

Drawings and the design process

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A characteristic of the design process in all areas of design is the use of a number of different types of drawings. The different types of drawings are associated with different stages of the process with one type, the relatively unstructured and ambiguous sketch, occurring early in the process. Designers place great emphasis on the sketch often because it is thought to be associated with innovation and creativity. Because of this emphasis researchers have also begun to focus on the sketch and its role in design. The first aim of this paper is to collect together and review the results of this research and to relate it to similar research that has looked at the role of drawings in problem solving in other disciplines. Recently, however, researchers in the design area have begun to relate their work to a number of areas of research in cognitive psychology and cognitive science. This work provides theoretical frameworks, experimental methodologies and a considerable body of research results that are of great potential importance to design research. The second aim of this paper is to review three of these areas, working memory, imagery reinterpretation and mental synthesis, and to examine their implications for design research generally but with a particular emphasis on the role of sketching in design. © 1998 Published by Elsevier Science Ltd. All rights reserved

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1 Herbert, D M 'Study drawings in architectural design: their properties as a graphic medium' *Journal of Architectural Education* Vol 41 No 2 (1988) pp 26-38



In the early conceptual stage of the design process, it is typical for an engineer or architect, for example, to use various relatively unstructured forms of pictorial representation such as sketches. As the design develops, other more structured forms of pictorial representation, such as plans or sections, become a part of the process. The use of these forms of pictorial representation have long been considered to be an essential part of the design process and the more unstructured forms to be related to creativity and innovation in design (see, for example Herbert¹). Empirical evidence regarding these beliefs is however relatively sparse. This applies to both the general question of the role that pictorial representation plays

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and the more specific issue of the cognitive processes involved in using such pictorial representations and how they might lead to creative and innovative problem solving. There is also evidence in a number of disciplines outside the design area, such as physics, that expertise and innovation may be closely connected to the appropriate use of diagrams (see, for example, Anzai²). The following discussion has two broad aims. The first is to review the available empirical evidence regarding drawing in the design disciplines and that regarding the use of diagrams in non-design disciplines to identify underlying themes present in each area and similarities and differences between the two sets of disciplines. The second is to review recent research in cognitive psychology relating to working memory, imagery and mental synthesis. These areas provide insights into possible cognitive processes that could be associated with the use of pictorial representations in problem solving in the design area.

1 Drawings and diagrams in design and other problem solving areas

1.1 Drawing and design

In those disciplines concerned with the design of objects or artifacts, there has been a long tradition of using drawings and other pictorial forms as part of the design process. This can involve the use of quite abstract diagrams, such as functional diagrams or sketch plans and sections, in the early part of the design process, together with unstructured forms of pictorial representation such as sketching. In addition, less abstract and more realistic visual representations such as perspectives may also be employed. In the later part of the process highly structured and detailed representations are used to document a design that has been developed. Designers also spend considerable time looking at representations of previous designs that act as precedents in the design process. However, little attention has been paid until recently to the function that such representations have during design and the cognitive processes that are involved in their use. In effect the process of developing pictorial and diagrammatic representations has traditionally been treated as a skill rather than an essential part of the process of thinking about a design problem and developing a design solution.

There has been some work however that has begun to indicate what role these pictorial representations may play in design. Gross *et al.*³ argue that drawings, as they are used in the early part of the architectural design process, are important because they embody abstract and high level design ideas; they allow a degree of uncertainty about particular physical attributes to exist and they impose constraints. The focus of this paper was, however,

2 Anzai, Y Learning and use of representations for physics expertise. In Ericsson, K A, Smith, J (eds) *Toward a general theory of expertise: prospects and limits* Cambridge University Press, New York (1991) pp 64–92

3 Gross, M D, Ervin, S M, Anderson, J A and Fleischer, A 'Constraints: knowledge representation in design' *Design Studies* Vol 9 No 3 (1988) pp 133–143

on the development of computer support for producing these types of drawings and no empirical evidence is presented in relation to these claims. Herbert¹ identifies the capacity of architectural sketch drawings to provide a graphic means for adding information from cognitive experience, that is conceptual knowledge, and for recalling and manipulating visual representations or images relevant to the solution of design problems as the reasons for the importance of drawing. While examples of sketches are used as illustrations of the ideas put forward, again no systematic empirical evidence is reported. There have however been a small number of recent empirical studies that have focused on or indirectly yielded information about the role of drawing in design.

In a series of papers, Goldschmidt⁴⁻¹⁰ has carefully analyzed protocols of design sessions involving novice and expert architectural designers. From this material Goldschmidt has developed both a model of the design process generally, the role that sketching plays within the process and the psychological processes that could be supporting the observed design activities. She divides the design process into 'moves' and 'arguments'. 'Moves' divide a stream of design activities in a protocol into the smallest units or chunks of design reasoning present, that is '... a coherent proposition pertaining to an entity that is being designed' (Goldschmidt⁵, p 125). 'Arguments' are related to a particular design move and are statements about the design or aspects of it. Sketching activities can be related to moves in terms of whether there is active sketching within a move, whether the designer is thinking about a sketch and 'reading off' a sketch, that is deriving information from a sketch or whether the designer is reasoning without the involvement of sketching activity. Arguments within moves can be of two types—'seeing as' and 'seeing that'. 'Seeing as' is directly linked to sketching because it involves the designer in 'seeing' figural properties in the sketch, that is in reinterpreting the figural properties of the sketch or what can be referred to as the emergence of new figures within the current figural interpretation of the sketch. Arguments involving 'seeing that' are non-figural statements about the design. Analysis of the design protocols revealed that 'seeing as' and 'seeing that' arguments alternated and further that all 'seeing as' arguments were made while sketching and 'seeing that' statements were made both while sketching and while examining a sketch. Goldschmidt then argues that this dialectic between the two types of argument and its relationship to sketching allows the designer to bridge between two core facets of design. On the one hand the design process has to result in a sufficiently specified and coherent physical object. Conversely, statements about what is to be designed and the knowledge that is relevant to it take the form of abstract, conceptual, propositional knowledge which is without specific physical referents. The dia-

4 Goldschmidt, G 'Problem representation versus domain of solution in architectural design teaching' *Journal of Architectural and Planning Research* Vol 6 No 3 (1989) pp 204–215

5 Goldschmidt, G 'The dialectics of sketching' *Design Studies* Vol 4 (1991) pp 123–143

6 Goldschmidt, G 'Serial sketching: visual problem solving in designing' *Cybernetics and Systems: An International Journal* Vol 23 (1992) pp 191–219

7 Goldschmidt, G On figural conceptualization in architectural design. In **Trappl, R** (ed.) *Cybernetics and systems research '92* Vol 1 World Scientific, New Jersey (1992) pp 599–605

8 Goldschmidt, G Visual analogy in design. In **Trappl, R** (ed.) *Cybernetics and systems '94* Vol 1 World Scientific (1994) pp 507–514

9 Goldschmidt, G 'On visual design thinking: the vis kids of architecture' *Design Studies* Vol 15 (1994) pp 158–174

10 Goldschmidt, G Visual displays for design: imagery, analogy and databases of visual images. In **Koutamanis, A, Timmermans, H, Vermeulen, I** (eds) *Visual databases in architecture: recent advances in design and decision-making* Averbury, Aldershot (1995) pp 53–76

lectic process ‘... allows the translation of the particulars of form into generic qualities and generic rules into specific appearances’ (Goldschmidt⁵, p 139).

In addition to this thoughtful analysis, Goldschmidt, in this series of papers, also presents an argument, again based on her analysis of the design protocols, about the psychological processes that lie behind and bring about these various characteristics of the design process. At the heart of her model is a necessary consequence of the nature of design problems alluded to in the preceding discussion. While it is well recognized that design problems are ill-defined, ‘insight’ problems^{11,12}, they are different to other types of ill-defined problems. While there may be many possible solutions to a particular problem, the designer has to arrive at a single, realizable physical artifact. However this occurs in a situation where the constraints on the problem are both not exhaustive (the typical case for ill-defined problems) but also contain little information about specific materials, forms and their arrangement that can be used to produce a realizable physical artifact. Perhaps the central problem facing the designer therefore is how to generate, develop and test relevant physical forms. Goldschmidt argues that long-term memory contains both relevant conceptual knowledge and knowledge about previously analyzed and experienced examples or precedents. She proposes that these precedent examples are used to create images of possible physical forms relevant to the specific problem. However the complexity of the majority of design problems and the need to explore the relationship of the image generated from long-term memory to the particular problem means that it would be difficult to perform the required operations entirely in the ‘mind’s eye’. Goldschmidt argues that sketching provides a particularly effective procedure for dealing with these aspects of the design process. Sketches externalize the content of an image at a particular point in time and consequently act as an external memory aid as proposed by Simon¹³. Sketches however are relatively unconstrained and ambiguous (although they can be more or less ambiguous) and consequently allow for new ways of interpreting the sketch of an image to emerge. These new ways of seeing a sketch then result in a new sketch or in accessing different material from long-term memory which then produces a new sketch. Sketching therefore is linked to the formation of images that provide a starting point related to a possible physical form and a way of developing that form. Goldschmidt then suggests, again on the basis of a careful analysis of a number of protocols, that the images are generated from material in long-term memory through essentially an analogical reasoning process. In contrast to many analogies however they are basically visual rather than conceptual in character; that is configurational properties are transferred from the base analogue (the precedent material) to the target, which is the specific problem being dealt with.

11 Simon, H A ‘The structure of ill-structured problems’ *Artificial Intelligence* Vol 4 (1973) pp 181–201

12 Hayes, J R *The complete problem solver* 2nd edn Lawrence Erlbaum, Hillsdale NJ (1989)

13 Simon, H A *The sciences of the artificial* MIT, Cambridge MA (1981)

Schon and Wiggins¹⁴ presented a similar view of the role of sketching in architectural design. Based on the analysis of a number of design protocols, these authors suggest that sketching presents a visual display which can potentially be perceived in different ways; that is the sketch can be reinterpreted. These perceptual reinterpretations or discoveries then produce a drawing episode with the protocols appearing to indicate that the drawing is based on the image in the 'mind's eye' that resulted from the reinterpretation of the original image. Reinterpretations also often have unintended as well as intended consequences in terms of more abstract aspects of the design problem. For example sketches may have implications for functional aspects of the design, which are only appreciated after the perceptual reinterpretation has been drawn. Perceptual reinterpretations are referred to as moves while the judgements of the consequences and implications of the move are referred to as 'seeing'. The authors consider these unintended consequences of a move as giving the designer access to other domains of their knowledge that are relevant to the design being worked on but which were not a part of the designer's thinking at the time the move was made. Schon and Wiggins¹⁴ argue that design consists of sequences of seeing–moving–seeing with the unintended consequences of moves allowing the designer to bring more and more facets of their knowledge into conscious thought allowing them to handle the complexity associated with ill-defined problems. They argue that it is the interconnectedness between the various domains of knowledge relevant to a design that brings the unintended consequences of a move into consciousness and that it is the degree of interconnectedness which differentiates between expert and novices design knowledge. This conception is very similar to Goldschmidt's 'seeing as' and 'seeing that' episodes linked together in a dialectic process.

Goel¹⁵ presents evidence, again based on protocols of design sessions, relating to both the overall design process and to the specific role of sketching within that process. In a first experiment, Goel collected protocols of design sessions involving participants from three disciplines—architecture, mechanical engineering and instructional design. Analyses of these protocols, where the problems from all disciplines are ill-defined, were compared to protocols from the existing problem solving literature involving well-defined problems. The analysis of the design and nondesign protocols demonstrated that they were different on a number of criteria:

- design in contrast to the solving of well-defined problems involved personal stopping rules and evaluation functions;
- few developments of a design involved deductive reasoning;
- changes were made to the problem constraints as given;
- the problem was structured into many modules with few interconnections;

14 Schon, D A and Wiggins, G 'Kinds of seeing and their function in designing' *Design Studies* Vol 13 (1992) pp 135–156

15 Goel, V *Sketches of thought* MIT Press, Cambridge MA (1995)

- the designer has flexibility in determining how the problem was decomposed into modules and how they were connected;
- design involved incremental development of the artifact with limited commitment to any particular facet of the proposal but with propagation of the commitments that were made through the design process;
- problem structuring was distinct from problem solving and involved a quite high proportion of the design session;
- the design process involved several distinct problem solving phases (preliminary design, refinement and detail design)
- the design process involved manipulating two abstraction hierarchies— one involved the level of generality or detail associated with the problem solving phases and the other categories of design development that were considered during the process (people, purposes, behavior, structure and function).

