Diagrams about Thoughts about Thoughts about Diagrams

Alan F. Blackwell

MRC Applied Psychology Unit
Cambridge, UK.
alan.blackwell@mrc-apu.cam.ac.uk

Abstract

The study of diagrammatic reasoning often focuses on computational models of diagram use rather than on studies of human performance. This paper considers diagrams as a notational system that can be used and studied in an experimental context. It presents a review of the experimental psychology literature rather than a complete theoretical framework, and is intended as an introduction to the field for those who are commencing research projects into diagrammatic reasoning, having come from a discipline other than cognitive psychology.

Introduction

How is using diagrams related to things that happen inside our heads? This paper presents a survey of the empirical and theoretical research that has investigated these processes. It considers the origins, interpretation and manipulation of diagrams, with the structure of each topic presented in diagrammatic form.

Any cognitive study of information other than text or speech encounters the lingering remnants of the imagery debate, as examined in the collection edited by Block (1981). Much early research on diagram use was motivated by one of the entrenched positions in this debate: if seeing a diagram causes an image-like mental representation, it is the nature of this internal representation that was studied, sometimes without any external diagram; alternatively, if a diagram causes a mental representation like any other, research concentrates on the ways that we use the external diagram. Are the special properties of diagrams inside the head, in the world, or common to both? This review is structured accordingly, as illustrated in Figure 1.

Diagrams as Notation

How do diagrams differ from text or pictures? This section describes their formal properties (whether internal or external), but also where those properties come from and how they support reasoning.

What are Diagrams?

We can describe diagrams according to their status in the world, in thought or in communication. All three are informed by Peirce's (1903/1932) analysis of signs.

Ittelson (1996) has described how perception of markings differs from other perceptual tasks. Markings do not occur naturally – they are human artefacts whose function lies in the intention behind their creation. Ittelson distinguishes these types: *Designs* are decorative, *writings* carry meaning by agreed conventions, and *depictions* evoke objects or experiences. *Diagrams* are separate. They provide non-visual information in a visual form. Diagrams are like writing – in depending on agreed conventions – but unlike in that the overall form affects the interpretation.

Bertin (1981) describes graphics in terms of the ways in which ink can be distributed on a surface. These *variables of the plane* include location on X and Y axes plus a

