New Directions in Design Cognition:
Studies of Representation and Recall

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Abstract

The purpose of this chapter is to pose some new questions for design cognition and outline some paths for studying them. After a short review of design cognition's current status, I pose some issues that seem important to understand if design education is to be improved. Two broad areas are addressed:
    (1) Learning new representations, their internalization and automatization, as a foundation for developing design expertise;
    (2) Learning and recall used to structure a design context, framing the design task and retrieving relevant design concepts.
I survey recent work in the psychology of mental imaging and knowledge representation as a basis for addressing these issues. Studies in these two areas are reviewed and new ones proposed and the benefits of the new directions outlined. Two design domains are considered, architecture and mechanical engineering.

1. Introduction

We now have over 30 years of work in the area of design cognition. I use the term "design cognition" to refer to the study of human information processing in design, using different theoretical and empirical paradigms. Design cognition has become a defined field with a high quality journal, several conference series and some major references. The intention of this volume has been to take stock of the current status of design cognition, especially with regard to knowledge useful in improving design education. This chapter poses some new questions for design cognition and outlines some paths for studying them.

Below, I review the major results of work to date and the methods used. Other chapters of this volume survey these issues in more depth. The rest of this chapter is organized as follows. After the review, this first section ends by posing a set of issues of importance to design cognition, especially design education, that have not yet been well addressed. These issues form the framework for the succeeding sections. Section 2 reviews work in mental imaging and knowledge representation, which are proposed as foundations for new studies for better understanding the education of designers. This section reviews and interprets this literature, without making the strong connections to designing; these are made in succeeding sections. Section 3 applies to design what is known about

learning and using external representations and their internalization and mental use. Section 4 reviews studies of how designers structure a design context, recalling relevant criteria and features. It builds upon recent work in knowledge representation, memory and recall. Methods for studying the issues are outlined as we go.

1.1. A Review of Design as Ill-defined Problem-solving

The emergence of cognitive psychology in the 1960s offered both a conceptual paradigm for describing design, as well as a method for studying what is mostly an invisible, mental activity. The initial efforts drew on earlier work in problem solving in cognitive science and artificial intelligence (these two fields initially had common roots (Feigenbaum and Feldman 63)). Design was initially studied as a type of problem solving (Newell 69), as a search of a space of possible solutions for the best or a "satisficing" solution, in an approach similar to studies of chess, crypto-arithmetic, and puzzle solving (Eastman 70).

Design was quickly recognized as different than other forms of problem solving. The structure of the problem is usually not given and the criteria applied are at best only given abstractly, seldom in terms that can be directly applied. The terms "ill-structured" and "ill-defined" were introduced to signify that design tasks required definition of the problem space and also the criteria applied to candidate solutions (Reitman, 64, Simon 73, Akin 86). Design researchers have studied various sources of information (Eastman 69, Visser 96) including access to relevant physical artifacts (Harrison and Minneman 96).

It was also recognized that large design tasks are decomposed and organized into multiple levels of detail and different functions (Baya and Leifer 96, Ullman, Herling and Sinton 96). Studies were undertaken regarding how mental resources were allocated within this structure (Günther, Frankenburger and Auer 96), how these different tasks were organized within the whole process and how designers iterated between the different sub-tasks (Purcell, Gero et al 96, Akin and Lin 96) and how designers manage time (Baykan 96, Radcliffe 96). Others have considered the social roles people play within design teams (Cross and Cross 96, Brereton, Cannon et al 96)

Parallel to the study of design behavior has been the analysis of the structure of design problems. Better understanding of the structure of some design spaces may allow further insight into the processes followed by designers. One popular structuring of design information has been to distinguish between structural, behavioral and functional information (SBF) (Takeda, Tomiyama et al, 96, Goel, Gomez et al 96). *Structure* is the form—materials and geometry—of the design solution, *functions* are the general objectives to be realized, and *behavior* is the measurable performances into which the functions are translated.

A general insight was that traditional search within a narrow design space was undertaken only occasionally, in response to specific situations. More often components, features or attributes were identified from the general goals (Akin 78). That is, design (at least the early conceptual parts of design frequently studied) was more involved with defining the solution space than the search of specific solution

points within it. However, later stages, particularly those in engineering design, focused on decisions regarding solution points (Ullman, Herling and Sinton, 96).

1.2. Protocol Analysis

The primary empirical method for studying design introduced at the beginning of cognitive psychology was *protocol analysis*. Protocol analysis involves giving small but realistic design tasks to subjects and monitoring their behavior. Data was collected using video, plus any drawings produced. Design thinking is induced from the behavior captured from the protocol, including verbalizations, drawing and gestures. The methods and formal assumptions of protocol analysis were laid out in Ericsson and Simon (84). They presented it as both an empirical method for studying behavior and as a theoretical approach, based on the problem-solving paradigm and mental processing using symbolic knowledge representations (to be discussed later).

1.3. Critique

There has been a steady stream of criticism regarding both protocol analysis as a method of empirical method for studying design and ill-defined problem-solving as a paradigm for design. Protocol analysis relies heavily on the information provided in external representations, both verbally and in drawings and notes. There has been criticism of the distortions introduced when verbalization is forced (Davies 95, Lloyd, Lawson and Scott 96, Baya and Leifer 96). Protocol analysis, as described in Ericsson and Simon, does not address well the differences between internal and external representations (Chi 97). Another criticism is the gap between the levels of description offered within most studies based on protocol analyses and a designer's perception of that he or she is doing (Dorst 97:c 1). Variations and refinements of the task definition and for analyzing the behavior have been made, leading to a family of related empirical/formal methods of study (Chi 97, Crismond 97) (see Craig's chapter in this volume). Others have approached design through various forms of case study (Krauss and Meyer 70, Candy and Edmonds 96).

Many groups have also criticized the ill-defined problem solving design paradigm. Winograd and Flores have argued that it is ill-suited for studying design, noting that designers are part of the situation in which they act. Designers mentally construct their view of the situation as well as the actions taken within it (Winograd and Flores 87). They and others refer to the Heideggerian notions of "throwness" and "ready-to-hand" (Heidegger 62). With these concepts, Heidegger means to articulate the embeddedness of designers' actions in the real world. Partially from this perspective, some studies have approached design from different paradigms than ill-defined problem solving. Some have approached it as a socially organized set of actors (Brereton, Cannon et al 96) and also based on a contextual situatedness (Cross and Cross 96). Others have taken a more phenomenological perspective, arguing that the designer mentally constructs a design world (Trousse and Christiaans 96, Schon 88) beyond the entities, attributes and relations usually employed to define a problem state space. This included mental simulations of use, expected contextual changes over time, and other issues that go far beyond the defining of parameters of a state space (Schon, 92, Dorst 97).