Goel argues that these characteristics of the design process stem from the ill-defined nature of design problems in contrast to the well-defined problems.

Of particular interest in the context of drawing and the design process is the more detailed analysis given of the problem-solving phase of the design process. First, as the design moves from the preliminary stage through refinement to detailed design, there is a marked increase in the level of detail and explicitness of the drawn and written material that is produced; that is, the drawing moves from unstructured sketches to more precise and explicit drawn representations. Second, two types of transformations can be identified in the drawings. There are lateral transformations where there is movement from one idea to a different idea and vertical transformations where one idea is transformed into a more detailed form. Predominantly lateral transformations occur in the preliminary design phases and are associated with unstructured sketches while vertical transformations occur during the refinement and detailed design phases and are associated with more detailed and precise drawings. Goel then performed a second experiment designed to assess why lateral transformations and sketching were characteristic of the preliminary phase of the design process. He argued that sketching constitutes a particular form of symbol system, which is characterized by syntactic and semantic denseness and by ambiguity, and it is these aspects of sketching which allow lateral transformation to occur. This hypothesis was examined by comparing protocols of design sessions where expert graphic designers either solved a problem using sketching or using a computer based drawing system. In contrast to sketching, the computer based drawing system is nondense and unambiguous and should consequently make lateral transformations difficult.

The protocols were coded into episodes, where an episode corresponded to sequences of verbalization associated with a single subgoal and where the subgoal also corresponded to an alternative solution. The drawings and sketches that occurred during each episode were then identified and related to the episode. The drawings accompanying each episode were then coded in terms of the source of the drawing (from long-term memory or from a previous episode); how the drawing was generated (whether it was a new drawing or a transformation of a previous drawing) and whether or not the drawing was reinterpreted. Where drawings originated in a previous episode they were coded in terms of whether they were a variation (whether the drawing was recognizably similar to a previous drawing) or whether they were identical to a previous drawing except for specifiable differences. Transformations could be either lateral or vertical while reinterpretations occur when the meaning associated with a drawing in one episode is subsequently changed. The frequency with which variations occurred was used as a measure of density while the frequency with which reinterpretations occurred was used as a measure of ambiguity. Comparisons between the computer based design sessions and the sketching sessions revealed that there were significantly higher numbers of variations and reinterpretations in the sketching sessions that were associated with larger numbers of lateral transformations. Goel concludes that sketching is associated with preliminary design because it is a symbol system that is dense and ambiguous and consequently facilitates the lateral transformations that are an essential aspect of this phase of the design process.

Suwa and Tversky¹⁶ collected protocols of design sessions from advanced student and expert architectural designers. They differentiated their work on the role of sketching from the research reviewed above on the basis of the focus used to segment the protocols. Schon and Wiggins¹⁴ had noted in their analysis of design protocols that the moves associated with sketching were also associated with the designer bringing into the process previously unused design knowledge from a number of different domains. Suwa and Tversky developed a two level coding of different information categories or domains of design knowledge that were used while sketching in the design sessions. At the highest level were the categories of emergent properties, which included elements depicted in the sketches as well elements that emerged from inspection of the sketches—sub-divided into spaces, things/items, shapes/angles and sizes, spatial relations (local relations or global relations), functional relations (views, lights, circulation of people/cars, other functional relations) and conceptual or background knowledge which was not further sub-divided. The protocols were then divided into segments that concerned the same item/space/topic with each segment being made up of parts relating to the information categories.

16 Suwa, M and Tversky, B
What architects see in their sketches: implications for design tools. In *CHI 96 Companion* Vancouver BC Canada (1996) pp 191–192

Where segments were conceptually related they were grouped to form dependency chunks. The first segment of a dependency chunk was associated with a shift in focus by the designer while the subsequent segments in the dependency chunk were regarded as continuing segments.

The focus of the authors' analysis was the size of the dependency chunks for the students and the experts and the information categories contained within each of the focus shift and continuing segments. For both the student and expert designers the predominant information in the focus shift segments concerned spaces while that in the continuing segments was concerned with local spatial relations. They interpret this result as indicating that the stimulus for shifting focus to a different part of a sketch was finding or seeing spaces while examining local spatial relations was associated with further consideration of related information categories. The two groups of designers differed however, in that the experts had more and longer dependency chunks indicating that the experts were able to retrieve more information, often of an abstract form, on the basis of a focus shift. In focus shift segments the experts considered information about shapes/angles, sizes, circulation and other functional relations more than the students. Suwa and Tversky interpret this result as indicating that the experts began thinking about more complex visual and some functional relations as soon as a focus shift occurred in comparison to the students. By contrast, in the continuing segments, the only difference between the two groups related to functional relations indicating that the experts continued to interpret functional relations as their thinking progressed. The authors conclude that, because the experts were able to think about both perceptual and functional features and relations at the same time, they could pursue the implications of focus shifts more deeply than the students could. For both groups, sketches contained both perceptual and abstract information however the experts could more effectively extract function from perception.

1.2 Themes and issues in protocol studies of the role of sketching in design

A basic theme in this literature is the role that sketches play in reinterpretation; that is, in the emergence of new ways of seeing the perceptual (drawn) representation of a potential design. 'Seeing as' in Goldschmidt's work, 'moves' in Schon and Wiggins, 'lateral transformations' in Goel and 'focus shifts' in Suwa and Tversky all refer to the phenomenon of reinterpretation and emergence. This would also appear to be the basis for what has been referred to as the opportunistic nature of design in contrast to an ordered, deductive design process (see, for example Visser¹⁷). Either

17 Visser, W 'More or less following a plan during design: opportunistic deviations in specification' *International Journal of Man—Machine Studies* Vol 33 (1990) pp 247–278

explicitly or implicitly in this literature, sketches are considered to be based on imagery.

A second theme that can be identified concerns the properties of sketches that bring about the focus shifts. Goel's work identifies two of the basic properties of sketches, their denseness and ambiguity, which are important in the preliminary design phase while more structured forms of drawings are used in the refinement and detailing phases. Similarly Goldschmidt argues that it is the ambiguity and unstructured characteristics of sketches which result in reinterpretation. Although not specifically recognized, one issue that needs attention in this context concerns not just how to sketch but how to sketch in ways that facilitate emergence and reinterpretation—an issue of considerable educational significance.

A third theme concerns the consequences of re-interpretations of sketches. Either during or following sketching, new knowledge becomes part of the problem solving process. This is referred to variously as 'seeing that', 'seeing' or 'continuing thoughts'. This new knowledge significantly involves both new perceptual and abstract or conceptual knowledge.

A fourth theme is that reinterpretation and the examining of the new knowledge produced by such re-interpretation result in further reinterpretations and access to new knowledge; that is, there is a cyclic, dialectic process involved. A particularly significant consequence of this process, recognized explicitly in Goldschmidt, Schon and Wiggins and Goel, is that this is a mechanism that allows two fundamental characteristics of design problems to be addressed. The bringing in of new knowledge, brought about by re-interpretation, is a process that progressively reduces the ill-defined nature of design problems. In addition, where this new knowledge is perceptual in character, it allows the designer to move towards a physical object. This overcomes the problem associated with the fact that abstract, conceptual knowledge relevant to a design does not in itself specify the physical attributes of a designed artifact.

Finally Schon and Wiggins and Suwa and Tversky also consider the issue of expertise. Experts access different types and amounts of knowledge and make more extensive use of this knowledge during episodes of exploring the implications of knowledge brought into the process by re-interpretation. Expert knowledge is considered to vary not only in terms of type, amount and pattern of use but also in terms of its interconnectedness in comparison to novices. This interconnectedness facilitates the experts' access to knowledge in long-term memory.

While these constitute broad themes in the analyses of design protocols, there are also a number of issues that can be identified. The evidence reviewed in a number of design disciplines indicates that relatively unstructured drawing or sketching is important in the early stages of the design process and that more structured types of drawing occur later in the process. However, there is little evidence regarding what is being drawn. There is some anecdotal evidence that sketching is associated with relatively random forms. For example, Alvar Aalto (quoted in Quantrill¹⁸, p 5), in describing his architectural design process, talks about making relatively random pencil marks on paper from which emerge relevant forms and this is a process often described in conversations with designers. In the case of Goldschmidt's⁹ student architectural designer there appears initially to be random drawing activity which then shifts to a structured drawing activity (repeatedly writing the student's name) with the relevance of this drawing for the particular design problem then being noticed. Interestingly this appears to correspond with the results of Finke's¹⁹ experiments, using the mental synthesis task to be discussed subsequently, where a form is first generated via imagery which does not have a specific interpretation and that the meaning and relevance of the form is discovered subsequently. While it is not apparent from Aalto's description what is noticed, in the case of the student it is clear that it is a possible plan for the building. This accords with the results of some of our protocols of architectural design sessions where the forms that are drawn appear to be plans. Initially these plans are ambiguous and dense to use Goel's¹⁵ terms but become more specific as the sessions proceed and are associated with another, related type of drawing—the section. It is only relatively later in the session that more directly representational types of drawing such as perspectives and elevations are used. Broadly this can be seen to be consistent with Goel's results, however more empirical data is needed. Particularly this should involve comparisons between design disciplines. Plans and sections may be the significant types of drawing in architectural design but does this apply to disciplines such as industrial design which involves much smaller scale artifacts or to interior design where perspectives and elevations could be more appropriate or to graphic design which often involves only two dimensions? The question is whether some types of sketching and drawing are more potent in terms of their design implications both at different stages within the design process and between different design disciplines.

18 Quantrill, M *Alvar Aalto: A critical study* Secker and Warburg, London (1983)

19 Finke, R A *Creative imagery: discoveries and inventions in visualization* Erlbaum, Hillsdale NJ (1990) pp 204–244

This issue also is important in relation to three more general issues in the design process. The first concerns the issue of emergence and reinterpretation. If certain types of drawings occur early in the design process, whether they are similar across disciplines or not, is it that the type of

drawing involved is particularly appropriate for facilitating emergence? This can clearly be examined empirically by relating drawing type to the occurrence of emergence. The second general issue concerns the question of expertise. Are expert designers characterized by the use of particular types of drawings when they are compared to novices and is it that learning to use the right type of drawing increases the occurrence of emergence relative to novice designers? This is also potentially related to a difference that has been identified between experts and novices. Katz²⁰ has demonstrated that a key difference between expert and novice architectural designers lies in the experts' ability to recognize key constraints or issues in a particular design situation that must be addressed first. Is it that particular types of drawing facilitate the identification of such constraints? Again, this is an issue which is clearly open to empirical investigation. The third issue relates to the quality of the design outcome. This is a question that has not been generally addressed in the research literature to date and which consequently requires specific attention. Often it appears that there is an implicit assumption in the expert and novice research that experts produce higher quality design outcomes. In the specific context of drawings however, it may be that particular types of drawings are associated with higher quality design outcomes. This in turn poses the question of what is a superior design outcome—a question that would appear to be central to the area. Is it that a superior design outcome is one that is original and/or creative; is it one that meets all of the constraints present in the problem; is it one that both addresses all the constraints in a new and original way for the type of problem or is it one that meets all the constraints in a particularly simple and elegant way? The questions posed by considering the quality of design outcomes are clearly difficult but would appear to require urgent attention as it could be argued that this is a core issue in the field.

There would also appear to be another implicit assumption in much of the work on drawings in design. Is it that drawings are an inevitable and essential part of the design process? Or is it that there may be designers who make minimal use of drawing because they have developed effective means of using imagery to the same end? Is it possible for designers to work entirely on the basis of abstract, conceptual knowledge? This would appear to be unlikely, as it is unclear how they could move to the representation of a specific physical artifact. However it is possible that designers who have difficulty in accessing this type of knowledge, the visually dominated designers, may have difficulty in producing a fully resolved design. It may be that the frequently observed structure of design practices, where a small number of individuals are responsible for the conceptual design while many others develop the idea, is a way of addressing these issues. Different styles

20 Katz, I Coping with the complexity of design: Avoiding conflicts and prioritizing constraints. In Ram, A, Nersessian, N, Recker, M (eds) *Proceedings of the Sixteenth Annual Meeting of the Cognitive Science Society* Erlbaum, Hillsdale NJ (1994) pp 485–489

of designing, how much design can be done without the use of drawings and the effectiveness of such styles are therefore issues that require empirical attention.