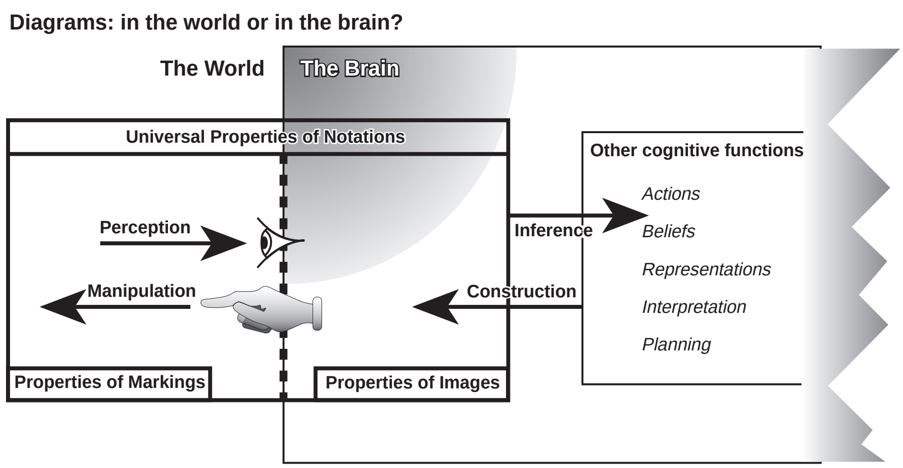

Figure 1 – Structure of the review

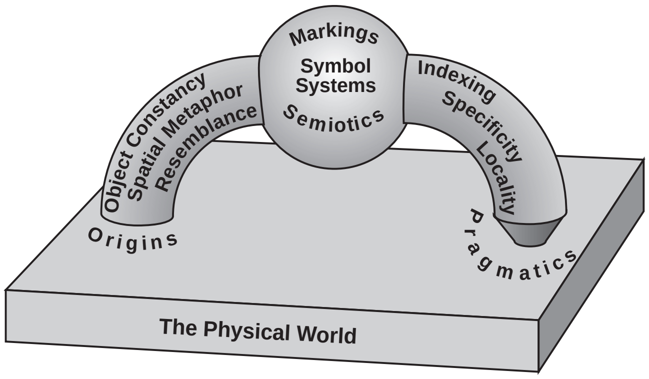

Figure 2 – The origin and use of diagrammatic notations

number of "Z axis" variations. These include the size of a mark, density and colour of ink, or orientation and shape. His analysis is based on information-carrying potential; information to be communicated must be mapped to these variables. Where information is topographical, X and Y are devoted to location. Ordered values must be mapped to an ordered scale – size or density, if X and Y have been allocated – while unordered values can be mapped to differential variables such as colour or shape.

Goodman (1969) offers a general account of representational *symbol systems*. In order to say whether two messages are different, the characters of a notation must be both disjoint and unambiguous. Syntactical disjointedness is distinguished from syntactically dense (or analogue) notations, which have infinitely many characters – between any two there can be a third. In many symbol systems, further information is added when the message is interpreted, and this can result in a message that is semantically dense, even though syntactically differentiated. Goodman places diagrams in the class of *models*, which are analogue (semantically dense) in some dimensions, but digital (or syntactically disjoint) in others.

Where do Diagrams Come From?

Resemblance. The most naive account (more likely to be made of diagrams with a strongly pictorial element) is simply that they resemble the things they refer to. Goodman (1969) was particularly concerned to address this *fallacy of depiction*. Denotation, the core of representation, does not rely on resemblance. If it did, it would not be possible to depict things that do not exist, so cannot be resembled. Ittelson (1996) challenges the *pictorial assumption* in psychology: that "the processes involved in the visual perception of the real world and the processes involved in the visual perception of pictures are identical", and Scaife and Rogers (1996) warn of the *resemblance fallacy* – the intuition that diagrams resemble the visual world.

Metaphor. Gibbs (1996) has found experimental evidence for mental images that underlie common idioms, and uses this to support Lakoff's (1993) *conceptual metaphor* theory – that abstract concepts are derived from embodied experience in the physical world. This applies especially to spatial metaphors for abstract concepts. The use of metaphor to structure representations is familiar in computer systems. The now ubiquitous computer *icon* was intended as a metaphor: 'PYGMALION is a visual metaphor for computing. Instead of symbols and abstract concepts, the programmer uses concrete display images, called "icons"' (Smith 1977).

The Frame Problem. How do icons make a computer more usable? Shneiderman (1983) defined *direct manipulation*: objects are continuously represented on the screen, the user acts on them, and actions have immediately visible impact. By comparison to symbolic references in verbal commands, diagrams have no *frame problem* – the consequences of any action are apparent in the representation. Lewis (1991) argues that humans are "attuned" to constraints in our physical environment, and this helps us recognise how to use diagrams.

What do Diagrams Provide?

Locality and Labels. Larkin and Simon (1987) described a computational model that directly uses diagram features. Diagrams group related information in the same area, so searches can be constrained to the vicinity of a goal. Correspondences can also be established from topological relationships – unlike symbolic systems, where they are found by searching for related labels.

Expressive Power and Specificity. Stenning & Oberlander (1995) argue that diagrams aid cognitive processing because of their *specificity* – the way in which they limit abstraction. Diagrams have fewer interpretations, so are more tractable than unconstrained textual notations. Goodman (1969) similarly noted that interpretation of language involves a potentially infinite search for meaning because it is syntactically differentiated but semantically dense.