The information gained from the duality of protocol analysis and ill-defined problem solving have been primarily normative, identifying common aspects of design as an activity. The motivation of much of this work is to articulate the distinctions of design cognition from other forms of problem solving. It has also sought to develop a general taxonomy of design cognition activities. While there has been little work clearly distinguishing processes supporting good design from less good, it has allowed identification, along with more prescriptive approaches (Hubka and Eder 88, Suh 90), of some of the constituent activities used by experienced designers. These include definition of the context of the design, examination of the design from multiple perspectives, generation of multiple alternatives, formulating critical performances, etc. These results have been used to identify differences between beginning and more advanced designers (Atman, this volume) and to assess progress in design education (Atman, Chimka et al, 99).

While research in design cognition has been successful in identifying *what* designers do, it has been less so in identifying *how* they do it. How do experienced designers frame design problems with regard to their context? We know that experienced designers are different from beginners; but what were the learning experiences that lead to the differences? How are multiple perspectives generated? How are performance criteria identified that are not given? What mental capabilities are used to generate alternative design concepts or features? These are new questions that could not be framed or articulated ten years ago. Their articulation is one of the contributions of recent work in design cognition.

A second area where protocol studies have not shed much light involves design representations. Design and engineering involve special representations that are central to their fields. Architecture emphasizes plans, sections and 3D models (manual or computer generated) and sketching. Engineering emphasizes mathematical modeling, especially differential equations, and various forms of diagram, such as circuit, network or kinematics. While these representations are taught and used throughout a university education, questions exist regarding how they are learned, applied and integrated with other knowledge. For example, there are concerns that architecture students select external representations based on their visual effect rather than what they communicate (Johnson 97). In engineering, students are taught to solve analysis problems, but when given an unstructured design task, often have difficulty relating their analysis knowledge to the task at hand (Emkin 95). How these representations are used, and especially how they are related to other mental constructs, seem central in understanding effective design.

It is generally assumed that the manipulation of external representations is only a partial depiction of what is going on mentally. The "real" structure of the design task resides in the designer's head (Lawson 97:c 8, Dorst 97:c 2, Downing 87). Cognitive models of thinking assume that external representations are auxiliary structures enhancing but not necessarily isomorphic to the designer's own knowledge structure. In design education, it should be the designer's mental representation of the context and current design that are the main concerns. These types of issues deal with mental processes usually not articulated in the data collected in a design protocol study. While protocol studies have allowed identification of the different external representations used (Ballay 87, Goel

95), there have been no traditional protocol studies to my knowledge that have shed light into the internal representations used by designers.

1.4. Recasting of the Issues

The above design issues can be recast in a manner different from ill-defined problem solving. By doing so, we can identify a different set of issues of importance to design, defined in a way allowing them to be fruitfully studied. The concepts of interest are partially characterized in Figure One.

The central area of concern is the designer's conception of the design world, that is, of the design and its context. To develop this design world, a designer has multiple sources of information: the external world of objects and observation (example designs, the context of other designs), external sources of encoded information (such as books, the Web, drawings), and the internal recollection of previous experience and learning. The external sources provide information in different encodings. Books are encoded in words (in various colloquial or formal vocabularies) and mathematical formulas (in different notations such as sets, algebra or calculus), the physical world in the form of images and possibly tactile, motor and auditory memories. Information sources include drawings in different forms, such as floorplan, section, orthographic mechanical drawing, electrical, kinematics and other diagrams. From these sources, the designer has learned and mentally encoded a rich structure of information. Some of the designer's knowledge is *factual* (sizes, material limits), some *informal* (the processes of construction or manufacturing) and some is *procedural* (how to use a CAD system, how to use the Web) and some is tacit and *experiential* (what your car engine sounds like when running well or poorly).
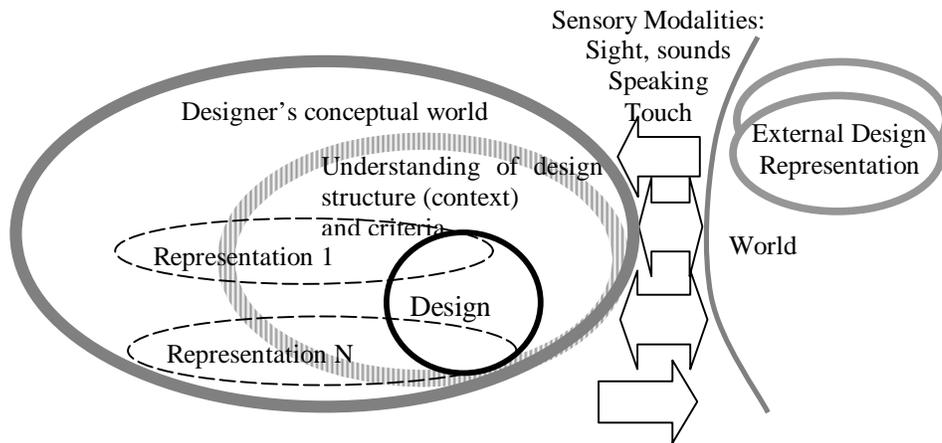
Figure One: A designer's conception of a design and its context is built up over time, using information from the designer's already gained knowledge and experience, and from external sources of information

Why do some beginning designers ignore their own experience when dealing with a design task? Why do others ignore what they have learned in college courses when they

encounter a real problem? Why does verbalization seem to have a strong influence in developing design skills? These issues focus on how design information is carried in people's heads, how it is recalled, structured, and particularly, how it is manipulated. Design expertise seems to draw upon knowledge in different representations and benefits from reasoning across the different representations. Knowledge representation, recall, use and structuring are central issues not only for design but for all of cognitive psychology (Glass and Holyoak 86:c 1).

A central task of design is defining its context[1]. This includes both the *external context*, ranging from the physical, social and cultural setting of a building to the mechanical, control and human interfaces of a mechanism, to the fabrication technologies, operating capabilities and resources available for making and operating the product. The *designed response* responds to the context by changing or adding something into it, in realization of some goals or intentions. Defining the context and the repertoire of materials and methods that make up the designed response are core issues in effective design. How do expert designers conceptualize the design context, and the designed response? How is relevant design information identified and applied? All design fields assume that designers rely on a wider base of information than is explicitly taught; experienced designers draw upon both formally learned knowledge and also information continuously learned experientially i.e., "in the field". Design education, then, ought to include a useful scaffold for building such an experience base, well integrated with analytical and other technical knowledge acquired in school. Strategies for expanding and using such an experience-base should be considered a fundamental part of design education.