1.3 Expertise in solving physics problems

The process of learning how to draw and use diagrams could be at the heart of physics expertise, not only for novice learners but also for expert physicists (Anzai², p 64).

Research into differences between experts and novices in solving physics problems was not initially concerned with questions relating to the use of diagrams. Rather, the emphasis was on the types of knowledge that formed the basis for the reasoning process and the characteristics of the reasoning process itself. For example, experts represented problems in abstract, conceptual terms while novices used naive concepts that were related to the real world (see, for example, Anzai and Yokoyama²¹ and Clement²²). Experts also possess procedural, as well as domain specific knowledge for solving problems. This particularly takes the form of reasoning in a 'forward' way from the information given in the problem statement to the goal while novices use the less efficient 'backward' reasoning strategy from the goal to sub-goals (see, for example, Simon and Simon²³ and Larkin *et al.*²⁴).

Differences were also demonstrated between experts and novices in the way they interpreted diagrams when these formed part of the givens in a problem. In an experiment using hydraulics problems, Larkin²⁵ found that experts and novices used diagrams in qualitatively different ways. Experts solved the problems by interpreting the associated diagrams to compare the initial and final states attempting to reduce the difference between those states in particular spatial ways. By contrast, novices attended to particular local features in the diagrams. In a subsequent experiment, Larkin and Simon²⁶ argued that expert reasoning used two forms of representations of a problem. One was sentential or conceptual representations of physics knowledge while the other was 'imagerial' representations in the 'minds eye' (Kosslyn and Koenig²⁷) which could then be externally represented in the form of diagrams. Larkin and Simon²⁶ suggest that such visual forms of representation lead to a more computationally efficient search for information relevant to solving problems because of the two dimensional, spatial structure of diagrams. That is, the diagrams allow the direct discovery of relevant spatial information for the solution of the problem.

Further clarification of the role of diagrams in solving physics problems can be found in Anzai². On the basis of the results of an experiment where

21 Anzai, Y and Yokoyama, T
'Internal models in physics problem solving' *Cognition and Instruction* Vol 1 (1984) pp 397-450

22 Clement, J 'Students' pre-conceptions in introductory mechanics' *American Journal of Physics* Vol 50 (1982) pp 66-71

23 Simon, D and Simon, H A
Individual differences in solving physics problems. In **Siegler, R** (ed.) *Childrens' thinking: what develops?* Erlbaum, Hillsdale NJ (1978) pp 325-348

24 Larkin, J, McDermott, J, Simon, D P and Simon, H A
'Expert and novice performance in solving physics problems' *Science* Vol 208 (1980) pp 1335-1342

25 Larkin, J H The role of problem representation in physics. In **Gentner, D, Stevens A L** (eds) *Mental models* Erlbaum, Hillsdale NJ (1983) 75-97

26 Larkin, J H and Simon, H A
'Why a diagram is (sometimes) worth 10 000 words' *Cognitive Science* Vol 11 (1987) pp 65-79

27 Kosslyn, S M and Koenig, O
Wet mind: the new cognitive neuroscience The Free Press, New York (1992)

a novice repeatedly solved a set of physics problems and a review of the relevant literature, Anzai proposed that diagrams have two functions in this domain. First, diagrams allow generalizations of possible relations between abstract entities. Second, diagrams can be used to represent specific problems for specific goals. This allows recognition of the underlying structure of the problem and the organization of computationally efficient inference procedures for solving the problem. He suggests that the dominant factor for the development of expertise is the co-ordination of recognition and inference. Recognition leads to the recall of relevant, often abstract, knowledge from long-term memory while the availability of appropriate procedures leads to the efficient and effective use of this knowledge. The co-ordination between the two, he suggests, is closely related to the ability to develop effective diagrams. Both the ability to draw diagrams and to co-ordinate recognition and inference using diagrams is learnt during the development of expertise and is a critical aspect of expertise.

1.4 Diagrams and expertise in related disciplines

The importance of diagrammatic representations in reasoning and problem solving has begun to receive attention in a number of other disciplines. Tabachneck *et al.*²⁸ reported experiments comparing the performance of experts and novices in using diagrams to solve economics problems and to explain the solutions obtained. Novices were found to have difficulty in integrating pictorial information in the form of graphs and verbal, semantic information. Inferences for the novices were shallow and novices often failed to notice relevant features of the graphs. Experts, however, used multiple representations easily and frequently. For example, when asked to explain how to solve a problem, the experts spontaneously used both verbal and graphical representations and the two were closely integrated. Experts had learned to notice the relevant features of the graphs; they possessed the relevant inference operators and could translate back and forth between the operators and their economic interpretations. Both the results with the novice and expert economic problem solvers therefore parallel a number of the significant aspects of the findings in the physics problem solving literature.

Kindfield²⁹ has also demonstrated parallels between problem solving in physics and biology. Using problems in meiosis, Kindfield found that, where specific knowledge relevant to the problem was present, experts routinely generated fine tuned diagrams that included the knowledge and used both to complete the task. Further, diagrams in which relevant knowledge is represented were found to cue the recognition of the relevance of that knowledge to the immediate reasoning situation. Kinderfield explicitly notes the parallel between Larkin and Simon's²⁶ work on physics problem

28 Tabachneck, H J, Leonardo, A M and Simon, H A How does an expert use a graph? A model of visual and verbal inferring in economics. In Ram, A, Eislet, K (eds) *Proceedings of the 16 th Annual Conference of the Cognitive Science Society* Erlbaum, Hillsdale NJ (1994) pp 842-847

29 Kindfield, A C H Expert diagrammatic reasoning in biology. In *AAAI Spring Symposium on Reasoning with Diagrammatic Representations* Stanford University, California (1992) pp 41-46

solving and the solving of meiosis problems. Experts used diagrams as information storage devices to overcome the limits of working memory and the diagrams facilitated problem solving by grouping information spatially and supporting perceptual inferences through the display of features and relationships essential to problem solving. Further the diagrams cued information not initially represented in the diagram. In contrast to the experts, novices tended to either overspecify their diagrams by representing what they knew best regardless of its relevance to the problem or to underspecify their diagrams by leaving out components relevant to the immediate reasoning task.

This overview of research relating to the use of diagrams has revealed a number of aspects of the problem solving process, which are similar across quite diverse domains. In summary, problem solvers must: (i) recognize the underlying structure of the problem and the relevant theoretical, conceptual knowledge; (ii) generate representations such as graphs and diagrams appropriate for discovering solutions, and (iii) make inferences from these representations using appropriate, efficient strategies such as working forward. While these are identified as critical aspects of the reasoning and problem solving process, it has also become apparent that it is essential that the various aspects be closely integrated. Kindfield²⁹, for example, argues that conceptual, abstract knowledge *coevolves* with skills in producing and using diagrams. The term *coevolution* is used to refer to the way in which abstract knowledge and diagrammatic skills mutually influence one another in the development of understanding. In this situation meaningful understanding includes specific knowledge about processes and entities, together with knowledge about domain specific diagrams and the procedures for and the utility of using such diagrams in solving problems. As has frequently been noted anecdotally in the design area, both drawing skills and the effective use of drawings in problem solving in these non-design disciplines has to be taught.

1.5 Diagrams and drawings in problem solving

Is the use of diagrams in solving problems in physics, economics and biology the same as the use of drawings in the design disciplines? From the preceding discussion there appears to be a number of important similarities between the use of diagrams and drawings. Perhaps the most consistent finding in the design area is that drawings are associated with reinterpretation or the emergence of new ways of seeing the drawing. This is also a fundamental aspect of the use of diagrams. Relevant features are noticed or recognized from a diagram once it is drawn—a process very similar to the reinterpretation of drawings in design. The consequences of reinterpretations appear to be the same for diagrams and drawings. In both cases,

reinterpretation cues access to other relevant knowledge and allows inferences to be made. This can be in the form of conceptual, abstract knowledge which is then integrated into the diagram or drawing. In the case of drawings the knowledge accessed can also be perceptual and associated with the physical attributes of the design represented in a drawing. It is not clear from the research in the non-design disciplines whether there is a similar accessing of perceptual knowledge associated with diagrams although some of the discussion appears to indicate that inferences are made about other forms of diagrammatic representation. This is also indicated by the way in which diagrams are used in the sequential development of a solution to a problem. The idea of coevolution in solving biological problems would appear to be very similar to the dialectic process that operates in solving design problems. Finally the differences between experts and novices are similar in both the design and non-design areas. There appears therefore to be quite striking parallels between using diagrams and drawings in solving problem in many different areas.

2 Working and long-term memory

The results of the recent research on the role of drawing in design indicate that there is a recursive sequence of activities involving thinking, imagery, drawing and reinterpretation and the accessing of different types of knowledge in long-term memory. Such a description of the design process closely parallels current models of the role of working memory in thinking and problem solving. These models are now reasonably well articulated and consequently can provide a theoretical context within which to develop the insights that are beginning to emerge from protocol studies of the design process. In addition, there are two areas of research related to the models of working memory that provide potential insights into and ways of exploring the role of imagery and sketching in the design process. These are the reinterpretation of images of perceptually ambiguous figures and the mental synthesis of forms. The following discussion reviews the models of working memory and the results of research in these two areas and examines their implications for the design process generally and for the role of drawing in design. In the discussion of each area some details of the experimental procedures used are included. There are two reasons for this. First, for those unfamiliar with these areas of cognitive psychology, it provides information about how the findings discussed were generated and gives, for those who are interested in reading in the area themselves, at least some familiarity with the ways of thinking and the methodologies employed. Second, we believe that these methodologies provide possible ways of experimentally examining some of the findings of existing protocol studies. Consequently such experimental studies may constitute one of the next steps forward in the area.

In what has come to be regarded as one of the seminal papers in cognitive psychology, Miller³⁰ demonstrated that the capacity of short-term memory was limited to seven plus or minus two chunks of information. This contrasted markedly with what appeared to be the very large capacity of long-term memory. This finding formed one of the corner stones of what became an equally important theory of problem solving developed by Newell and Simon (see for example Newell and Simon³¹, Simon¹³ and Ericsson and Simon³²). In brief, this model proposes that problem solving consist of a set of cognitive processes which occur in short-term memory. In response to a problem presented in the environment external to the organism, a representation of the problem is constructed in short-term memory. Knowledge and procedures relevant to solving the problem are retrieved from long-term memory and used in short-term memory. Subsequently Baddeley and co-workers (for a summary see Baddeley³³, Jonides³⁴ and Logie³⁵) developed this view of the role of short-term memory in problem solving to include other types of cognitive activity including the formation of images. Given its limited capacity, this model proposes that the majority of cognitive activities, such as thinking and problem solving, are too complex for all aspects to be processed and held in short-term memory. This is a consequence of the rapid decay of material held in short-term memory. The model proposes that any complex cognitive activity requires sequential processing with the results of earlier stages in the process needing to be held for use in subsequent stages. In addition, knowledge and procedures drawn from long-term memory need to be held in a way that keeps them available for ongoing processing. This is necessary for the efficiency of the cognitive activities given that retrieval of material from long-term memory is relatively slow (see Newell and Simon³¹ and Simon¹³). In order to deal with these issues, Baddeley's model proposes that the cognitive activities directly involved in thinking and problem solving occur in what is referred to as the central executive with the partial results of these processes and needed material from long-term memory held separately in stores or caches. However, because of the rapid decay of material in short-term memory, it is necessary that what is temporarily stored in the caches, needs to be refreshed to be retained. Given the greater articulation of the architecture of short-term memory in this model relative to the earlier work, this form of memory is now referred to as working memory.