Pragmatics. Theoretical work on notations seldom considers the question of usability. Green's *cognitive dimensions* (Green & Petre 1996) provide a vocabulary for discussing the way that notations are used. They are based on the observation that every notation highlights some kinds of information at the expense of obscuring others.

Diagrams as Thoughts

There have been many comparisons of verbal and visual tasks. They include the way that differing capabilities are distributed through the brain, the way that people choose strategies for different tasks, and psychometric measures to investigate variation between individuals.

Variation Within the Brain

The distinction between visual and verbal representations in the brain is often described as a simple dichotomy. This may be easier to implement as a computational model, but even simple experiments show that pictures and propositions cannot clearly be divided.

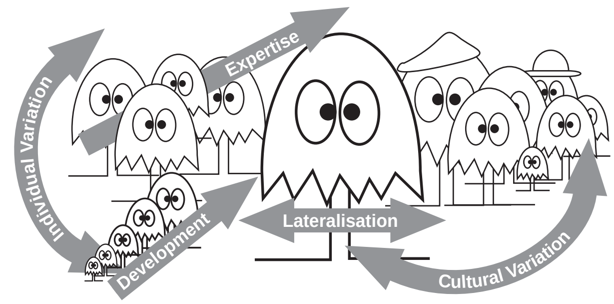

Figure 3 – Axes of variation in diagrammatic reasoning

Hemispheric Specialisation. The most impressive dichotomy in cognitive science is that of hemispheric specialisation in the brain. Advocates of diagrams have even suggested that the right hemisphere is "needlessly at rest and underutilised" when using text (Shu 1988). Evidence of hemispheric specialisation comes from neurological studies, functional imaging, and presentation of stimuli in one half of the visual field. Some simple visual tasks can require more time when carried out by the left hemisphere. Ratcliff (1979) found that patients with right hemisphere lesions are slower at a simple image inversion task. Kosslyn et. al. (1989) found that spatial judgements are faster when a stimulus is presented in the left visual field (right hemisphere) and categorical ones faster to the left hemisphere. Baker et. al. (1996) used functional imaging to find that spatial planning tasks result in more right hemisphere blood flow.

Interaction of Verbal and Visual, What and Where. Despite hemispheric specialisation, there are many tasks in which verbal and visual information is combined. Paivio's *dual coding* theory (1971) explained how memory improves when a concrete image can be associated with a verbal task. Spatial coding of words was observed by Santa (1977) – words are encoded verbally if they are arranged linearly, but a non-linear spatial arrangement impairs judgement of words far more than images.

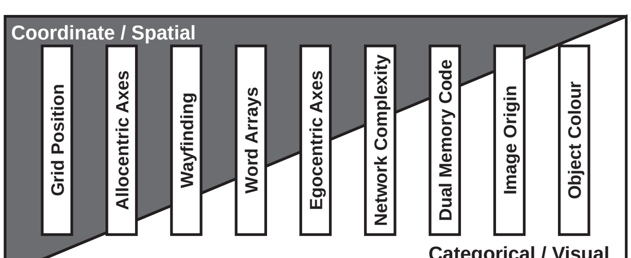

Figure 4 – Interaction of object and spatial descriptions

In addition to visual and verbal, we can distinguish categorical and coordinate, or "what" and "where" information. Categorical information might not be verbal – object identity is often encoded in terms of an image of the object. Farah et. al. (1988) describe this dissociation in a case study of a brain-damaged patient who has severely impaired memory for images, but normal spatial memory. Tresch et. al. (1993) found a similar dissociation using a dual task experiment: object memory was impaired by a colour judgement task, and spatial memory by a motion detection task. Mecklinger and Müller (1996) have measured differences in neural activity when subjects memorise either identity or location of objects in a grid.

Further evidence for complex interactions is found in apparently spatial tasks. Anooshian and Seibert (1996) demonstrated that navigation is not a "pure" spatial system – route memory depends on visual landmarks. Neither is memory for node and link diagrams purely visual (Chechile et. al. 1996). Even if subjects are asked to make purely visual comparisons, topological complexity of a diagram affects performance.