As potentially relevant information is recalled, it is in some sense integrated. During and after integration, a design is represented externally in a variety of representations: drawings (of various types), written specifications, numerical properties and their units of measurement. What is the relation of these external representations and the knowledge carried in the designer's head? Most studies of design have focused on the external representations (in part because they are accessible.) While it is intuitively clear that external representations are important, how do they relate to the designer's internal representations? Are external representations simply records of mentally determined changes? Or are they used to manipulate the design in a more generate-and-test manner with mental representations focusing on the criteria to apply and the procedural knowledge used to manipulate designs? Vinod Goel and a few others have begun to probe the general role of external representations in design (Ballay 87, Goel 95, Ulusoy

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[1] Here, I have switched terminology used to describe design. Ill-defined problem solving uses a terminology that is inadequate and unevocative of the rich structure encountered in most design situations. From here on, I use the term *design context* to identify the outer environment involving system, physical, social, cultural, environmental contexts. Design context identifies the functions in the SBF terminology and their translation into desired behaviors. *Design response* is the intervention made by designers and corresponds to the structure in SBF terminology. These are similar to Simon's notion of inside and outside environment (69:c 1) and Alexander's notions of setting and of design as correcting "misfits" (64). Together these two contexts are my focus in considering "design worlds". All human social activities additionally takes place in a cultural, organizational and social setting that also is part of a design world, and important for effective action. I ignore these last contexts here, focusing on the technical aspects of design.

99) but we know little about how the external representations used by designers relate to their internal representation. Schon's investigations offer provocative insights (83). Goldshmidt has studied the role of sketching in preliminary design (91,94) and suggested some relations between sketching and mental representations.

Some design knowledge is procedural. It includes the overall procedures needed to complete a design in some domain, to strategies for coordinating design actions within a team, to overall strategies for generating results emphasizing particular characteristics, such a high performance or economical operation, durability, or innovativeness. In design education, these procedures are sometimes reviewed explicitly. Equally often they are presented tacitly in the context of a studio or project course. It has been this procedural knowledge that has been the focus of most design research to date.

Recent advances in psychology provide a background and conceptual framework to study many of the detailed questions raised above. The next section presents an overview of some of the work in mental imagery, knowledge representation and related areas that seem to provide a useful basis for studying and understanding these issues.

2. Mental Imagery and the Structure of Knowledge

The mental representation of knowledge has been an issue of serious study since Plato's discussion of the theory of forms in the *Meno* and throughout the history of psychology (Maier 31). As psychology developed in the early twentieth century, mental imagery seemed personal and without any measurable trace; it was easily disputed and seemed not accessible through empirical studies. Most behavioral psychologists, who were trying to make psychology a serious science, held imagery in disrepute. Later, the beginning work in cognitive psychology also did not accept the notion of mental imagery as a form of reasoning. Their early efforts focused on problem solving tasks that could be easily represented symbolically, such as crypto-arithmetic and chess. Newell and Simon argued for a node-and-link structure of semantic memory (1972:c14), (but later broadened their view, see (Simon 76)). Pylyshyn (73) argued that there were no "little men" in one's head to look at images and argued strongly for a symbolic, propositional structure.

Yet Paivio (71) found that learning ability was influenced by the ability to mentally visualize the information referents. Cooper and Shepard (1973) showed that the response time required to match 2D and 3D mental images was proportional to a degrees of rotation required to the source and target images. That is, measurable performance carrying out some operation could distinguish whether people used mental images in some task rather than a node-and-link or other symbolic structure. The initial mental operations associated with imagery were applicable to perceptual images, such as rotation of a form, scaling it or measuring distances between forms. A variety of experiments indicated that these capabilities were easily carried out mentally and not coherently explained using symbolic representations. Developing tests for these types of functions, attempting to distinguish mental representations by their functional capabilities, led to many debates and continued refinement of experimental technique (Kosslyn 96:c 2).

Over the last fifteen years, a wide variety of operations on mental images have been studied. Among these are interesting capabilities for mentally operating on 3D shapes, including the integration of multiple orthographic views into a 3D shape and then recognizing new views of the shapes (Cooper 89), mental folding of a flattened shape and judging joined edges and other properties (Shepard and Feng 72), emergence of new shapes based on mentally composing known or easily understood 3D shapes (Finke 90). Shepp (89) has begun to identify how visual features of shapes are extracted from an image and the properties of the features and their articulation during an infant's maturation. There is no straightforward or coherent explanation of these activities based on symbolic processes.

Evidence suggests there are varying types of mental images, ranging from 2D images (possible derived from 3D models) to detailed 3D models, to more abstract topological relations of connectivity (Denis,96). Johnson-Laird specifically argues there are at least two levels of imagery, (though his arguments seem to argue there are three levels of model) (Johnson-Laird 96). One kind of image is a *mental model*: an abstracted spatial form that can carry different kinds of relationships: topological, directional, etc. A mental model roughly corresponds to a diagram. A *3D model* is a complete shape in 3D from which 2D views may be projected. Last, there are *2D images*, which resemble pixel images with a fixed size and resolution. Fodor proposes a large, indefinite number of mental image types (75). Most researchers take the position that a mental image has a limited amount of information fully. Complex images or 3D models are not retrieved whole from long-term memory; rather they are constructed from a collection of imagery information about the object of interest (de Vega, Inton-Peterson et al 96, Kosslyn 80). This suggests that it can be constructed in different ways, depending upon the need. These different functional capabilities have been only partially explored.

Recent neuroscience evidence also supports mental imagery. The issues being debated can be cast in terms of the functioning of emsembles of neurons (Kosslyn 96:pp 4). Using positron emission tomography (PET) scans, the visual field was found to have a specific mapping to adjacent neural regions (Fox, Mintun et al 86). Moreover, soldiers with brain damage sometimes lost functioning on part of their visual field, and also the ability to form mental images in that part of the field, suggesting that stimulation of the region was not an epi-phenomological event, as argued by some psychologists, but was a functional one (Fareh, Soso, Dasheiff 92). These studies verify the sharing of some processing pathways by both perception and imaging (Kosslyn 96:c 11).

This debate evolved so that it was no longer about whether people experienced mental imagery; it was acknowledged by most researchers to be a personal phenomenon. The question was whether imagery could be used for reasoning. Similarly, the imagery adherents were not taking the position that all thinking is based on imagery; language processing and mathematical processing was readily accepted (vision tasks usually had to be given to people in words.) Rather, the question was how these internal representations are used, the capabilities associated with them and the role of referents and cross referents (Kosslyn 96:c1). Based on the kinds of functional capabilities reported above, it is now generally accepted that people can do some reasoning using mental imagery.

