks in the blocks' world. Provision is made for moving information between the proof system and the blocks' world.

One of the problems that arises is when the proof requires the enumeration of all the possibilities so that each can be tackled one at a time. This 'case split' is difficult to represent in the blocks world since only one world can be shown at a time — so the Hyperproof diagrammatic system 'encourages' students to systematically 'break into cases' and work with a single case (at a time).

Formal logic encourages the user to make the case split explicit prior to handling the individual cases and allows scanning of this structure throughout, while Hyperproof's blocks world only permits one case to be visible at a time. Hence, the learner may miss opportunities to notice any discrepancy in the case split structure. Also, since only one 'blocks world' case can be seen at a time, it is easier for students to generalise incorrectly.

So it would appear that Hyperproof's blocks world may not help students develop their skills at finding good case splits — however, there may be other features of the blocks world that compensate for this though it is uncertain as to whether this is so[6].

Additionally, the issue of generalising and transferring diagrammatic skills has both intra and inter domain extensions. For example, does learning a graphical representation for program design facilitate the learning of, say, a visual programming language? Even further afield, will this same knowledge give students any advantage when they come to learn the diagrammatic representation system used by Hyperproof?

We can regard the transfer of diagrammatic reasoning skills as a complex process of becoming familiar with the current reasoning context, decontextualising what is learned through working on a number of different tasks in a variety of different social situations at different stages of the student's experience, becoming familiar with other representation systems, and then learning to move 'gracefully' between them. This is a complicated process!

Facility in translating between external representations commonly used within some community is a key test of expertise. It can be argued that learning to translate is of vital importance to learning. Kaput, for example, provides an analysis of the ways in which meaning is developed through translation (**?**).

5 Learning too much at the same time?

Question 5: How can we partition the cognitive load in a sensible way?

> Is it realistic to teach the external representation system prior to teaching the particular domain knowledge of interest? How important is this period of learning? ie what effect can we measure or predict will occur in terms of the student's development, as evidenced both by learning the representational system and by learning the new subject-based material?

Question 6: Should this experience be avoided?

> If so, how, and if not, why not? Is it better or worse to protect students from this kind of experience? How is student's prior knowledge factored in to provide individualised support? How should this be done (if at all)? What combination of task and semantic characteristics of external representation systems might help to ease the problem?

Students (singly, in pairs and in larger groupings) often learn some domain of knowledge which is represented with the help of a (diagrammatic) external representation system at the same time as also 'learning' the representational system.

In these situations, students are often faced with representations that may be — to them — ambiguous. Therefore they may commit to an interpretation of the representational system (or even some specific representation) which may be inconsistent or flawed in some way in relation to the intended meaning. Thus students have to *interpret* elements of the representation and *identify* (parts of) the representational system (**?**). Things are complicated because students are simultaneously constructing a model of the domain knowledge derived from the domain-based material they are still studying.

For domain specific diagrammatic representation systems, the explicit provision of some of the key components of the domain knowledge may help but Lowe has pointed out how many educators implicitly assume that the representation system itself will help the student to understand these key domain knowledge components (**?**). This makes the task much harder for the student.

In the initial stages, the student is struggling with both learning the representation system and learning the domain knowledge. Some may argue that the period of time during which students are 'learning too much' is quite brief compared with the length of time over which the external representation system is used, and hence that it is unlikely to make a difference to the student's development. On the other hand, the period during which students need to actively seek to understand external representations and the external representation system itself may in fact have significant long term effects which we need to take into consideration.

6 Some further issues

We can identify some further pervasive issues that have been attracting a fair amount of interest. We consider these to include:

- Sense Making through Diagrammatic Representations
- The Self Explanation Effect and Diagrams
- Diagrams and Educational Discourse
- Sensori-Motor Experience and Diagrammatic Reasoning

6.1 Sense making through diagrammatic representations

Question 7: What activities does a learner engage in when 'sense making'?

Can we describe the process of understanding the task in a more detailed way than hitherto? Can we do the same for the process of verifying (partial) solutions?

Question 8: How can diagrams be used to promote 'sense making'?

What techniques do we have at our disposal? What are the best examples from the research literature which demonstrate the benefits of diagrammatic representations as aids to 'sense making'?