This model of working memory was developed largely on the basis of research in audition. Given the limited capacity of working memory, in order to produce coherent speech it is necessary, for example, to store words that are retrieved first from long-term memory so that subsequent words can be retrieved and processed in the central executive. This is referred to as the phonological store, buffer or cache. The words that are

30 Miller, G A 'The magical number seven, plus or minus two: some limits on our capacity for processing information' *Psychological Review* Vol 63 (1956) pp 81–97

31 Newell, A and Simon, H A *Human problem solving* Prentice-Hall, Englewood Cliffs NJ (1972)

32 Ericsson, K A and Simon, H A *Protocol analysis* MIT Press Cambridge MA (1984)

33 Baddeley, A D 'Is working memory working? The fifteenth Bartlett lecture' *Quarterly Journal of Experimental Psychology* Vol 44A (1992) pp 1–31

34 Jonides, J Working memory and thinking. In **Osherson, D N, Smith E E** (eds) *An invitation to cognitive science* Vol 3 MIT Press, Cambridge MA (1995) pp 214–266

35 Logie, R H *Visuospatial working memory* Erlbaum, Hillsdale NJ (1996)

stored should be able to be quickly retrieved because of the relatively long time it takes to retrieve material from long-term memory, however it is also know that material held in working memory decays rapidly. Consequently there must be a mechanism that allows refreshing of the material that is held in the phonological cache. In the case of audition this involves rehearsal via sub-vocalization, essentially talking to oneself. That there are these two aspects of what has come to be called the phonological loop has been amply documented using a particular experimental technique. If there are these two aspects to the phonological loop it should be possible to interfere selectively with each. For example, if an individual is required to memorize a list of words that is beyond the capacity of the working memory system, the earlier parts of the list will have to be held in the phonological cache and rehearsed. If the rehearsal component is interfered with by having participants sub-vocalize irrelevant material, memory performance should be poorer than where they perform an irrelevant task. This is found to be the case and is paralleled by similar results where procedures are used to interfere with storing material in the phonological cache but not the rehearsal process. The results of these experiments using the double dissociation technique have provided a considerable body of evidence for the reality of the phonological loop as a component of working memory.

However, complex thinking and problem solving does not only involve the manipulation of verbal material. Planning a route through a city, imagining how an object or artifact such as a building would look from a different position or counting the number of windows in your home appear to be tasks which would be very difficult to accomplish using words alone. Similar research to that carried out in relation to hearing provides evidence that there is a similar system involving vision, referred to as the visuo-spatial sketch pad. Further there is now evidence that there are two visual systems of this type. The one that has received the most research attention to date is a spatial system where spatial information is stored and possibly rehearsed via implicit movements, for example imagining moving through an environment or imagining manipulating an object. The second visual component of working memory would appear to be associated with non-spatial visual properties such as color. There is also evidence (see Kosslyn³⁶) that this type of information is used to construct visual imagery which is an integral part of this type of thinking and problem solving. While these auditory and visual components of working memory have received experimental support, it is now argued that there should be similar systems associated with the other senses and, given that processing in the central executive involves semantic, conceptual and propositional aspects, there may be a similar mechanism that allows storage and retrieval of this type of information.

36 Kosslyn, S *Image and mind*
MIT Press, Cambridge MA
(1980)

While these storage and rehearsal mechanisms for the products of thinking and problem solving have received considerable experimental attention, there is less evidence concerning the central executive part of the system. At least two functions have been identified for the central executive. Given that complex thinking often involves goals and sub-goals, there must be a mechanism that monitors progress in these terms. Similarly there must be a mechanism that orders the sequence with which goals and sub-goals are attended to. These monitoring and scheduling functions are attributed to the central executive component of working memory. However, in a recent paper Shah and Miyake³⁷ present a somewhat different view of the architecture of working memory. They argue that the Baddeley model is one where the central executive is concerned with processing and the articulatory loop and visuo-spatial sketchpad are peripheral in the sense that they are passive stores. The model as a result deals with working memory as involving both processing and storage of the results of processing together with passive storage systems such as the phonological loop with the limits on working memory being associated with the total amount of cognitive resources associated with working memory. Shah and Miyake³⁷ pose the general question of whether working memory consists of one pool of activation or cognitive resources that can be allocated between different functions or a number of pools each associated with particular processes and representations. They argue that the latter is the appropriate model in contrast to the more traditional model. Further they argue that the dual task methodology has addressed the role of essentially peripheral sub-systems and that there is evidence that these sub-systems have a relatively limited, passive storage role in complex cognitive activities.

Shah and Miyake³⁷ developed a quite different methodology to the double dissociation technique used in much of the working memory research. The logic of their approach was as follows: if measures of spatial and verbal working memory predict performance on spatial visualization and language tests equally well, this would provide evidence for a single pool of general resources. However, if a measure of spatial working memory only predicts performance on tests involving spatial visualization abilities and measures of verbal working memory predict performance on tests of verbal abilities, such a pattern would be evidence for the separability of cognitive resources in working memory at a higher level than that involved in the peripheral phonological loop and visuo-spatial sketch pad. The measures of verbal and spatial working memory involved verbal and spatial memory span tests. The verbal memory span task was the standard task involving reading span. In this test participants read aloud a set of unrelated sentences and then have to recall the final word in each sentence at the end of each set. The number of sentences included in a set is manipulated and the verbal

37 Shah, P and Miyake, A 'The separability of working memory resources for spatial thinking and language processing: an individual differences approach' *Journal of Experimental Psychology: General* Vol 125 (1996) pp 4-27

span is the number of words at the end of each sentence that can be recalled correctly. This task requires that verbal information be simultaneously processed and stored. The spatial span task was specifically developed as an analogue of the verbal span task. Participants were presented with sets of varying size consisting of English capital letters and their mirror images with the letters also being rotated to one of seven possible orientations. Participants had to identify whether the letters were normal or mirror images while keeping track of the orientation of the letters. At the end of the letter sequence participants had to recall the orientation of each letter in the sequence by indicating where the top of each letter was located. The spatial span was the largest letter set where the orientations were correctly recalled. The task involves simultaneous spatial processing and storage in a similar way to the verbal span task. The visual and spatial span scores were correlated with scores on tests of spatial visualization and verbal ability. The pattern of correlations demonstrated that spatial span was consistently correlated with the results of the spatial visualization tests and not with the results of tests of verbal ability while the reverse pattern was found with the verbal span tests. These results are consistent with a model where both processing and storage occur together, in contrast to earlier working memory models, and that there are separate pools of cognitive resources allocated to each. However these authors also argue that there are relatively passive, short-term stores such as the phonological loop and the visuo-spatial sketchpad and that there are also general purpose cognitive resources associated with central executive functions such as goal management and scheduling.

2.1 Working memory and design

One of the central concerns in the Newell and Simon (Newell and Simon³¹ and Simon¹³) analysis of human problem solving were the issues raised by the limits on short-term memory. When the complexity and/or size of the problem is such that it exceeds these limits, Newell and Simon^{13,31} propose that the problem is broken up or decomposed into sub-problems with problem solving occurring incrementally, that is short-term memory involves sequential or serial processing. In addition, external memory aids, such as written material, drawings and diagrams, are used. Decomposition, serial processing and the use of external memory aids are, as a result, ways in which the load on working memory can be reduced. The first two of these aspects of short-term memory also form a part of the subsequent models of working memory. Perhaps more clearly articulated in these models however is the concept of central executive processes that draw knowledge and procedures from long-term memory relevant to the particular task type involved, together with more general knowledge related to task management, scheduling and planning.

Design problems would appear, and have been considered by Simon¹³ to be, of a complexity and size that would exceed the capacity of working memory. This can be seen to be a consequence of the fact that the design of artifacts involves the manipulation of perceptual/spatial information, the use of conceptual knowledge from a considerable number of disciplines together with knowledge about procedures specific to design problem solving. For example, design involves the use of visual information concerning materials and their colors and textures and other properties, conceptual knowledge relating to structure, manufacture or construction, to functions and activities and to the ways in which users will interact with and experience the artifact being designed. Consequently it can be argued that design problem solving should exhibit decomposition, sequential processing and the use of external memory aids. Similarly the design process should involve planning and goal management indicative of these aspects of the central executive component of working memory.

The results of a number of protocol studies of design are consistent with these possibilities. Goel¹⁵, for example, identifies four stages in the design process—problem structuring, preliminary design, design refinement and detailed design and this type of organization has been recognized in many other protocol studies in a variety of design domains (Lloyd and Scott³⁸ and Purcell *et al.*³⁹). The design process therefore appears to be decomposed into a number of macro segments. However the decomposition appears to involve different types of reasoning and thinking at the different stages. An interesting issue, in the context of both design and working memory generally, resulting from this finding concerns the basis for this particular organization of the decomposition of the problem. These results also demonstrate that the design process involves sequential processing at the macro scale in that the type of thinking and reasoning involved at each stage differs. Design problem solving further demonstrates both decomposition and sequential processing at a smaller scale. For example, Purcell *et al.*³⁹ identified cyclic, systematic variation through time in terms of a number of aspects of the analysis, synthesis and evaluation of different aspects of the solution to an industrial design problem. The now well-documented phenomenon of focus shifts and the characteristics of subsequent problem solving activities discussed in the preceding sections can also be seen to be another facet of decomposition and sequential processing. Similarly there is evidence in this literature regarding the central executive in working memory. Purcell *et al.*³⁹ found brief episodes of goal management and planning interspersed between the other types of problem solving activity. Analyses of the content of designer's thinking, such as those conducted by Suwa and Tversky¹⁶, also identify the use of abstract, conceptually based and verbally coded material and visual, perceptual material with the use of

38 Lloyd, P and Scott, P 'Difference in similarity: interpreting the architectural design process' *Environment and Planning B: Planning and Design* Vol 22 (1995) pp 383–406

39 Purcell, A T, Gero, J S, Edwards, H M and McNeill, T The data in design protocols: The issue of data coding. In *Analyzing design activity: the Delft protocols workshop* Faculty of Industrial and Design Engineering, Delft Technical University, The Netherlands (1994) pp 169–187

these different types of material alternating. This possibly indicates that the different types of material are being drawn into central executive processing from the phonological loop or the visuo-spatial sketchpad or that there is switching between two pools of resources associated with the different types of processing as in the Shah and Miyake³⁷ model.

It is also clear from the design research that external memory aids are used in the design process. Books and other written material are consulted, written notes are made during the problem solving process, as are drawings of various types (see, for example, many of the chapters in Cross *et al.*⁴⁰). However the design research reviewed above indicates that not all of these act only as external memory aids. Drawings, or at least certain types of drawings, serve the function of allowing shifts in attention resulting in new ways of interpreting the problem. Drawing could also be thought of as playing a role in decomposition. For example, relatively unstructured drawings that are space defining but without dimensions, such as bubble diagrams and some plans in architecture, essentially focus on and therefore decompose the problem into one of spatial relations. The issue of when the different types of external memory are used during the design process, the events that lead to their use and the relationship between focus shifts and these various forms of external memory are all issues of considerable interest in the context of design. However they are also significant in the context of models of working memory generally. External memory in general and drawing in particular appears not to be a part of current working memory models. The fact that sketching and other forms of drawing appear to be an integral part of the cognitive processes in design poses the question of how drawing fits into these models. Some insights into possible answers to this question can be derived from a consideration of two further areas of research—the reinterpretation of images of ambiguous figures and the mental synthesis of forms.

Before turning to this literature it is worth highlighting another aspect of the research on working memory, particularly the work of Shah and Miyake³⁷. It has often been anecdotally observed that designers are visual and not verbal people. In the context of Shah and Miyake's view that there is an overall limit on the cognitive resources available to working memory and that these are predominantly divided between visuo-spatial and verbal working memory pools, it may be that the size of these pools can vary between individuals. If designers are predominantly visual people then they might be characterized as having a larger pool of visuo-spatial cognitive resources. Shah and Miyake's spatial span test together with the more commonly used verbal span tests could be used to assess this possibility. Further there is evidence (see, for example, Abercrombie *et al.*⁴¹) that

40 Cross, N, Christiaans, H and Dorst, K (eds) *Analyzing design activity* John Wiley and Sons, New York (1996)

41 Abercrombie, M J L, Hunt, S and Stringer, P *Selection and academic performance of students in a university school of architecture* Society for Research into Higher Education, London (1969)

ability tests do not perform well in predicting success in a design education. However the span tests are effectively different to, although they correlate strongly with, the relevant ability tests. The difference would appear to lie in the fact that the span tests are tests of processing and storage in working memory. This difference may make these tests effective in predicting performance at the beginning of a design education and examining whether a design education results in shifts in the allocation of resources between different working memory pools.