All of this work acknowledges what I suppose all architects and most engineers have always known; people can integrate multiple drawings and interpret the forms and spaces they define. They can mentally simulate various activities in as-yet-unbuilt spaces and use such simulations to assess the space. However, researchers have also begun to map out the general capabilities and limits of these mental skills. There also are a variety of reports regarding individual differences in the ability to form and process mental images (Kosslyn, Brunn et al, 84, Denis 96) and different strategies to deal with mental tasks, some involving imagery and some not.

What is the basis for these individual differences? Are they innate, genetically determined faculties or are they developed by exercising them? All people seem to have some level of proficiency in mental imagery. There have been a small number of studies that indicate that mental imagery skills can be easily improved through training (Wallace and Hofelich 92). In an attempt to get to a finer grained neurological level of imagery processes, Kosslyn has broken it into nine component functional capabilities (96:c 11). They include: an attention window, low-level pattern activation and matching, exemplar activation and matching, spatial relation encoding, categorical encoding and so forth. He and others have begun to generate evidence for individual variation in performance for each of these different mechanisms, rather then assuming mental imaging to be a single capability (Kosslyn 94: p. 395-407).

The imagery debate has been carried out somewhat separately from other sensory modes. A significant body of literature exists on the cognition of sound recognition and interpretation, body movements and taste. They provide strong evidence that learning, recall and mental reasoning occurs normally in each of these sensory-related modalities. For example, people are able to dynamically compose muscle actions (for example in writing or playing a sport) (Lindemann and Wright 98, Viviani and Cenzato, 85) and they can interpret unique compositions of sounds (as in listening to music or in interpreting what a person is doing in the next room from the sounds) (Bregman 95). Learning and reasoning regarding taste is a capability from infancy on (Harris 97). Thus the more general position is that there is some level of reasoning capability in most or all of our sensory modalities. The current issues involve the roles played by the sensory modal memory and knowledge in conjunction with the mental visualization, propositional processing and other forms of conscious reasoning. For us, an issue is if and how multi-modal information is used in design.

2.1 The Structure of Knowledge

If we store and later recall experience in each of our sensory modalities, and also have large amounts of symbolic information that is learned, how are these different types of knowledge organized, related and operated on? This question poses a current area of intense paradigm-building and research. Yet the general outlines, in relation to our interest in the structures used to carry design knowledge, can be defined. Most of the interpretation presented here draws heavily from Barsalou (93) and Kossyln (80, 96).

One starting point is the shared processing of visual and other sensory perceptions and processing of sensory memories. Many theories of cognition are strongly related to

perception (Langaker 86, Talmy 88). Perception is not the photographic capture of an environment. It rather relies on focusing on aspects of the whole phenomenal situation, whether the aspects are visual, kinesthetic or auditory, recording mostly those aspects attended to (Kossyln 96:c 3, Barsalou 93). Selective attention largely determines what is encoded in long term memory (Craik and Lockhart 72), distinguishing vague recollections from sharp memories.

Encoded perceptions are thought to be composed according to what Crowder (93) called *procedural theories* that organize the memory of an experience in similar neural units to those that processed the original experience. Barsalou calls this knowledge structure a *structural description* that is built up relationally and hierarchically (93). Perceptually, people see or hear a pattern, match it with an identifiable structure, then fill in the details in succeeding moments based on the assumed structure (Kosslyn 96:c6). These procedural[2] knowledge-structures are built up by "focusing strategic processing to the perceptual experience and extracting them as individual components" or chunks. Temporal or spatial relations between different inputs provide an initial automatic level of integration.

This does not mean that pixilated images are never stored, but rather that they require conscious attentional focus, and upon recall are part of a larger structure. Such an image has a limited level of detail and is located relatively within a spatial configuration (Kosslyn 96:c10). Singular mental images are of a detail and scale to correspond closely to the image captured within the retina. Multiple images may be composed and scanned over to identify relations (at a lower resolution). Similarly, sounds, strong feelings, smells and kinesthetic behaviors are similarly stored, if they are originally attended to. These perceptual structures may represent multiple states over time, corresponding to what Langacker called a "cognitive grammars" (86). These perceptual structures may carry a mixture of perceptual modes, including aspects of sounds, images, smell, and feelings, resulting in a potentially rich remembrance of an event. As a perceptual structure becomes familiar and retained in long-term memory, it can receive incremental elaboration. Thus a recognized face may gain associated tones of voice, a collection of expressions and the moods experienced with them, and so forth. Whether these structures are the same or different from the more logically based propositional features is an area of current contention.

Experiences and other knowledge stored in memory are made more accessible if they have differentiatable cues. Word descriptions or names are the obvious example cues. Words, encoded as sounds or images, have an arbitrary but culturally-defined relation with an appropriate perceptual structure. For example, the word "dog" or alternatively "chien" is related in ones experience with a class of house mammals that bark. In this way words and other symbols give us access to the properties of our perceptions. Symbols can be associated with experience in this way, to form a propositional structure for communicating experiences, from our past or as projections of the future. These propositional structures provide us with ways to access, and make temporal, numerical

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[2] Here, I am using procedural in Crowder's (Crowder 93) sense, that memory is associated with the senses that originally received it.

or logical inferences on our experiences—such as estimating the mileage from the time taken for a trip that included several stops. Thinking is not made up of logical operations on some isolated symbols alone.

In experience, Barsalou (93) suggests that propositional structures are developed secondarily from the procedural, experientially based ones. This explains why we are sometimes unable to initially express our experiences. Our experiences may initially have no verbal referent or stored interpretation. The first time someone describes an experience, it is a type of translation. In making the translation, linkages are built that enrich and elaborate the initial structure.

Later, upon recall of some event or concept, we recall only small portions at a time of what we know about it. That is, we may know a great deal about some concept or category, i.e., "dog", but we tend to recall only seemingly relevant sub-parts (Barsalou 93). If we ask the same question about a design of a doghouse next week as we did today, we are not likely to get the same answers.

So far I have emphasized the encoding of experiential information and treated symbolic information as secondary. But huge amounts of our knowledge are not directly experienced, but gained through external symbolic representations.

2.2. External and Internal Representations

By the time students reach the university, they are expected to have good skills in learning information and reasoning in several symbolic representations. They are expected to be able, at some level, to process them mentally, for example to make inferences, to identify inconsistencies, or to do mappings between them, such as between words and math or describing in words sensory experiences. These symbolic representations include written and spoken language and various forms of high school mathematics.