Axes and Orientation. Spatial axes seem to play a role that is complementary to visual and verbal codes in human cognition. They introduce a categorical element by dividing space into distinct regions. Hayward and Tarr (1995) showed that memory for spatial locations seems to be associated with horizontal and vertical axes. When subjects were asked to make judgements about relative positions of points on a map, accuracy was improved when near an axis. McNamara (1986) created axes by placing strings across a room in which the location of objects was to be remembered. These strings distorted position judgements toward the axis, while also influencing mnemonic coding.

Variation in Individual Capability

Are there innate differences between individuals in image manipulation skills, or in the ability to transfer information between visual and verbal modes? Do such differences have any effect on real-world tasks? The ability to rotate a mental image is controversial, as it shows a larger gender difference than any other psychometric test (Halpern 1992), but is it useful?

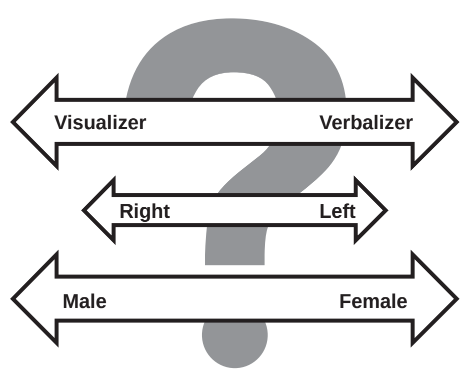

Figure 5 – Correlative factors in individual differences

Cognitive Styles: Visualizer and Verbalizer. As with hemispheric specialisation, there was a popular dichotomy between *cognitive styles* in early research on individual differences. A classic experiment compares judgement speed using pictures and sentences. MacLeod et. al. (1978) were able to predict performance by dividing SAT scores into spatial and verbal tasks. Shah & Miyake (1996) have devised a *spatial span* measure – memory for a sequence of locations. This too is correlated with visualisation tasks, but not with verbalisation.

It is possible to compensate for these differences by training, however. Frandsen and Holder (1969) identified subjects with lower scores on a spatial manipulation test, and trained them to use Venn diagrams. The previously observed difference between visualisers and verbalisers disappeared. Even without training, people often choose either a verbal or visual strategy according to their own abilities.

Gender Correlations. Paivio and Clark (1991) found a systematic element in strategy choice: more males used imagery for dynamic problem solving tasks, while more females used it for static memory tasks. Delgado and Prieto (1996) carried out a large study looking for possible strategic differences that might account for gender differences in mental rotation, but could only confirm Halpern's (1992) observation. Silverman et. al. (1996) carried out a cross-cultural study, aimed at finding different patterns of gender difference as a result of differences in gender associations between cultures. Once again, the same gender effect was found in all groups studied.

Development of Strategies

Although there appear to be innate differences between the strategies that individuals choose in visual reasoning tasks, strategy is also affected by education, expertise and culture.

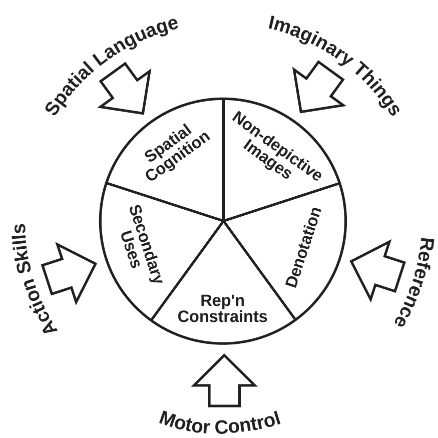

Figure 6 – Development of diagram skills

Developmental Studies. The ability to interpret a denotative relationship between a representation and the real world is not innate. DeLoache has found that children learn to transfer relationships from a scale model or picture to the world between the ages of two and three years (DeLoache & Marzolf 1992). Presson (1987) records the development of spatial reasoning skills for use in *secondary spatial reasoning* tasks such as map reading.