For most of us — especially when we are learning material that is conceptually challenging, sense making takes place throughout the problem solving process. From comprehending the task to finding an acceptable solution, we are involved in making sense of the information. This sometimes leads to radical revision of our understanding of the task, of the representational system selected, or even the way in which the representation is constructed.

Lowe has been investigating the ways in which novices make sense of meteorology diagrams for some time (**?**). He has noted that the student may often select inappropriate low level details upon which to base an interpretation of the domain. Additionally, patterns of search and inference depend to a great extent on prior knowledge (**?**). He observes that novice meteorologists tend to work from superficial features and rarely find significant relationships — especially when spread across the weather map. This is entirely consistent with research in the area of the novice/expert differences (see, e.g. (**?**)).

Lowe further reports that, in describing weather maps using a card sort methodology, novices use domain-general visuo-spatial descriptions while experienced meteorologists use domain specific terms (**?**). His conclusion is that mental model construction can be seriously hindered if the diagrammatic representation is too abstract.

Schnotz and his colleagues have investigated the role of structural analogies in learning to understand and use diagrammatic representations (**?**). As a result of examining the course of problem solving in a series of tasks relating to knowledge about time zones, Schnotz has provided an argument that diagrammatic representations have an important role in the construction of an appropriate mental model. He reports that successful and unsuccessful learners accessed and used information derived from the diagrammatic representation in different ways with successful students using the diagrammatic representation to build a schematic mental model and using the supplied text to elaborate the schema. The reason for the worse performance of the 'unsuccessful' learners was that they failed to access necessary new information when it was needed, and utilised the graphic information to a much lesser extent.

Hall, Kibler, Wenger and Truxaw have observed that much of a problem solver's activity is devoted to reaching an understanding of the problem. They collected written protocols from 85 mathematically competent undergraduates as they solved a range of algebra word story problems. Hall et al. (1988) noted that many subjects construct solutions to problems rather than smoothly execute a highly practiced skill and that the constructions often involve reasoning that is only partly connected with algebraic or arithmetic formalisms. Competent reasoners often use problem solving techniques from "outside" algebraic formalism. With language, learners may re-write or translate a problem in somewhat abstract terms and may even conceal from themselves their less than complete comprehension (**?**). They observed that problem comprehension and solution are complementary processes and that integrating dual representations of a problem is a key aspect of competence.

They write:

> ...reasoning about the situational context of a problem can serve as a justification for assembling quantitative constraints that may eventually lead to a correct solution. Thus, a substantial portion of a problem solver's activity is devoted to *reaching* an understanding of the problem that is sufficient for applying the routine of formal manipulation." (p.269).

Thus it may be the interplay between problem descriptions in natural language and in diagrammatic form that assists the individual to understand the nature of the task in some deeper way.

Grossen & Carnine provide evidence for the advantages of students to construct their own diagrammatic solutions (**?**). The process of constructing a diagram is a form of sense making that transforms the student's understanding of the task. From a theoretical perspective, the notion of sense making is not well defined. Sense making is a powerful unifying concept but more needs to be done to clarify the ways in which people function when 'making sense'.

6.2 The self explanation effect and diagrams

Question 9: Can the self explanation effect be enhanced by the use of multiple representations?

How does self explanation function with multiple representations? Can self explanation be supported through the use of diagrams — as found, for example, in a computational environment (**?**)?

Question 10: What relationships are there between task, prior knowledge and self explanation?

Can Zhang and Norman's (1994) approach be adapted to model this complex interaction? What other promising approaches are there for the elucidation of this interaction?

The self explanation effect, in its original presentation, is associated with good performance on problem solving through the use of example solutions (**?**). It appears that more successful problem solvers have three special characteristics. Relative to the poorer students, the better students tend to: more frequently explain and justify actions to themselves; monitor their comprehension performance more accurately; and refer back to an example for a specific piece of information. In other words, their (metacognitive) self-communication is frequent, rich and accurate.

Cox has described how the use of diagrammatic representations might facilitate this effect via their effect on the nature of the self-discourse (**?**). He suggests that the low expressivity of graphical external representations may assist, to a greater extent than sentential representations, a reflective, self-explaining student by confronting him/her with the need to consider more than one model of the information in question. Cox further argues that there has not been enough work to determine the mechanisms that might lead to the effect, nor on the ways that diagrams play a part in this process.