How were these external representations learned? Consider for example how we all learned to write. In primary school we learned to recognize and write the alphabet. We also learned the hand-eye coordination to write them. We practiced writing by filling pages of As, Bs, Cs etc., paying attention to each letter form and our mental tracing of them, until the muscle actions became accurate, smooth and automatic. Study of learning muscle movements for acts like writing show that such movements are organized hierarchically, with low level muscle movements being different, for example, for writing on paper versus a chalkboard, while the high level controls are the same (Lindemann and Wright 98). Successful students after several years are able to write fluently, meaning that the processes have become *automatic*, transparent and relatively effortless. They are not aware of the complex muscle and mental process of writing, but can focus directly on their ideas and phrasing. Similarly, with practice, typing can become automatic, resulting in the direct expression of ones thoughts on paper. Learning to read develops in a similar way. We began by learning to identify the alphabet and also whole words. We then put them together, drawing upon our existing knowledge of spoken language. With much practice, the process of reading becomes automated, allowing the meaning of the words to be received directly through the

transparent interface of visually interpreted words and sentences. The processes of learning to read (Massaro 98) and to write (Gregg and Steinberg 80, Ericsson and Charness 94) have been well studied and documented.

Written language and math are taught as external representations, using paper and pencil. Through practice, two things take place: skills in reading and interpreting the representations are developed to the point of automatization, so these activities can be done without conscious effort; secondly, they are internalized, allowing some processes initially learned externally to be carried out mentally. That is, the learned math representation allows us to solve simple problems in our heads. Learning to read and write allows us to phrase and compose words in our heads, often used for mentally planning what to write (as this author is doing sitting at his word processor). The point is that learned external representations become internalized and become part of the mental representation capabilities available for cognitive processing. They become an additional intrinsic part of our reasoning capabilities. The ability to learn new representations and to internalize them is not limited to written language and high school math. It can also apply to a variety of other special representations. The range of representations potentially available for thinking is open-ended.

This view of cognition emphasizes that we have many different ways to internally represent information. People may attend to different aspects of the same event and gain different information from it. We often have multiple alternative representations and solution methods for dealing with a single problem. Current understanding allows us to appreciate several phenomena; explaining an emotion requires translation from the original modality to spoken language. Explaining a design action may also require translation and be difficult, if the reasoning for it was not verbally based. Different experiences and learned information need not be consistent nor fully integrated. Different people may internally represent the same experience differently, and interpret it differently. Short-term attention to recalled information (what might traditionally be called reflection) may identify conflicts and possibly resolve them. Reflection can also identify new relations between stored information, developing inferences. Using mental imagery, we can often simulate experiences or events only conceived mentally, imagining how we might walk through a space or view a scene. This view suggests the richness, power and great variation of uses available in human cognitive abilities.

This rough, abbreviated overview of recent research has attempted to summarize what is known of how humans mentally represent and structure knowledge and especially some of the capabilities regarding mental imaging. It identifies at a crude level the cognitive apparatus with which design students are thought to function. In the next two sections, I reframe the questions raised at the end of Section One according to this work and to pose them in a form that can be studied and potentially answered. First, I consider the teaching of design representations and whether they should be considered external and/or internal representations. I also address some of the roles of mental imagery in design.

3. Design Representations

All design students are taught new specialized representations at the university, as a foundation of their design education. These add to the representations learned earlier. The new representations broadly distinguish different types of design fields and serve as a base for more advanced learning.

Calculus and other forms of mathematics are among these advanced representations, taught as a foundation for advanced topics in engineering. Students are expected to able to represent problems presented in words in the proper mathematical form and also to interpret real world cases. They are expected to be able to take the necessary measures and assign appropriate values to the parameters of the math models. Example operations for reducing the mathematical representations and solving them are given in class; homework assignments give students experience in applying similar solution methods. Students are expected to be able to plan sequences of operations to be executed using paper and pencil (or a math package such as Matlab®).

While mental planning of operations is required to be minimally competent in advanced math courses, experts in calculus are able to do more, to represent problems and carry out operations on them in their head, without paper and pencil. One need only listen in college hallways after a calculus or physics test to hear students discussing their process for solving the most recent problem. These discussions are held without paper and pencil, with the participants carrying the formulations in their heads and describing simple operations. It is clear that some students, possibly most, are able to internalize the representation of calculus and to operate on it mentally. Is this the norm or an exception? Is the mental exercise of solving calculus problems in ones head educationally of value? To what degree does learning calculus to the point of being able to represent and operate on it mentally significantly benefit student engineers?

Mental representation is one possible competence threshold. Another is familiarity with the symbol structure of calculus to the point of being able to interpret it automatically. Like written words, the interpretation can be learned to the point of automatization. Are there significant performance differences between students that know calculus to the point of interpreting it automatically and those that do not? An indicator of automated interpretation would be fast response time in processing simple calculus task. Do such measures correlate with scores in more advance courses? To what degree is internalizing the representation a measure of competence, in comparison to developing strong strategies for applying and manipulating integral and differential equations? Math competence is currently judged according to aggregate scores in tests. Such test scores ignore time and effort, teamwork and other compensating tactics. More detailed analyses, identifying specific representation-specific cognitive skills and capabilities could lead to refinements of how calculus was taught, and provide better diagnostics in response to student problems.

In architecture, the main representations learned are architectural drawings—plans, sections, elevations—and 3D models. The drawings may be generated manually or on a computer; the models may be physical or computer-based. Students are assumed to

quickly gain the capability to interpret architectural drawings and to interpret the 2D layout described. They are also taught, to varying degrees of proficiency, to generate architectural drawings of plans, elevations and sections. 2D drawing is taught within the context of 3D representations, so that the relation between 2D and 3D is given as part of the course context; the drawing process involves mentally mapping from 3D models or physical shapes to plans, sections and elevations. 2D floorplans and sections are important abstractions of a building of immense use in spatially understanding many kinds of circulation, space allocation, construction and other problems. 3D forms and spaces provide another more perceptual representation of a building useful for addressing other issues, including lighting, environmental comfort, and acoustics and appearance (Hewitt 85). Students are expected to gain a set of skills with regard to external representations: to be able to select appropriate representations, represent existing or proposed buildings within them, to be able to map between different representations in 2D and 3D They are expected to be able to make inferences regarding a building's function, carry out mental simulations of activities, assess perspective views and other complex tasks. All of the later capabilities are built upon the ability to "read" and "write" architectural drawings with fluency[3].