Finally, the limits on working memory also provide a way of thinking about and researching a phenomena that has been commented on anecdotally and also recognized in the literature. Conversations with designers often reveal that they are looking for an organizing principle or concept around which to develop the design—a ‘big’, ‘simple’ idea (see for example the interviews with a number of leading architects in Lawson⁴²). Cross and Clayburn Cross’s^{43,44} work has also identified the same type of phenomenon in other areas of design. While the ‘big’ idea is often associated with original and creative outcomes, it could be that it is another way in which the load on working memory can be reduced. A central organizing idea could be held in working memory with other aspects of the problem being dealt with sequentially in relation to this central idea. Using drawings to, in effect, expand working memory could further augment this approach to or style of designing. It may be that the reason why the ‘big’ idea often produces better design outcomes lies in the way in which the effectiveness of working memory is maximized. To summarize, the general working memory model therefore provides a rich conceptual framework within which many aspects of the results of protocol research can be understood. At the same time the richness of the phenomena researched in the design context add to the understanding of these aspects of working memory and equally have great potential for making further contributions in this area.

3 *The role of imagery in creativity and discovery*

Two research areas that relate imagery to creativity and discovery are relevant to the question of the role of drawings in the design process. The first grew out of the debate, in cognitive psychology, about whether the image of an object is functionally equivalent to the direct perception of the same object (see, for example, Pylyshyn⁴⁵, Shepard and Cooper⁴⁶ and Kosslyn⁴⁷). The second involves the use of a mental synthesis task where participants are asked to form an image from three randomly selected simple shapes. The following discussion presents a summary of the results of this research and then explores their implications for the design process.

42 Lawson, B *Design in mind* Architectural Press, Oxford (1997)

43 Cross, N and Clayburn Cross, A ‘Winning by design: the methods of Gordon Murray, racing car designer’ *Design Studies* Vol 17 (1996) pp 91–107

44 Cross, N and Clayburn Cross, A Expert designers. In *Darmstadt Symposium: Designers—The key to successful product development* Springer-Verlag, London (1998) forthcoming

45 Pylyshyn, Z W ‘The imagery debate: Analogue media versus tacit knowledge’ *Psychological Review* Vol 88 No 1 (1981) pp 16–45

46 Shepard, R N and Cooper, L A *Mental images and their transformations* MIT Press, Cambridge MA (1982)

47 Kosslyn, S M *Image and brain: the resolution of the imagery debate* MIT Press, Cambridge MA (1994)

3.1 Reversal of figures in perception and imagery

Central to the work on the relationship between perception and imagery are experiments involving the use of ambiguous figures one of which, the duck/rabbit, is illustrated in Figure 1. When this figure is viewed, one of two possible interpretations is seen. After a period of observing the figure, an uncued, spontaneous reversal will occur to the other interpretation. It is a characteristic of these figures that the two interpretations cannot co-exist. The experiments exploring the similarity between perception and imagery used the reversal phenomenon that occurs unambiguously in perception and asked the question whether similar reversals are found when images of an ambiguous figure are formed. Perhaps the key experiments in the area were performed by Chambers and Reisberg^{48,49}. They showed participants an ambiguous figure, such as the duck/rabbit, and asked them to close their eyes and form as detailed an image as possible of the figure. Participants were then asked if there was another way in which the image could be interpreted. Image reversals effectively did not occur. However this was not the result of a poor quality image. Participants were able to draw their image in detail and, once the image was drawn, they were able to see the alternative interpretation. This was taken as strong evidence

48 Chambers, D and Reisberg, D 'Can mental images be ambiguous?' *Journal of Experimental Psychology: Human Perception and Performance* Vol 11 (1985) pp 317–328

49 Reisberg, D and Chambers, D 'Neither pictures nor propositions. What can we learn from a mental image?' *Canadian Journal of Psychology* Vol 45 (1991) pp 288–302

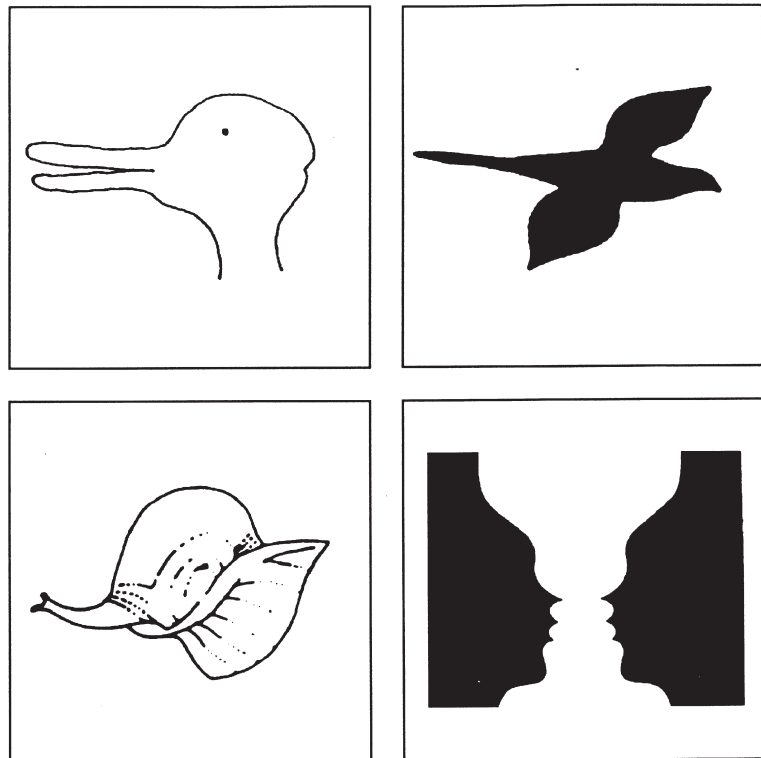


Figure 1 Four reversible figures—the duck/rabbit, the hawk/goose, the snail/elephant and the vase/face

that there were significant differences between perception and imagery and Chambers and Reisberg^{48,49} argued that mental images cannot be reconstructed in the sense that they cannot be separated from their interpretation—images both depict and describe.

Because of the importance of the perception/imagery debate in cognitive psychology, these results generated a large number of experiments designed to determine the conditions under which image reversals do, or do not, occur. While the results of these experiments have considerably clarified the issue, it is a large literature all of which is not directly relevant to the question of the implications of this work specifically for the role of drawings in design and the design process generally. However, there is a subset of the experiments which are relevant because of the particular aspects of the perception/imagery problem that were addressed.

Work on the imagery phenomenon itself has demonstrated that images have a number of properties. In particular images have a detailed area similar to that associated with the foveal representation of an object in perception and images and their parts fade over time and need to be reconstructed or refreshed (for a summary of this work, see Kosslyn^{36,47}). Kaufmann and Helstrup⁵⁰ used these properties of images to argue that the reconstrual of an image was difficult because the parts of the image that were relevant to the alternative interpretation may have faded and not been refreshed. Further they argued that maintaining a detailed image, which is required for reversal, is therefore difficult and may require superior imaging ability. In addition they pointed out that, while there are two interpretations of reversible figures such as the duck/rabbit, other interpretations are possible. In the Chambers and Reisberg⁴⁸ experiments only the duck or the rabbit alternative were scored giving a strict criterion of reversal. It is therefore possible that reversal would be found if other possible interpretations were considered as evidence that reversal had occurred.

In order to assess the role of imagery ability in reversals, Kaufmann and Helstrup⁵⁰ used students from the Norwegian National College of Arts and Design as participants in their imagery reversal experiments rather than psychology students who were typically used in the previous research. All of the students reported that they used visualization processes extensively in their academic and artistic work and all were shown to score above average on a measure of visualization ability. Two reversible figures were used—the duck/rabbit and the chef/dog. The results of the experiment demonstrated that image reversal could occur. Using the strict criterion of the Chambers and Reisberg experiments, the number of reversals of each figure were close to being statistically significant (0.055 in each case). However,

50 Kaufmann, G and Helstrup, T Mental imagery: fixed or multiple meanings. In Roskos-Ewoldson, B, Intons-Peterson, M J, Anderson R E (eds) *Imagery, creative and discovery: a cognitive approach* Elsevier, Amsterdam (1993) pp 123–150

the absolute number of reversals was low (15 and 14% respectively), particularly when compared to the successful reversal of the image when it is drawn. When the criterion for successful reversal was expanded to include alternative possible reversal figures, the number of reversals increased significantly (41 and 28% respectively) although again even the 40% reversal is well short of the 100% reversal using the strict criterion found with a drawn image. High imagery ability therefore resulted in a significant number of reversals and the production of alternative, possible reversal interpretations.

Peterson and her co-workers (Peterson, Kihlstrom, Rose, and Glisky⁵¹ and Peterson⁵²) identified two other aspects of the Chambers and Reisberg experiments, which could have limited reversals in imagery. They argue that there are three types of reversal present in the various figures used in Chambers and Reisberg's work. One involves reference frame reversals where the top and bottom or the front and back of the figure must be reversed for the alternative figure to be seen. For example, the duck/rabbit figure involves seeing the duck's beak as the rabbit's ears—a front/back reversal as does the goose/hawk figure also shown in Figure 1. Other figures such as the snail/elephant in Figure 1 involve a reconstrual of the image—a change in the meaning of parts or the componential structure of the figure which may or may not be associated with reference frame reversals. A third type of reversal is associated with the well-known figure/ground reversals such as Rubin's vase/faces figure also shown in Figure 1 where reassignments of the boundary contour occur. Peterson *et al.*⁵¹ argue that the different types of reversal may vary in how easy they are to achieve in imagery with reference frame reversals being difficult and reconstruals more likely to occur. Figure and ground reversals are considered to be different because of the reassignment of the critical boundary that is not involved in the other two types of reversal and which they argue is unlikely to occur in imagery. A second characteristic of the Chambers and Resiberg work identified by Peterson *et al.*⁵¹ which could have limited the reversals obtained in imagery concerned their use of other reversible figures to demonstrate the nature of the effect prior to the subjects forming an image. They point out that the type of reversal present in the demonstration figures was different to that in the figure used to test for reversal in imagery. They argue that this difference could provide a misleading, though implicit cue, about the type of reversal that was to occur when an image of the test figure was formed.

These authors then performed a series of experiments designed to test these predictions. Using the duck/rabbit figure, the type of reversal present in the demonstration figures was systematically manipulated. In common with

51 Peterson, M A, Kihlstrom, J F, Rose, P M and Glisky, M L 'Mental images can be ambiguous: reconstruals and reference frame reversals' *Memory and Cognition* Vol 20 (1992) pp 107–123

52 Peterson, M A The ambiguity of mental images: Insights regarding the structure of shape memory and its function in creativity. In Roskos-Ewoldson, B, Intons-Peterson, M J, Anderson R E (eds) *Imagery, creative and discovery: a cognitive approach* Elsevier, Amsterdam (1993) pp 151–186

Kaufmann and Helstrup⁵⁰, Peterson *et al.*⁵¹ found that the participants reported other types of reversals to those normally associated with the reversible figures used. Consequently they analyzed their results in terms of the strict reversal criterion and an extended criterion which involved other valid reversals. They found that duck/rabbit reference frame reversals did occur more frequently than in Chambers and Resisberg's work and that significantly more reversals occurred when the goose/hawk figure, which also requires a similar reference frame reversal, was shown as the demonstration figure. For example, when no demonstration figure was shown 10% reversals were obtained compared to the zero reversals in Chambers and Reisberg while with the goose/hawk demonstration 35% reversals were obtained. When other valid interpretations, which involved reference frame reversals, were included in the analysis, the percentage of reversals was increased significantly. For the no demonstration condition 21% reversals were obtained while with the goose/hawk demonstration 38% reversals occurred. When interpretations involving reconstruals were also included 69% reversals were obtained. Peterson *et al.*⁵¹ then repeated the experiment using the snail/elephant figure which involves reconstrual only. In addition, detail was removed from the figure to emphasize the critical features in the figure. Significantly higher proportions of participants were able to reverse their image of this figure on a strict criterion (50%). When other valid interpretations were included in the analysis, 83% of participants were able to reverse the image. The results of these experiments therefore appear to demonstrate that reference frame reversals can occur, particularly if a similar demonstration figure is used, that reversals involving reconstruals can be achieved quite easily and that simplifying the figure may play a role in achieving these reversals. However it is also apparent that the frequency of reference frame reversals is very low without a demonstration figure and, even with such a figure, the rates are well below that obtained with a drawing of the image. By contrast reconstruals occur with a high frequency approaching that found with a drawing.