Studies of drawing in children observe the development of depictive conventions. Many features of childhood productions, such as arms and legs connected to the head, can be attributed to undeveloped planning skills (Thomas and Silk 1990) or motor skills (van Sommers 1984). Nevertheless, some special cases show the development of representational strategies. Scott and Baron-Cohen (1996), found that autistic children are unable to draw imaginary objects. This is interesting in the light of Goodman's theory of depiction. Does it mean that for autistics, drawing can only be depictive? Would this also prevent them from using some diagrammatic conventions? More work here could provide valuable insights.

The Nature of Expertise. Lowe's (1993) study of weather maps found that novices read surface notational features, while experts are primarily aware of underlying structure, including information not visible in the notation. Expert circuit designers also use configural information independently of spatial organisation (Egan and Schwartz 1979), while being well aware of which graphical properties can express relatedness (for example) independently of connectedness (Petre & Green 1990).

How is expert knowledge encoded and related to the visual aspects of a diagrammatic notation? Computational models of diagram usage access previous solutions via visual elements of the diagram that look the same. McDougal and Hammond (1995) indexed diagrams based on overall configuration, Koedinger and Anderson (1990) indexed using local detail, and Thagard, Gochfeld & Hardy (1992) simply matched the structure of visually adjacent elements. Each of these models is supported by empirical studies. If solutions are accessed by spatial configuration, decreased performance is observed when it is not available (Carroll et. al. 1980). Chambers (1993) describes the importance of local detail in determining the interpretation of a figure, and Beveridge and Parkins (1987) demonstrated that a diagram emphasising structure of a problem maximises discovery of an analogical solution.

Cultural Differences. Many diagrams rely on expert knowledge, but are there any universal diagram properties? Tversky, Kugelmass & Winter (1991) asked English, Hebrew and Arabic speaking children and adults to illustrate various quantities and points in time. They found several universal conventions. Adults from all cultures show quantity increasing from bottom to top of a page. Children sometimes show quantity horizontally, but still not top to bottom. More unexpectedly, a left to right time direction was preferred by all children too young to read, regardless of whether they came from a culture with left to right or right to left writing systems.

Evidence for cultural differences in imagery skills comes from Kearins' (1981) studies of Australian Aboriginal children, who score poorly on supposedly "culture fair" IQ tests. She devised a test in which children had to memorise, then reconstruct, the positions of objects in a grid. The performance of Aborigines not only equalled, but greatly exceeded that of Europeans. Kearins observed strategic differences that may explain the results; European children muttered to themselves while memorising, and made many corrections during reconstruction. Aborigines observed the array quietly, and reconstructed it methodically without corrections.

Application of Diagrams

The first two parts of this review have discussed general properties of diagrammatic notations, and specific properties of mental representations. The main claims for diagrammatic reasoning depend, however, on the way that these two are combined in diagram applications.

Information Input: Diagrams as Models

Denis (1991) defines the situations in which it is useful to build an analogue model of a problem. When modelling a physical situation, there may be physical dimensions which can be directly represented in an image, allowing comparative judgements. A similar strategy can be used for abstract problems, if there are abstract dimensions that can be treated spatially. In this case there is a trade-off between the benefit of accessing information from an image, and the cost of transforming the abstract problem. Huttenlocher's (1968) experiments are an early demonstration of the way that a verbal description of a problem can result in visualisation of the problem rather than a grammatical representation. These "three term series" problems showed that people often reason about relative height from images rather than propositional terms.

When an illustration of a problem situation is given, it can form the core of a spatial representation – so the main contribution of a diagram may be that it reduces the cognitive load of assigning abstract data to appropriate spatial dimensions. For example, Glenberg and Langston (1992) found that where information about temporal ordering is only implicit in text, a flow diagram will reduce errors in answering questions about that ordering.