Up to the last decade, architectural drawing has been a basic course in architecture curricula. Today, many schools of architecture have eliminated such courses, assuming that it can be picked up within the context of studio courses. Some schools assume high school mechanical drawing is a sufficient prerequisite. In general, quality control on student capabilities in drawing has been reduced in US architectural education. Yet studio courses, the center of an architectural curriculum, assume that students have adequate skills to use these representations in design work. Drawing competence is usually determined by the quality of the drawn product. Knowledge of how representations are used allows posing the competence question differently. Is learning to read drawings to the point of becoming an automatic process a necessary skill for effectively working in architecture? Is integration of multiple 2D drawings into a mental image of the 3D form a necessary skill for architectural expertise? Do expert architects rely being able to "read" drawings? We have all partially learned some external representations that we have not internalized, such as a foreign language or some form of higher mathematics. Such examples point out the varying degrees to which we learn external representations and our differing abilities to reason or think in them.

The special representations learned by engineers and architects are not exclusive. Architects also learn new symbolic representations, including calculus. It is not expected that architects will often encounter calculus-based representations in their professional work, however. Similarly, most engineering fields learn some form of orthographic drawing, usually using a CAD program. Whether engineering students are expected to be able to transparently read, and mentally interpret, integrate and manipulate shapes and compositions, represented in drawings, varies from school to school.

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[3] Here, architectural drawing is distinguished from sketching and doodling, which is a very informal and personal type of drawing, to be discussed later.

The point is not that interpreting calculus formulas or architectural drawings are themselves examples of expertise. Rather the issue is whether understanding models represented in integral or differential equations and being able to reason about those models requires the more basic ability to easily read and interpret them. Similarly, the question in architecture is whether certain advanced capabilities, such as the functional and cultural interpretation of buildings, are based upon the ability to automatically read architectural drawings.

3.1. design capability as a hierarchy of representational and reasoning skills

After gaining capabilities in calculus, engineering curricula requires students to undertake work in statics, thermodynamics, circuit flows and so forth to address analysis of physical phenomena. Students spend time learning the mathematical representations of a design's different behaviors with regard to forces, resistances, flow, to which a design responds. They learn to both characterize particular behavioral issues in terms of mathematical models, and also how to solve the formulated problems. They learn the measurements that correspond to the parameters of the models and how to extract these from real situations. They also are expected to understand and respect the limit conditions of the model and any other built-in assumptions. The different kinds of analysis are initially taught singularly. Later, they may be combined in more advanced courses that address integrating multiple basic forms of analysis in application areas, such as thermal stress, analog-digital circuits, electro-mechanical systems and so forth.

Similarly, the reading and interpretation of architectural drawings becomes a basic, assumed skill early in architectural education. Drawing reading is quickly assumed to lead to the integration of multiple views to interpret 3D building shapes and spaces. Later work builds upon these integration capabilities to deal with reasoning about the spatial qualities, functionality or use of the spaces defined in the multiple drawings. Students without the ability to mentally image 3D spaces may resort to making such assessments by constructing external representations of them. Repeated construction of an external 3D representation probably helps students to learn to mentally image spaces. In this way, the tasks have a potentially self-correcting structure. Only after learning to "read" and effectively use such external representations can issues of decision trade-offs, of values, risk and other high level judgmental issues be productively applied.

The skills used to address advanced engineering issues appear to build upon a complex set of previously learned capabilities. The composition of these capabilities define a lattice of skills, upon which more elaborate forms of reasoning are based.

Diagramming the individual capabilities required to carry out some high level design task allows us to better understand the atomic skills needed to accomplish the task. A small example is laid out in Figure Two. It identifies some of the prerequisite skills assumed in mental simulation of activities within a space, something expected of students in advanced architecture courses. (Other knowledge, for example regarding activities in the designed space, is omitted from the diagram.) The more basic skills are at the top of the figure, which are specialized by the capabilities below them.

Read arch. drawings and interpret in terms of geometry and entities

Interpret floorplan in terms of Circulation and workplace layout

Integrate multiple drawings to derive 3D layouts

Imagine 3D form defined in drawings

Mentally simulate construction operations

Mentally simulate activities in 3D space defined by drawings
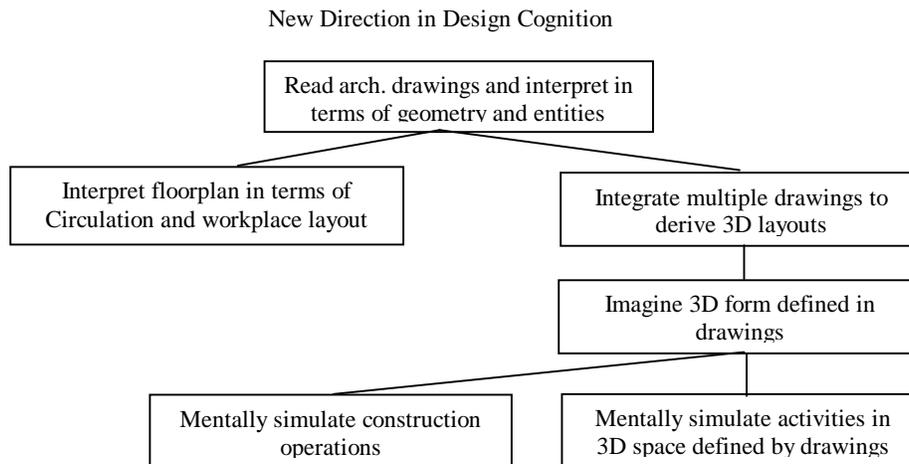
Figure Two: A partial semantic hierarchy identifying architectural drawing skills needed to mentally simulate portion of a design

Such a lattice articulates what needs to be known to possess particular design skills. Systematic study of the capabilities of students with regard to such hierarchies could lead to articulation and refinement of what the hierarchy of skills is and how we might facilitate learning its components. In addition, such articulation allows better diagnosis of student's problems. For example, why is a student not able to recognize visual or functional issues that arise within a specific layout? What is the cause of a student's generation of a building elevation based on a known style but that ignores basic proportional issues?

3.3. Use of mental imagery in solving design layout tasks

A large literature exists of anecdotal reports from people thought to be creative that report the contribution of mental imagery to their creative efforts. Some are by scientists: Einstein, Maxwell, Kekule, Watson, Bohr, Faraday, Pauli and Feynman, and others are by artists: Mozart, Wright, Surls (reported in (Intons-Peterson 93a, Miller 84, Shepard 78)). All of these examples deal with problems or issues that have an aspect that can be characterized spatially. Often, it is that spatial characterization that provides the crucial insight. Most areas of design, such as mechanical engineering and architecture, involve the spatial composition of entities. Spatial layouts are an important if not a central aspect in most areas of design.