In order to clarify their results further and to examine the relationship between semantic/propositional knowledge and imagery based knowledge, these authors carried out a number of follow up experiments. In one, participants were asked to generate as many associations as possible when they saw the word duck or rabbit while separate groups were asked to generate as many associations as possible to images of ducks and rabbits. The results demonstrated that the proportion of associations in common between the semantic and imagery conditions was very low; that is the associations drawn from long-term memory are different when memory is accessed via imagery or words. While these results clarified the nature of the effects in the earlier experiments, in that reversals do not appear to result from sem-

antic knowledge of ducks and rabbits, they also have interesting implications for the role of imagery. Peterson *et al.*⁵¹ argue that, because the knowledge that can be accessed via imagery is largely different to that obtained via words, problems solved using imagery based knowledge may appear to be unusual when the usual is defined by propositional or semantic knowledge. In addition it would appear that, if both conceptual and image based knowledge are used during problem solving, this broadens the knowledge base available to the problem solver increasing the possibilities of finding a superior or creative solution.

The possible role of dual coding, that is verbal (semantic, conceptual) and visual (imagery) representations (Paivio^{53,54}), in imagery reinterpretation has also recently been highlighted in the work of Brandimonte and Gerbino^{55,56}. These authors review evidence that forming both a visual and a verbal representation of visually presented material can lead to interference in a number of cognitive tasks. For example, recognizing faces, a task based on visual memory which is difficult to put into words, is interfered with if the individual is asked to describe the face prior to the recognition test (Schooler and Engstler-Schooler⁵⁷). Similarly Schooler *et al.*⁵⁸), demonstrated that verbalization interfered with solving insight problems that require non-verbal cognitive processes. However, the visual material was not lost but made inaccessible by the verbal processing, an effect referred to as verbal overshadowing, that could also be reversed under the appropriate conditions (Brandimonte *et al.*⁵⁹). Brandimonte and Gerbino⁵⁶ argue that the conditions used to examine the imagery reinterpretation effect establish the conditions for verbal overshadowing and that it is the inaccessibility of the visual image that leads to the inability to reinterpret the image. Participants in the experiments are shown a picture of the duck/rabbit figure and asked to identify, that is verbally label, what they see. If this produces verbal overshadowing, then preventing verbal labeling should increase the frequency of imagery reinterpretation. Brandimonte and Gerbino⁵⁶ report experiments where the technique of articulatory suppression developed in working memory research was used to prevent verbal labeling while an individual formed an image of the duck/rabbit figure. Under these conditions there was a significant increase in the frequency with which participants could reverse their images indicating that verbal coding and verbal overshadowing were playing a role in imagery reinterpretation. The introduction of issues associated with verbal and visual coding into the debate about the reinterpretation of images therefore makes a significant contribution to understanding why images are difficult to reinterpret. However, combined with the work of Peterson⁵² on the differences between knowledge accessed by words and images, this work has particular

53 Paivio, A *Imagery and verbal processes* Holt, Rinehart and Winston, New York (1971)

54 Paivio, A *Images in mind: the evolution of a theory* Harvester Wheatsheaf, New York (1991)

55 Brandimonte, M A and Gerbino, W 'Mental image reversal and verbal recoding: When ducks become rabbits' *Memory and Cognition* Vol 21 (1993) pp 23–33

56 Brandimonte, M A and Gerbino, W When imagery fails: effects of verbal recoding on accessibility of visual images. In **Cornoldi, C, Logie, R H, Brandimonte, M A, Kaufmann, G, Reisberg, D** (eds) *Stretching the imagination: representation and transformation in mental imagery* Oxford University Press, Oxford (1996) pp 31–76

57 Schooler, J W and Engstler-Schooler, T Y 'Verbal overshadowing of visual memories: some things are better left unsaid' *Cognitive Psychology* Vol 22 (1990) pp 36–71

58 Schooler, J W, Ohlsson, S and Brooks, K 'Thoughts beyond words: when language overshadows insight' *Journal of Experimental Psychology: General* Vol 122 (1993) pp 166–183

59 Brandimonte, M A, Schooler, J W and Gabbino, P 'Attenuating verbal overshadowing through color retrieval cues' *Journal of Experimental Psychology: Learning, Memory and Cognition* Vol 23 (1997) pp 915–931

significance for design because design inevitably involves the use of both verbally coded and visually coded knowledge.

3.2 Imagery reinterpretation and design

While the research on the relationship between imagery and perception was primarily concerned with the question of the functional equivalence between the two, imagery has been seen as an essential part of creative problem solving (for a review see Shepard⁶⁰). Imagery as such was not seen as essential to creativity but rather the insights that appeared to be supported by reinterpretations of images—that is, creativity was associated with the emergence of new ways of seeing images and this occurred in the ‘mind’s eye’. The basic Chambers and Reisberg⁴⁸ experimental results, which appeared to show that images could not be reinterpreted, consequently appear to present a considerable challenge to this view. However, perhaps paradoxically, the finding that reversals always occurred when an image was drawn provides a possible perspective on the role of drawing in design. Drawing an image of a reversible figure creates the same conditions, that is perceptual conditions, to those that exist when people are shown a drawing of a reversible figure. Under these conditions the evidence is that 100% reversals are found. Drawing during the design process could be performing the same function, which is of maximizing the conditions necessary for the reinterpretation of an image and the emergence of new ways of ‘seeing’ it.

The experiments that followed the Chambers and Reisberg^{48,49} work did, however, demonstrate that reinterpretations can occur without drawing and the frequency with which they occur can be increased where appropriate conditions are established. For example, reinterpretations will increase if individuals with high visualization abilities are involved, if the appropriate (for the type of reversal) demonstration figures are used and if the type of reversal is easier to reinterpret (reconstruals) rather than difficult to reinterpret (reference frame reversals). However, reinterpretations always occur when an image is drawn whether it involves reconstrual of parts of an image or changes in the reference frame associated with an image and interestingly figure/ground reversals also occur with drawn figures which it has been argued do not occur in imagery. Drawing an image therefore both maximizes the conditions for reinterpretation and avoids any difficulties associated with particular types of reversals in imagery, which may be why drawing is so important in design.

It is also apparent however that this discussion raises a number of further questions in relation to design imagery. First, when a designer draws are they externalizing an image that has been created in working memory? An

60 Shepard, R N ‘The mental image’ *American Psychologist* Vol 33 (1978) pp 125–137

alternative would be that working memory is engaged in conceptual thinking about the problem and potential solutions and that the drawing process is a method by which the implications of these abstract problem solving processes are put into the physical form that is the required result of the design process. The drawings that are the result of an abstract problem solving process as a consequence provide the conditions necessary for emergence independent of any imagery. However there is another aspect to the significance of the finding that drawings of images facilitate re-interpretation. The drawings that were produced were of images formed on the basis of seeing a figure. Images therefore are capable of supporting drawings even if they cannot be re-interpreted themselves. Consequently imagery processes, rather than abstract reasoning processes could be the basis on which drawings are produced in design. Whether or not drawings are the externalization of imagery is therefore an issue that needs to be addressed empirically.

A second question raised by the research on the reversal of images concerns the complexity of the images involved. A characteristic of this research is that the drawings on which the images are based are relatively simple consisting of a single small-scale object. If, however, design images are more 'complex' in some sense and involve combinations of types of reinterpretation then it is possible that the potential reinterpretations of a drawing may not be found, in contrast to the more 'simple' reversible figures used in the research reviewed. Evidence for a failure to discover possible interpretations of imaged forms is found in the work on mental synthesis tasks to be reviewed subsequently and is an anecdotal part of the experience of designers. If it were the case that design images are 'complex' then it could be that drawing design images creates the *best* possible conditions for reinterpretation to occur rather than ensuring that reinterpretation did occur. Drawings made during the design process do not appear to always be reinterpreted and data regarding the frequency with which reinterpretations occur and the conditions associated with reinterpretation would provide evidence relevant to this point. Research into this aspect of design images is clearly needed.

The issue of the nature of design imagery raises a further question. Do the images involved in design require reference frame reversals, reconstruals, figure/ground reversals or some combination of all of these types of reinterpretation? Each of these types of reinterpretation would appear to be relevant to design. For example, reference frame reversals involve *spatial* reinterpretations, that is in terms of depth (front/back) or orientation (top and bottom), and would seem to be relevant to design because of this spatial quality. Reconstruals, where the interpretation of the parts or struc-

ture of an image occurs, would also appear to be potentially relevant to design because they involve another type of spatial effect where the structural relationship between one part of an image and another part is changed. The relevance of figure and ground reversals for design may be less obvious. However, the issue that this points towards is an empirical one—is it possible to determine from an analysis of design protocols (both the drawings produced and the concurrent or subsequent verbalization) what types of reinterpretations occur in the design process.

There is also an associated and equally important set of issues. What is the overall frequency of reinterpretations, both within a particular design session and across design sessions; do the different types of reinterpretations occur with different frequencies and are reinterpretations associated with particular design outcomes such as creative and original designs. Or is it that reinterpretations produce relatively small shifts in most design episodes and that large shifts occur infrequently and are associated with the most original designs. It may turn out that reinterpretation and emergence do not form a typical part of the design process. It may be that different designers use different types of reinterpretation. Or it may turn out that designers do not use complex imagery and the effective images are simple. This could lead to ease of reinterpretation and the relevant question concerns how such simple images come to be generated with the discovery process being relatively automatic once the image has been formed. Again the need for empirical evidence is apparent. There is also a significant design education dimension associated with the issue of the conditions that can help in the reinterpretation of images. Exposure to examples of the differing types of reference frame reversals, reconstruals and figure/ground boundary shifts, using both the classic reversible figures and examples developed specifically for a particular design discipline, could be used to teach students how to facilitate change in the interpretation of both imagery and drawings.

Finally, the results of one of Peterson's⁵² experiments could have particular significance in the context of design problem solving. She demonstrated that the types of knowledge accessed from a word or the formation of an image associated with the word were different. Words lead to access to conceptual and propositional knowledge while images access more perceptually based knowledge, that is knowledge about materials, forms and precedents. Similarly Brandimonte and Gerbino's⁵⁶ work indicates that creating verbal representations can make visual/imagery based representations inaccessible. Design requires the accessing and use of both types of knowledge for the reasons outlined in much of the preceding discussion. The absence of attention to relevant conceptual knowledge could result in inap-

appropriate design because significant facets of the problem may not be addressed. A deficit of imagery based knowledge by contrast could result in problems in producing and resolving the physical attributes of the design. Anecdotally many designers use both written notes and drawings that could be ways of accessing these two different types of knowledge. It may also be that designers access conceptual knowledge by sub-vocal speech that is by talking to yourself. This possibility could be assessed by recording muscular activity in the throat during design sessions together with the retrospective protocol analysis techniques developed by Suwa and Tversky¹⁶. While the issue of accessing conceptual knowledge through writing or talking to oneself is important in relation to the activities of an individual designer, the issue of the role of talking and its relationship to drawing is also obviously significant in the context of design as a team activity. Indeed it may be that design teams are more effective because talking is a natural part of the process and because the combination of talking and drawing inherent in a design group maximizes the accessing of both abstract knowledge and knowledge about physical forms and materials.

There is also a further aspect to the question which concerns the relationship between verbal activity (in the form of covert speech, talking aloud or writing) and drawing. If verbal activity and imagery do access different types of knowledge, then there may be a subtle interplay between the two. Verbal activity could be used in the initial stages of the design process relating to the exploration and understanding of the design problem—that is identifying the conceptual issues or constraints which are relevant to the particular problem. This could be associated with covert speech and with the externalization of this speech in written form to act as an external memory aid. This could also, in a sense, free working memory to use imagery to access physical forms of knowledge to move from the conceptual to the physical in order to solve one of the basic problems associated with design. Drawing then could perform the function of both exploring the implications of this type of knowledge and establishing the conditions for possible re-interpretation.