Information Processing: Diagram Manipulation

Once a problem is represented in diagrammatic form, how is the diagram used? The experiments described above simply involve "reading off" an answer by inspecting a model. Inferences can also be made by directly transforming an image, without converting information from the image into propositional form. Ullman (1984) proposed a number of *visual routines* that could be used to derive information directly from an image, although it is difficult to demonstrate that these are involved in human reasoning.

An algorithm that has been observed in the use of mechanical diagrams is *mental animation* of the depicted machine. Hegarty (1992) used a gaze tracking procedure to find that inferences were made about a diagram of ropes and pulleys by imagining the motion of the rope along a *causal chain*. Schwartz (1995) has been able to influence when subjects choose an animation strategy. If a device is represented with a realistic illustration, his subjects made judgements at a speed proportional to the amount of motion, indicating that they were mentally animating the device. If the problem is presented in simple geometric terms, judgements were made in constant time, suggesting an alternative strategy.

One of the most extensively investigated image algorithms is seen in Finke's research on the use of images for creative synthesis (Finke, Pinker & Farah 1989). In these experiments, subjects are shown a set of geometric shapes, and asked to suggest a creative combination of them. Finke's model of creativity claims that new configurations can be generated and explored by manipulating and combining images.

Information Output: Verbalisation from Diagrams

Once an image-like model has been constructed, and a problem solution found by manipulating it, how is the solution reported? The image could be copied out as an external diagram, but it is more common to report problem solutions verbally. This is described by Levelt (1981) as the *speaker's linearisation problem*. He proposed that, given a diagram to describe verbally, people make a *gaze tour*, guided by connectivity, with nodes mentioned in the order they are visited.

The gaze tour is based on the observation by Linde & Labov (1975) that New Yorkers, asked to describe their apartments, list the rooms in order of walking through them. They conclude from this that topological structure is

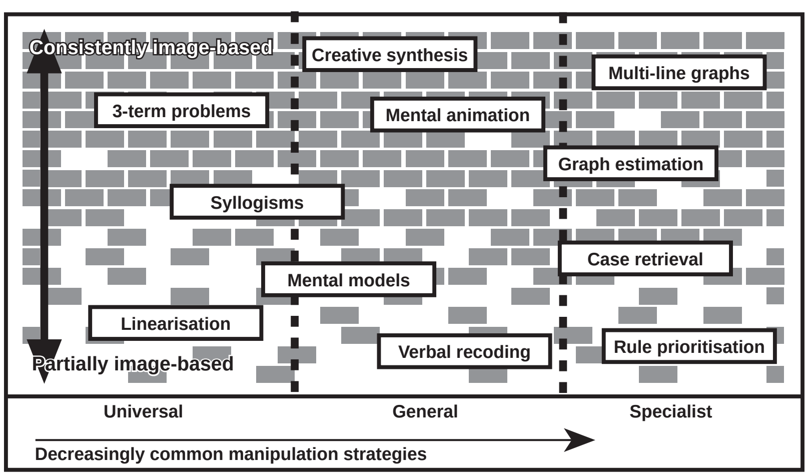

Figure 7 – Range of image-based strategies for diagram use

represented in terms of events, but Taylor & Tversky (1996) provide a far richer model of how spatial descriptions are structured. Depending on the configuration of the space to be described, either a *route* structure, a *survey* structure, or a mixture of the two can be used. Linde and Labov's observation of route structure, they claim, resulted simply from the fact that most New York apartments have a linear arrangement of rooms.