At the cognitive level, spatial layouts may be generated using different processes. The range of processes may be defined by two extremes. At one extreme, the design may be fully generated in an externally drawn representation. It is composed and refined by manipulating the symbols and structure of the drawing. In this case, the designer's knowledge consists of procedural operations that manipulate the drawing and applies various criteria regarding an appropriate layout. A variation of the first extreme is using a master layout to record major decisions, but to generate small more detailed but partial layouts to deal with aspects of the design. That is, external representations are used, but they are hierarchically decomposed, then recomposed. At the other extreme, the designer can build up the design layout mentally in his or her head, applying

manipulation operations and criteria mentally to the layout, until an appropriate layout is generated. The external representation is later used to record the layout generated mentally. In between these extremes are various mixed strategies where portions of the design are generated mentally, then added to the external drawing.

A famous anecdotal example of the second strategy was reported by Frank Lloyd Wright's staff at Taliesin. Mr. Wright had been hired by Edgar Kaufmann of Pittsburgh to design a summer home at Bear Run, in central Pennsylvania. Mr. Kaufmann telephoned Mr. Wright from time to time to learn the progress of the project and Mr. Wright always reported that the project was proceeding well. No drawings were generated however. This type of communication continued for over a year, with Mr. Wright always reporting that the project was proceeding well. After about 15 months, Mr. Kaufmann called unexpectedly and asked the same questions. When Mr. Wright reported that the project was proceeding well (again), Mr. Kaufmann told him he was nearby and would like to come by and review the drawings. He said he would be there in an hour and a half. Mr. Wright said fine and hung up, then sat down and in about an hour drew up the plans, very near to their final form. He design became known as Fallingwater, one of the most famous residential buildings in America. He had clearly developed the design fully in his head, and then produced the drawings to record it for the client[4]. Wright wrote about his design process in 1928.

> "Conceive the building in the imagination, not on paper but the mind, thoroughly—before touching paper….Let it live there—gradually taking more definite form before committing it the draughting board. When the thing lives for you—start to plan it with tools. Not before. To draw during conception or sketch, as we say, experimenting with practical adjustments to scale is well enough if the conception is clear enough to be firmly held…But if the original concept is lost as the drawing proceeds, throw all away and begin afresh" (Wright 28).

The report on the design of Fallingwater seems to be an exceptional case of developing a full design in ones head. It and Wright's admonition and the other creative breakthroughs mentioned earlier, seem to argue that the development of designs mentally, with minimal reliance on external representations, is the desired mode of creative design. But is this true? Does creativity rely on mental imaging? Or are these examples really pointing out people who either have unusual imaging capabilities (Wright) or have had to resort to such activities out of necessity because they could not draw (some scientists)? Do better results usually occur with greater reliance on external representations? Or is creative ability significantly enhanced through mental imagery?

Finke (90) has carried out a number of studies that show that average people are able to use mental imagery to compose forms and derive emergent practical objects from them. He had them memorize shapes such as those shown in Figure Three. He then asked them to make interesting compositions in their heads of the memorized shapes, without reference to any function.

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[4] This event was described in the Public Broadcasting Service special biography of F.L. Wright, televised in 1998. It is also reported in Tafel (79:p3-7).
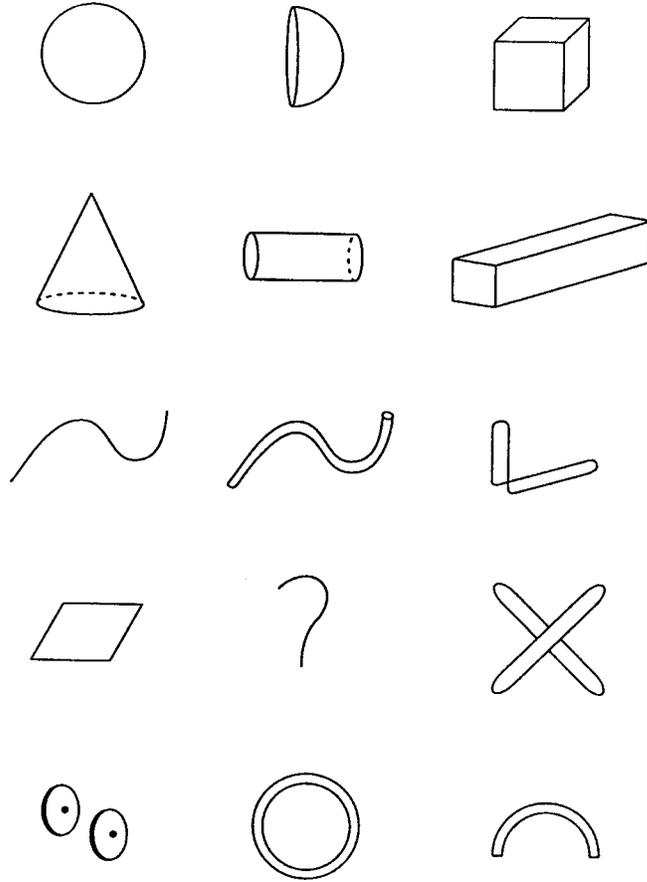
Figure Three: Component objects and parts used in creative invention experiments (from Finke 90)
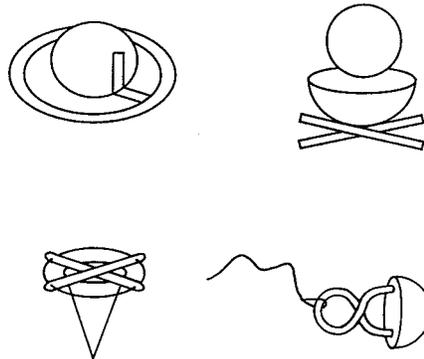
Figure Four: Example compositions generated in the creative invention experiments in Finke (90).

Examples of the composed shapes are shown in Figure Four. He then gave them categories of uses—furniture, personal item, transportation—and asked subjects to apply the uses to the composed shapes. The number of objects identified as applicable were small, since they were created without the assigned function in mind. However, the objects defined were independently considered as very creative.

These studies have been used to argue that mental imaging can enhance creativity in average people, further reinforcing the mental imagery hypothesis. While studies have shown that mental imagery can be enhanced through training (Wallace and Hofelich 92), the effect of such training on creativity has not been tied together. Shepard (78) sought to show a direct linkage between creativity and the ability to mentally image but was only partially successful. Tests of children for correlations between creativity and IQ show a positive correlation, but these results are hard to separate from other correlations with IQ (Intons-Peterson 93a).