The distinction between talking and drawing and the type of knowledge accessed via each also extends an issue raised in the discussion of different types of drawings. Katz's²⁰ work indicated that a critical difference between experts and novice architectural designers was the experts ability to recognize the key constraints in a particular problem situation; a result similar to work in the area of expertise generally (see for example Reimann and Chi⁶¹). Is it that drawing facilitates the recognition of key constraints or is it that the conceptual knowledge accessed via words identifies the key constraints with drawing allowing the development and exploration of

61 Reimann, P and Chi, M T H
Human expertise. In Gilhooly K
J (ed.) *Human and machine
problem solving* Plenum Press,
New York (1989)

a physical representation of the constraint. This possibility is again consistent with the general work on expertise, where experts spend more time in the early part of problem solving identifying the abstract principles which are relevant to solving the problem while novices are tied to the superficial or surface characteristics of the problem. However, Clement's⁶² work with high level physics experts attempting a difficult problem indicates that the key constraint in these situations is derived from simple, perceptual-motor schemas often associated with imagery, with drawing and with overt actions. In the design context it may therefore be that, for well recognized or familiar types of design problems in a discipline, experts would use lexically accessed, abstract knowledge while for difficult and unfamiliar problems imagery, enacted imagery or drawing generate the key constraints. These possibilities can clearly be empirically investigated using design protocols. The protocols would be collected however, using specially designed problems which were both familiar and less difficult or unfamiliar and consequently more difficult. This discussion also makes the general point that protocol studies may have to become more sophisticated in terms of the selection of the problems to be used and the conditions under which the protocol is collected. In other words protocol studies will have to move towards becoming more experimental rather than primarily descriptive.

3.3 *Mental synthesis, imagery and drawing*

Designers often say that it is a synthetic process. It would also appear that what is meant by a synthetic process is not clear. At times the synthesis referred to appears to be related to a synthesis of competing and or conflicting possibilities inherent in the ill-defined nature of design problems. The main focus of this view would appear to be related to competition and conflict between different areas of knowledge, that is abstract/conceptual knowledge. In contrast to this approach is one that emphasizes the mental synthesis of physical forms as the way in which design is a synthetic activity. Both types of synthesis involve the potential for creativity, however it is the second view, involving the synthesis of forms, which links closely to psychological research into mental synthesis and creativity.

In a pioneering set of experiments Finke^{19,63,64} and his colleagues studied peoples' ability to mentally synthesize a number of relatively simple forms (letters, simple geometric shapes), randomly chosen from a larger set, into an overall form. Participants were required to form an image of each part and then to combine them mentally into a single, imaged form. This task was performed under a number of conditions. For example, the objects that were created had to belong to one of eight possible object categories (e.g. furniture, personal items, appliances) and constitute a practical object

62 Clement, J Use of physical intuition and imagistic simulation in expert problem solving. In Tiroshi, D (ed.) *Implicit and explicit knowledge* Ablex, New Jersey (1994) pp 204-244

63 Finke, R A *Principles of mental imagery*. MIT Press, Cambridge MA (1989)

64 Finke, R A and Slayton, K 'Explorations of creative visual synthesis in mental imagery' *Memory and Cognition* Vol 16 (1988) pp 252-257

within the category with either the experimenter or the participant nominating the object category to which the synthesized form belonged. Participants were required to write a description of the form they had created and how it was related to the category and then to draw their image. Independent judges then scored each form in terms of the correspondence between the drawing and the description (a measure of the practicality of the object) and in terms of the originality of the object that had been synthesized. Objects that were scored as both practical and original were considered to be creative. It is important to note that, for the participants, there had been no mention of creativity or originality. Practical forms were generated on approximately half of the trials while creative forms were generated on 14% of the trials. It was also apparent that the percentage of both practical and creative objects increased the more constraints were placed on the imagers. For example, the highest percentage of creative forms occurred when participants were given randomly chosen parts to synthesize and when these had to be associated with a randomly chosen category. Creativity seems to increase the more constrained the situation, a result incompatible with the view that creativity is associated with maximum freedom.

Finke and his associates also interviewed the participants in their experiments after they had completed the task. Most participants reported that they had begun by imagining interesting, suggestive forms that had no specific referents. These forms were then related to the category of object that was specified. Finke¹⁹ calls these imagined forms *preinventive forms*. Finke^{19,66} examined this possibility in a further series of experiments by separating the creation of an image from randomly selected parts from the specification of a category of object in relation to which the imaged form had to be interpreted. After participants had imaged a form, they were asked to draw it so that they could not change the form afterwards and were then given a randomly selected object category. Participants were able to generate preinventive forms quite easily and 19% of the forms were judged to be creative. In these experiments participants were allowed one minute in which to interpret their form in terms of the nominated category. With longer periods for this part of the task (up to 15 minutes), more creative solutions were produced indicating that the figure of 19% probably underestimates the actual potential for producing interpretations of preinventive forms.

As Finke⁶⁶ points out one interpretation of these results is that ‘function follows form’ rather than ‘form follows function’ which is a commonly held view in design. Creativity was enhanced when the image generation phase—the form—was separated from the interpretation phase—the func-

tion. Finke⁶⁶ also points out however, that the generation of a preinventive form is then followed by an exploration of the possibilities inherent in the form—a process formalized in the experimental procedure but common in anecdotal reports of creative activity. He reports that the participants in the experiments reported a number of strategies that they employed in this exploratory phase. They looked for interesting or novel features in the forms; they imagined themselves using the forms or they transformed the context in which the forms might occur. On the basis of these various experimental results Finke and his colleagues (Finke⁶⁶ and Finke *et al.*⁶⁵) proposed a model of the creative process. In the first phase of the process preinventive structures (one example of which is a preinventive form) are generated. These structures have properties that stimulate creativity in that they are novel, ambiguous and support emergence or reinterpretation. These properties are exploited during an exploratory phase in which the form is interpreted in a meaningful way. If this exploratory phase is unsuccessful then either the initial preinventive structure is abandoned and a new one generated or the old one is modified and re-explored. Finke *et al.*⁶⁵ argue that, where the process takes place in the context of a particular product or outcome, the constraints imposed by the outcome can operate on either the generate or the explore phases. They consider that a strength of a model that separates the generation of preinventive structures from their exploration is that it focuses on the process as one that occurs through time with different phases which may involve different cognitive processes.

The work on mental synthesis by Finke and his colleagues does not address the issue of a role for drawing in their model of the creative process. However direct evidence of the relevance of drawing in a mental synthesis task was obtained by Anderson and Helstrup^{67,68}. They used the basic mental synthesis task as developed by Finke but compared the results of participants who used imagery alone to generate the form with those who were allowed to draw while they performed the task. They argued that drawing should assist performance in this task for two reasons. First the experiments on image reversal (e.g. Chambers and Reisberg⁴⁸) demonstrated that reinterpretation was markedly facilitated by drawing an image of a reversible figure and consequently interpreting a mentally synthesized form should be facilitated by drawing. Second they argued that forming an image by mental synthesis takes place in working memory which has a limited capacity. If the form could be externalized by drawing then the demands on working memory would be lower than if all aspects of generating, maintaining and manipulating the image were carried out in working memory. A similar two stage scoring procedure was used—correspondence ratings and creativity ratings for those patterns that showed good correspondence. The results were quite clear-cut. With the participants who did not draw

65 Finke, R, Ward, T B and Smith, S M *Creative cognition: theory, research and application* MIT Press, Cambridge MA (1992)

66 Finke, R Mental imagery and creative discovery. In Roskos-Ewoldson, B, Intons-Peterson, M J, and Anderson R E (eds) *Imagery, creative and discovery: a cognitive approach* Elsevier, Amsterdam (1993) pp 255–286

67 Anderson, R E and Helstrup, T 'Visual discovery in the mind and on paper' *Memory and Cognition* Vol 21 No 3 (1993) pp 283–293

68 Anderson, R E and Helstrup, T Multiple perspectives on discovery and creativity in the mind and on paper. In Roskos-Ewoldson, B, Intons-Peterson M J and Anderson R E (eds) *Imagery, creative and discovery: a cognitive approach* Elsevier, Amsterdam (1993) pp 223–253

their synthesized forms, the results essentially replicated that obtained in previous work, both in terms of correspondence and creativity. Those who were allowed to draw produced more correspondence patterns and there were fewer trials on which no pattern was produced but there was no increase in the creativity of the output. This difference occurred whether participants had only to produce one synthesized form during the experimental session and where they were encouraged to produce as many forms as possible during the session. Drawing, which took the form of doodling or sketching, therefore does not appear to increase the creativity of the mentally synthesized forms.

Anderson and Helstrup^{67,68} also analyzed the sketches and doodles that were produced in a number of their experimental conditions where drawing was allowed as a way of assessing the relationship between composition or construction of a form and its interpretation. In the experiments where only one pattern was asked for, an average of about four doodles were produced for each successful trial with an average of nine doodles being found for the unsuccessful trials. However on both the unsuccessful and the successful trials only an average of two doodles were interpreted. Clearly not all of the forms constructed were interpreted indicating that the two process occur separately. They also examined the number of times a particular form was repeated to determine whether new forms were being constructed or the same form interpreted. Repetition rates were high (40 and 65% in two of the experiments) and participants rarely provided more than one interpretation for each form. The authors interpret these results as indicating that the repetition of drawings of a particular form represents attempts to refine an interpretation of a pattern. They also examined the doodles to see if there was systematic variation of the parts of a form to create novel patterns. This type of variation did not occur indicating that what was being drawn appeared to reflect events that were occurring in imagery prior to drawing. Although Anderson and Helstrup do not comment on the issue, these results would appear to indicate that drawing is being used as an external memory aid. Given the lack of increase in creativity associated with drawing, it could be argued that, where drawing is used in this way, creativity is not enhanced. Such a result is clearly at odds with accepted wisdom in the design area.

However there is recent evidence that drawing can play a role in a task that is very similar to the mental synthesis task. Finke and Slayton⁶⁴ also used a somewhat different version of the mental synthesis task to that discussed above. Participants were asked to form images of pairs of upper case letters on the basis of verbal instructions and then to perform a series of mental manipulations of their images. These mental manipulations

should produce an image of an object and participants were asked to name the object. This task is similar to the mental synthesis task discussed above in that it requires the formation, manipulation and interpretation of visual images however in this case there is a known object that is formed as a result of the image manipulation. Pearson *et al.*⁶⁹ used this task to examine the role of the various components of working memory in a task involving visual imagery and whether or not the stimulus support provided by drawing the final image affected peoples' ability to identify the object. A series of secondary tasks performed while carrying out the image manipulation were used to assess the role of central executive processes and the visual and verbal components of working memory. The pattern of results with the various tasks demonstrated quite clearly that the imagery manipulation task primarily involved the executive component of working memory and not the passive caches associated with the specific visual and verbal aspects of working memory. Equally clear was the beneficial effect of drawing the final image on the recognition of the object formed via the image manipulations.

3.4 *Mental synthesis, creativity, discovery and design*

The generate and explore (Genplore) model developed on the basis of the mental synthesis task appears to be particularly relevant to the design process and many of the results of the protocol studies of design activities are consistent with it. For example, the model proposes that the generation of preinventive forms is distinct from the process of exploration and discovery. The protocol studies consistently document shifts in a designer's attention that are associated with reinterpretation, the results of the reinterpretations then leading to an examination of the implications of the shift. The Genplore model also clearly identifies mental synthesis as a dynamic process that alternates between generating preinventive forms and exploring their implications. This concept clearly parallels the dialectic process that has been identified in design protocols. In the Genplore model it is considered that reinterpretation can occur both during the generate and explore phases. However the model does not articulate what is meant by reinterpretation. By contrast the design literature indicates that there may be a number of types of reinterpretation, which are related to the way the term is used in the mental synthesis literature. Reinterpretation in design can involve perceptual emergence based on a new way of 'seeing'. In the case of mental synthesis this would appear to parallel the type of reinterpretation that occurs with preinventive forms. Interestingly the proposal that mentally synthesized forms can be reinterpreted appears to be at odds with the literature on the absence of reversal of images of ambiguous figures. However, the rates with which creative forms are generated by mental synthesis is quite low (between 10 and 20%). This parallels the rates of

69 Pearson, D, Logie, R H and Green, C 'Mental manipulation, visual working memory and executive processes' *Psychologische Beitrage* Vol 38 (1996) pp 324-342

reversal that have been obtained in studies of the reversal of images of ambiguous figures subsequent to the work of Chambers and Reisberg⁴⁸ where effectively no reversals were obtained. Finke also notes that subjects who produced creative forms also reported that they had mentally manipulated the forms. This may have created the conditions that allow reinterpretation of the preinventive forms, an issue to be discussed in the following section on enacted imagery. The types of reinterpretation that could occur in the exploration phase of the mental synthesis task could be similar to the accessing of new types of knowledge that is a characteristic of the design problem solving process after perceptual reinterpretation has occurred.