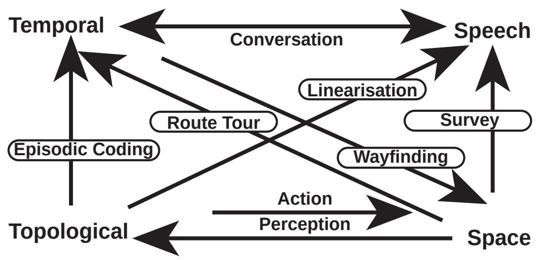

Figure 8 – Empirical studies of verbalisation

Evidence of verbalisation strategies also comes from working memory experiments. Baddeley's (1986) model of working memory defines a *phonological loop* and a *visuo-spatial sketchpad*. The phonological loop depends on verbal articulation speed; the VSSP should be independent of articulation. Smyth and Scholey (1996) measured, however, a correlation between articulation speed and locations remembered in an array. This suggests the kind of verbalisation strategy that Kearins (1981) thought might be culture-specific.

Interaction between verbalisation and images can compromise diagrammatic reasoning. Many investigations of problem solving have asked experimental subjects to "think aloud" (Ericsson & Simon 1985). Schooler et. al. (1993) found that solutions to insight problems fall by 25% when thinking aloud. If such problems are normally solved using imagistic processes, verbalisation may impose inappropriate coding.

The Need for Externalisation.

This review started by asking whether diagrams are representations "inside the head", or simply markings in the world. There is ample empirical evidence for image-based mental representations, both visual and spatial, that can be used to carry diagrammatic information. Are external representations even necessary, given these internal strategies? Research on mental models indicates that an illustration can help form an appropriate image when working with abstract information, but does that mean that an external diagram is only of transitory use when encountering a new type of problem?

When We Need an External Image. Evidence for the importance of external representations comes from an experiment by Chambers & Reisberg (1985). Subjects who memorised an ambiguous picture were only able to report one of two possible interpretations on the basis of their memorised image. If they then copied it onto paper, they could immediately see the alternative interpretation. This result has been controversial, as it raises the question of how much the mental image is like a visual image. Chambers (1993) has noted more recently that the ambiguous picture they used must be reoriented for the alternative interpretation. She suggested that orientation information is associated with the image, so the two cannot be separated until the image is externally perceived.

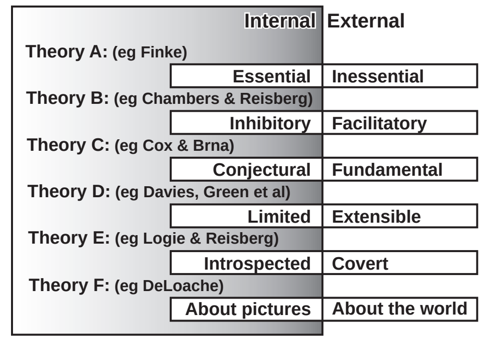

Figure 9 – Alternative theories of externalisation

In an expert domain, Davies (1996) has shown that computer programmers rely on the ability to inspect their own previous productions as they create a program. This supports the *parsing/gnisrap* theory of how external representations are used as a perceptual extension of working memory (Green et al. 1987).

When Internal Images Suffice. The Chambers and Reisberg (1985) result prompted a vigorous response from researchers who believe that mental images must be reinterpretable. Anderson and Helstrup (1993) investigated whether an external representation would improve performance in the Finke creative synthesis task. They allowed half of their subjects to doodle on paper when generating creative combinations. They found that the availability of an external image did not result in improved creativity. This suggests an opposite conclusion from that of Chambers and Reisberg.

Diagrams in Context. There is still much need for investigation and debate on the relationship between diagrams as external representations and internal representations. We know something about the general properties of diagrammatic representations. There is some evidence of how expert diagram users employ external representations. And we are still designing experiments to test the nature and capacity of mental representations. It is already clear that they are far more complex than would be suggested by the imagery debate.

The greatest danger is that we produce cognitive models that account only for the limited evidence from one of these richly interacting streams of investigation. Schwartz (1995) and DeLoache and Marzolf (1992) both provide examples of minor variations that make a critical difference in the ability to use a diagram as an internal representation. Such issues cannot easily be explained by current cognitive theories. In order to address them we need to broaden our scope of enquiry to include cultural conventions, theories of metaphor and pragmatics, and the working practices of the technical specialists who are the largest population of diagram users.

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