Wilkin has studied the interaction of self-generated diagrams in relation to the self explanation effect (**?**). Poor learners, defined by a median split of subjects, used self-generated diagrammatic representations in trying to understand motion along a curved path. Her results indicated that the adjacency of diagrammatic features would often lead to error, a result quite consistent with Lowe's detailed analysis of the interaction between domain expertise and accuracy in a study of ER usage (**?**). The general thrust of the argument is that diagrams may mislead the novice diagram constructor without additional instuctional support.

Zhang and Norman have outlined a theoretical framework for analysing the ways in which internal and external representations interact (**?**)[7]. Their approach provides one starting point for an investigation of the cognitive mechanisms underlying the self explanation effect.

6.3 Diagrams and educational discourse

Question 11: In what ways does the teacher-student discourse affect learning new diagrammatic representation systems?

Question 12: In what ways does student-student discourse affect the learning of new diagrammatic representational systems?

In the context of education which we are considering, learning is not a fundamentally solitary activity. Even in the physical absence of a teacher, the student's behaviour is still governed by the nature of the teacher/student relationship. Thus we consider there to be an ongoing discourse between the student, his/her peers and the teacher (or teachers).

The nature of the educational use of diagrammatic representational systems is constrained by the kinds of discourse possible. For example, if we wish to provide tools for students to build new diagrammatic reasoning systems then perhaps we should ask "what kind of educational discourse can be realised through this?"

The argument for encouraging learners to participate in the construction of diagrams is often accompanied by a reluctance (parsimony?) to generate new diagrammatic representational systems. We can find many examples where students are expected to use a specific diagrammatic representational system to solve a problem but few examples where the student participates in the construction of a new diagrammatic representational system. The education system may be intrinsically less tolerant of novel (idiosyncratic?) representation systems being generated by students, perhaps in part because there may be a risk that systems containing semantic inconsistencies or errors could reinforce student misconceptions by perpetuating them. Perhaps, from an early stage in the educational process, students should be encouraged to generate their own diagrammatic conventions or to borrow from existing diagrammatic approaches (**?**)?

In addition, teachers do not always fully cooperate in the discourse. There is a sense in which they 'hold back' information according to their goals —and these are not always made explicit to the student. Often, teachers require students to offer explanations 'as if' they (the teachers) were ignorant of the concept — both participants are aware of the game. This 'uncooperativeness' can also be seen in the ways in which word problems are posed (**?**).

In terms of student/student discourse, some work has been done to study the ways in which diagrams are, or can be, used to co-construct meaning. For example, Baker and Lund have examined the ways in which such a discourse involving a diagrammatic representation system can be supported through a structured communicative interface (**?**). However, they have not yet provided an analysis of the support needed in terms of the diagrammatic aspects.

6.4 Sensori-motor experience and diagrammatic reasoning

Question 13: How does sensori-motor processing interact with the use of diagrams? Can systems that stress sensori-motor experience (such as Virtual Reality environments) benefit from integrating them with diagrammatic information?

What are the benefits of doing so for education?

Question 14: In what ways does 'presence' interfere with diagrammatic reasoning?

How can we exploit the notion of presence?

The relationship between perception and reasoning has been discussed many times. Recently, it has become apparent that the rise of Virtual Reality technologies offers tantalising possibilities for research into the area of perception, the use of ERs and education. However, there are well reported cases of people effectively learning to perform manual skills but scant evidence that current immersive virtual reality systems provide any significant benefits for conceptual learning (**?**; **?**). It has been argued that part of the problem is a failure to provide support for more abstract forms of reasoning (**?**). This support might well take advantage of diagrammatic representations.

Little attention has been given in the Virtual Reality (VR) community to the relationship between sensori-motor experience and conceptual learning — the most common provision for symbolic communication is the availability of a whiteboard. The current VR system builders have spent a great deal of effort in rendering objects in 3D with shading and texture. They have also incorporated 3D audio and various forms of haptic feedback in order to provide VR environments with a strong sense of presence (a measure of the fidelity of sensory cues that engender a sense of "physical presence" or "direct experience"). However, the problem of communicating in diagrammatic or textual symbolic form has not been fully confronted. That is, the new communicative possibilities have concentrated on the sensori-motor aspects. There are signs that some researchers want to include various forms of dialogue with pedagogical VR environments (**?**) but there is very little sign that diagrammatic reasoning has been explored within VR environments. No doubt this will change!