However a number of aspects of the results of this research on mental synthesis pose challenges to the design literature. First, as Finke⁶⁶ points out, the finding that preinventive forms can be generated prior to their relation to a particular category within which they are to be interpreted, indicates that function (the interpretation of the form) follows form (the generation of the form). This contrasts to the widely held view in design that form follows function. The results of the protocol studies of design are however also consistent with the view that function follows form. This is most apparent in the work of Suwa and Tversky¹⁶ where the focus shifts associated with perceptual reinterpretations of drawings were then followed by reasoning about function. However the results of Anderson and Helstrup's^{66,67} experiments, where drawing was shown not to increase the rate at which creative synthesized forms were produced, appears to challenge another widely held view in design. Drawing is both believed to be, and the protocol evidence appears to demonstrate that it is, important in the design process. There are a number of possible explanations for this apparent inconsistency. One possibility is that the mental synthesis task is one that can be performed within the limits of working memory and consequently drawing does not provide any additional benefit. In opposition to this possibility however is the fact that drawing an image appears to establish the conditions that facilitate perceptual reinterpretation. Given that reinterpretation is regarded in the Genplore model as an important aspect of generating creative forms, drawing would be expected to increase the frequency of such forms. A second possibility relates to the nature of the imagery in the mental synthesis task and the reversal of ambiguous figures. In the latter case the images formed have an existing meaning, as does the alternative interpretation. In the case of mentally synthesized forms any possible meanings have to be discovered, either in the image or in the drawing. The powerful effect of drawing in facilitating reinterpretation in the case of ambiguous figures may therefore depend on the pre-existing meanings associated with the drawing. The work reported by Pearson *et*

*al.*⁶⁹ is consistent with such an interpretation. Participants in their experiment were required to form images of a number of simple, known objects and then to carry out instructions which involved manipulating the images to produce a particular composite image which had a known meaning that had to be recognized. Performance of this task was reliably increased in a number of experiments if participants were allowed to draw their image. This experimental task differs to the work using ambiguous figures in that the latter does not involve the manipulation of images. However both result in images which have pre-existing, defined meanings. If this were correct, it would imply that the reinterpretations that occur with drawings in the design process also depend on discovering pre-existing meanings and not on generating preinventive and effectively meaningless forms. There is also a third possibility. In the design area, there is much anecdotal evidence that the effective use of drawings to facilitate reinterpretation must be taught. If this is the case, it may be that Anderson and Helstrup's subjects, because they were drawn from a general student pool, were not able to draw effectively. If subjects, such as designers, were used who had experience in drawing in this way, it may be that drawing would be shown to increase the output of creative forms. Conversely, it should be possible to teach novices how to draw in ways that would facilitate the production of creative forms. All of these possibilities are open to empirical examination either through appropriately designed mental synthesis experiments or studies of the design process.

3.5 *Enacted imagery*

The preceding review of research into the role of imagery in reinterpreting ambiguous figures and in making discoveries in synthesized images has clear relevance for design and for the role of drawings in the design process. However Reisberg and Logie⁷⁰ have recently presented an analysis of the research results in these areas, which opens up further horizons for the role of imagery in design. They point out the apparent disparity between sources which indicate that images can be involved in supporting discoveries, creating inventions and in problem solving and the results of research involving the reversal of images of ambiguous figures. They argue that this difference may be the result of a difference between the geometry of the image and the reference frame applied to it by the imager and the reference frame associated with the target. For example, when an image of a map of Africa rotated through ninety degrees is formed, very few recognize it as the map of Africa. In this case the top specified by the geometry of the image and the top in the imagers reference frame corresponds with the geometry and recognitions are infrequent. In order for recognition to occur imagers must identify the top in their reference frame with that part of the geometry of the image that is rotated through ninety

70 Reisberg, D and Logie, R
The ins and outs of working memory. In Roskos-Ewoldson, B, Intons-Peterson M J, Anderson R E (eds) *Imagery, creative and discovery: a cognitive approach* Elsevier, Amsterdam (1993) pp 39–76

degrees. Reisberg and Logie⁷⁰ consider that the reference frame is associated with stimulus or image attributes such as top and bottom, front and back, the three dimensional organization of the image and its figure and ground properties. They then argue that discoveries in images occur almost universally when they are compatible with the image frame or when the reference frame created by a picture determines the reference frame of a percept. In the case of imagery various techniques that can change the reference frame, such as instructions or the use of examples, can increase the number of reversals, the variations in the success of these manipulations presumably depending on the success with which the reference frame is shifted.

However, as Reisberg and Logie⁷⁰ point out, spontaneous redefinitions or reinterpretations of a reference frame seem to occur very infrequently in imagery as is evidenced by the very low reinterpretation rates. A question of basic interest therefore is why redefinitions are so infrequent. Their answer to this question begins with the results of experiments with auditory rather than visual imagery (Reisberg *et al.*⁷¹). In a direct parallel of the imagery experiments using visual ambiguous figures, participants were asked to form auditory images of words which, if rapidly repeated are perceived as another word. For example if the word stress is rapidly repeated, the word dress is heard with very high frequency. When participants imagined these repetitions they often detected the stress to dress transformation in contrast to the very low frequency with which such reinterpretations occur with visual ambiguous figures. When participants were however prevented from subvocalizing, that is repeating the words to themselves, reinterpretations dropped to chance levels. Resisberg and Logie⁷⁰ interpret the results of these and other experiments as indicating that the participants are talking to themselves and listening to the results. In effect this covert, subvocal behavior establishes the equivalent conditions to when listening to the word being rapidly repeated. The reinterpretation requires what the authors refer to as stimulus support. Where words are rapidly spoken aloud, it is the spoken word which allows the reinterpretation to occur; where the word is created as an auditory image it is the covert, self-created speech which provides the stimulus support allowing the image to be reinterpreted. Resisberg and Logie refer to this as a partnership between the 'inner ear' and the 'inner voice'. They point out that such a mechanism is entirely consistent with the considerable research results in auditory working memory relating to the articulatory loop which involves subvocal rehearsal and a phonological store as discussed in the section on working memory.

71 Reisberg, D, Smith, J D, Baxter, D A and Shoenshine, M "Enacted' auditory images are ambiguous; 'pure' auditory images are not' *Quarterly Journal of Experimental Psychology* Vol 41A (1989) pp 619-641

Since it is also known that, in the case of visual ambiguous figures, reinterpretation effectively always occurs when a picture of the ambiguous

figure is present or participants draw their image, it would appear that the pictures or drawings are providing the equivalent visual stimulus support which allows reinterpretation to occur. Given that reinterpretations only occur with very low frequency in vision, it would appear reasonable to argue that there is no parallel to the 'inner voice' in vision to provide covert visual stimulus support allowing reinterpretation. However, as Reisberg and Logie⁷⁰ point out, the working memory literature (for a summary, see Logie³⁵) also contains evidence for a visual buffer or store similar to the phonological store and what is referred to as the visuo-spatial sketch pad—the 'inner eye' and the 'inner scribe' respectively. It is possible therefore that the difference between audition and vision is that the 'inner voice' is used spontaneously and naturally to provide stimulus support to the 'inner ear' but that this does not occur spontaneously with vision.

These authors argue however that the domain of visual imagery may involve several components or types of imagery and that this has been unrecognized in the visual imagery reversal work. Visual images can be formed which have visual attributes such as brightness and color as well as spatial attributes such as size and locational characteristics; that is the reference frame characteristics which appear to be associated with difficulties in visual image reinterpretation. Where, for example, a visual image of a grid is formed and participants are asked to place letters at various locations in the grid, subsequent retention of the location of the letters in the grid is disturbed if the participants have to make an irrelevant arm movement while performing the letter placement task. By contrast retention of the spatial information is not disrupted by a concurrent but irrelevant brightness judgement task. Experiments such as this provide evidence that visual and spatial imagery may be separate types of visual imagery. This suggests, in the spatial imagery case, that the spatial components of the task may be being rehearsed by the 'inner scribe' in effect may be being enacted. While the role of enacted visual imagery in reversal has not been tested, Reisberg and Logie point out that, where spontaneous reversal has occurred, it could result from participants spontaneously enacting their image, for example by covertly sketching out some pattern of motion associated with manipulating the image. They suggest further that enacted imagery could also play a role in other tasks particularly the mental synthesis tasks used by Finke and others reviewed previously. Here participants are asked to put together a number of parts to form a new overall figure—an inherently spatial task. The rate of creative discoveries obtained in this task could reflect the proportion of participants who spontaneously use this strategy. Further this rate could be increased if participants were encouraged by sketching out, using covert motions, the imaged forms.

Evidence for the importance of enacted imagery also comes from experiments in complex problem solving. Clement⁶² argued that the accepted view of expertise, which is that a key difference between experts and novices lies in the experts use of high level abstract schemas to identify the principle relevant to solving the problem, may be the result of comparing the two groups on everyday text book problems. Clement studied the way high level physics experts, including a Nobel Prize winner, solved a difficult physics problem by recording detailed protocols of the problem solving process. Analysis of these protocols revealed that a key component of the process was the use of what he refers to as relatively simple perceptual/motor schemas rather than high level abstract knowledge. The evidence for the use of these schemas came from both what the participants said and the way they behaved at particular points, generally early, in the problem solving process. Participants reported that they had formed images of elements of the problem situation and that they had physical intuitions about how the objects would behave under the given conditions. These verbal reports were often accompanied by physical movements (and by drawing activities) which appeared to be associated with the imagery, that is by enacting the imagery.

3.6 Enacted imagery and design

While the evidence relating to the importance of enacted imagery is sparse, it would appear to have considerable implications for design generally and the role of drawing in particular as well as providing a number of experimental approaches to the study of the design process. Design in a number of fields, for example many engineering disciplines, industrial design, architectural design, interior design and graphic design all involve a significant spatial component as well as a purely visual e.g. color and texture of surfaces, component. This spatial component often requires that elements be synthesized into a spatial whole, a process that is often considered in these disciplines as involving the use of imagery. Further, creativity in design is often considered to be associated with emergence or reinterpretation of the forms created during this synthetic process. Protocols of design sessions should provide evidence regarding the use of enacted imagery and whether or not it is associated with reinterpretation or emergence. Examining the protocols of expert designers dealing with difficult problems and novices dealing with problems that are difficult at that level of expertise should reveal how widespread the use of enacted imagery is. Where evidence for enacted imagery is found, the creativity of the output of the design process could be assessed and compared to the output of sessions where there is no evidence for the use of such imagery. It may be that the use of enacted imagery is not widespread but that it occurs with particular designers or where creative solutions are found. It would

also appear that it may be possible to teach designers how and when to use enacted imagery, given that it does not appear to occur spontaneously, with associated improvements in the synthetic and creative aspects of design.

Does the potential importance of enacted imagery mean that drawing as a central part of the design process would be replaced by enacted imagery? Here a number of possibilities exist. As pointed out previously, drawing may be important because it provides the conditions under which reinterpretation is likely to occur given the evidence from the research on the reversal of ambiguous figures. If enacted imagery is important it may be that the significance of drawing lies in the way in which it is effectively overt enactment of imagery.

4 Conclusions

The preceding discussion has demonstrated that the analyses of design protocols have revealed a number of regularities in the way in which drawings are used as part of the design process. Further there appears to be considerable similarity between the use of diagrams in a number of other disciplines and the use of drawings in design. These regularities lead to many further questions regarding the role of drawings in design. However, while the design research has produced interesting results, it is essentially descriptive in that the regularities are tied closely to the design protocols. While it would be possible to build models and theories using such a bottom up process, it would be a gradual, incremental and time-consuming. However we have attempted to demonstrate that there are a number of theoretically developed areas of cognitive psychology which can be used to facilitate the theoretical enterprise in the design problem solving area. The extensive recent work in the area of short-term and working memory and the related areas of imagery reversal and creative synthesis mesh well with the results of the design research. In addition to providing a cogent theoretical framework, this research also provides many new and interesting ways in which the role of drawing in design can be examined. Conversely it would also appear that research in the area of design problem solving, because of the particular characteristics of design problems, could make a significant contribution to expanding our understanding of working memory, imagery and creative synthesis. Finally we would argue that all of the preceding discussion has inevitable implications for design education and practice—implications which it is essential for researchers to address and articulate.

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