Currently, there is a growing interest in modelling how people use diagrammatic representations both for personal uses and for communication. Educational issues include how students work with physical contexts and theoretical concepts to make sense of situations. Brna and Burton have been developing a model of how this process might take place in a collaborative context but have paid little attention to perceptual issues (?). Shrager, for example, has sought to explain how people using different representational systems might align their understanding of the underlying phenomena (?) though he did not really address non-attentional factors. Current models of learning how to use an unfamiliar computer interface, such as Kitajima and Polson's LICAI, are good at explaining how people exploit the cues given but such models do not directly address the interaction between the learner's perception and conceptual aspects of learning.

Another major effect of the introduction of Virtual Reality has been to raise (again) the issue that motivational aspects of educational environments need to be addressed. Virtual Reality has introduced the notion of presence, the sense of 'being there' in some environment. Although this concept has proved to be elusive to measure, either in subjective or objective terms, there is no doubt that VR environments have a complex effect. Whitelock, Brna and Holland (1996) have sought to develop a framework to study conceptual learning in which presence has a place but the relationship, if any, between presence and the use of external representations has not been explored in any detailed way.

So what does the technology of VR bring to the issue of diagrammatic reasoning? If diagrams are defined as intrinsically 2D then VR would seem to be a distraction. If, on the other hand, diagrams can have any dimensionality then what are the benefits of 'entering' a 3D diagram and moving in and around it? If VR provides the possibility for making very compelling presentations of information (e.g. in diagrammatic form) then how can this be exploited educationally? How can the use of diagrams in an educational context take advantage of the possibilities produced by current/future VR technology? For example, what advantages would a 3D AND/OR tree offer over the 'usual' 2D representation?

7 Conclusion

From an AI perspective, there are undoubtedly many possibilities for exploiting existing symbolic and non-symbolic approaches to modelling the processes involved in learning to think and communicate using diagrams. These models might range from detailed, low-level accounts of sensori-motor experience in VR environments to higher-level accounts of the communicational aspects of diagrams in an educational setting.

Several specific modelling approaches have already been discussed in this paper: one has addressed the issue of how to represent the interplay between internal and external representations (**?**) while the others seek to account for exploratory learning (**?**; **?**). However, more work is needed on the issues of how students learn to comprehend and use multiple ERs and how they learn to translate between ERs. Schnotz and his colleagues have made some progress toward explaining how such learning takes place (**?**; **?**) but has not yet developed a computational model. However, it is likely that simple cognitive models of the complex processes involved will appear within the next few years.

Some consideration has also been given to environments that provide support for people to learn and/or use diagrammatic representational systems. For example, just because a system can do some intelligent reasoning with diagrams doesn't mean it should. The learner may need to 'see' the reasoning being modelled by the system. The provision of multiple representations is increasingly popular but some thought needs to be given to the issues of how to a) encourage the transfer of diagrammatic knowledge between representations and b) assist with the integration of information from the diverse sources.

The way representations are linked might need to be dependent on the learner's state of knowledge. Unfortunately, there are still serious problems for presenting possibly large numbers of multiple alternatives — these can be ameliorated to an extent by providing accessible methods for generating new abstractions but they may benefit the stronger students rather than the weaker ones. Some attention needs to be paid to checking the design of diagrammatic systems intended for educational usage.

We have sketched out a number of issues and some key associated questions that need to be considered. We hope that AI researchers will find some promising challenges to accept.

Notes

[1] Mayer and Sims provide a dual coding explanation of the interaction between text and an animation (**?**) while Schnotz and Grzondziel give an explanation for their empirical results which argue that static pictures allow for deeper processing than animated pictures (**?**).

[2] In this paper, an external representation *system* is a coherent set of symbols and relationships which are used to represent the information of interest.

[3] However 'near' or 'far' the transfer. That is, whether the transfer is from training problems to new problems of the same overall type or from one domain to another.

[4] His use of the term media corresponds more to Stenning's use of the term modalities (**?**).

[5] e.g. Brayshaw's MRE (**?**), a program visualisation environment for PARLOG, provides multiple representations at different levels of granularity of the evolution of various program objects over the course of the program's execution.

[6] Of course, the proof could be represented in another way — say, as an AND/OR tree in such a way that case splits were more evident.

[7] They also support the argument that external representations change the nature of the task.

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