(a)

(b)
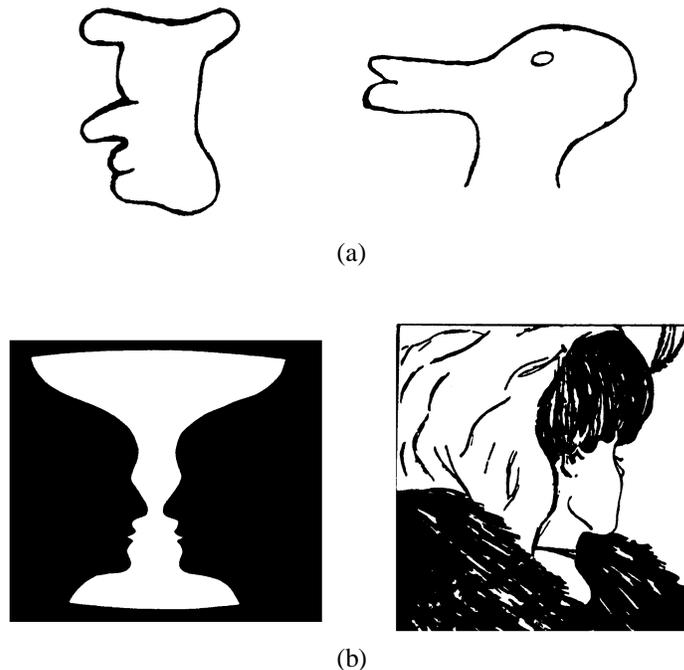
Figure Five: ambiguous figures used by to identify reference frames in imagery.

Other results that have been interpreted as showing that mental imagery can limit creativity. An often-cited study by Chambers and Reisberg (85) showed that mental imaging tends to fix the interpretation of the image. They had subjects memorize ambiguous figures, such as those shown in Figure Five, which were named to give a particular interpretation. Later when asked to imagine the shape and find another interpretation, they could not. However, if they were asked to draw the image, either on paper or virtually in their head, a significant number of Subjects could re-interpret the

image. These results were interpreted to show that the drawing could be reversed if it became a perceptual process. These results were construed to show that imaging relies on interpreted images, as distinct from less processed perceptions.

A number of studies have elaborated and further interpreted these results (Reisberg and Logie 93, Peterson 93). The current understanding is that mental images are interpreted within a *reference frame*. The reference frame includes orientation, scale, figure-ground relations, and classification of features (Chambers 93). Later operations on the mental image can be undertaken if they do not require changing the reference frame. The first form in Figure Five(a) can be interpreted as a chef looking to the left, or an upside down dog. The second form in Figure Five(a) can be interpreted as a duck looking left or a rabbit looking upper right. Both figures require change of the reference frame. In the left form in Figure Five(b), the martini glass or the two faces interpretations do not require changing the reference frame, nor does the young lady or old lady in the right image. It was found that the images in Figure Five(b) are easier to re-interpret mentally than those in Figure Five(a). Self-conscious action is required to alter an image's reference frame. Thus in certain situations, mental imaging may fixate thinking according to one interpretation.

From these and other studies, it seems that at least two kinds of actions can reduce such mental fixations. Asking a person to draw the figure seems to have a loosening effect, facilitating re-interpretation (Chambers 93). Also, if a person is instructed (by others or oneself) to re-interpret the mental image, re-interpretation may be undertaken. These results suggest ways to address the recognized problem of fixation in design, especially among beginning designers (Sachs 99, Atman, Chimka et al 99).

These studies support Wright's contention. Mental imagery seems to facilitate design creation, especially in generating new concepts or compositions. Through imagery, people can learn new things from images they have generated. Mental imaging may be limiting, however, if relied on alone (without sketching) and if re-organization of the mental design concept is required (Reisberg and Logie 93).

However, most design protocols don't describe designers thinking about their design contemplatively. Rather they describe designers as active, frequently sketching, making notes, generating layout drawings, describing issues, context and forms. Donald Schon's book and papers present and analyze protocols of Quist, (Shon 83: c 4), then Petra and Clara (Schon and Wiggins 92, Schon 92) that capture the dynamics of such processes. The analyses by Schon are different from most in that their interpretation seems to correspond more closely with what designers themselves think they are doing. Schon makes several important observations about the process of design, drawn from the protocols. One of them is the dialogue that a designer carries out between their internal mental representation of the problem and their external representations. This dialogue involves "moves" that take conceptual positions in response to the mentally understood context (slope of site, population, climate, social organization and activities). Moves seem to apply to both the internal representation and the external ones. He interprets how a sequence of moves—what he describes as "seeing, moving, seeing" build upon the context of earlier moves. Later he also shows how a form has multiple interpretations and is conceptually decomposed in different ways, for example

as multiple letter Ls or as a cluster with attached blocks. These different emergent structures lead to the remembering of different design issues and different moves. He also notes how a designer mentally simulates walking along a path to derive new design criteria.

Reading these dialogues carefully, one gets the impression that Schon's "seeing" involves internally representing spaces and forms that are drawn externally, then a "move" acts upon the two representations, either correcting undesired conditions or elaborating the design. "Seeing" again leads to repeating the cycle. Rather than the two extremes, this type of design process seems to rely heavily on a "dialogue" between mental representations and simple external representations that abstractly capture some geometric properties and relations, while most of the context is carried mentally. Sometimes a move is a change of form, other times it is a reframing or reinterpretation of the external representation, without a physical change.

Many design fields and designers revere sketching as central to creativity (Robbins 94, Henderson 99), but we know only a little about how sketches operate cognitively. A similar analysis of the tasks used in the Schon study[5], but focusing on the use of sketching, is presented is Goldschmidt (91). Goldschmidt identifies a "dialectics of sketching" that cycles between "seeing-as" and "seeing-that". She considers these actions from a perceptual and imaging standpoint. Seeing-as is a perceptual interpretation of a sketch, structuring it in various ways. Seeing-that applies non-figural arguments to the sketch. In other words, sketching generates new forms (or allows re-interpretation of an existing one) that are interpreted by the mental imaging process, which leads to revision of the sketch. Later Goldschmidt extends this viewpoint (94), presenting arguments that early phase "doodling" on paper is a form of interactive imagery. She proposes that doodling supports and augments mental imagery, allowing the quick formation and manipulation of complex forms, forms that would be challenging to generate or maintain mentally. The sketches provide cues for retrieving new information and for re-interpretation. Such doodling can be vague in the way that mental images have been shown to be vague (Chambers 93).

Goldschmidt's hypothesis that doodling is an extension of mental imagery is provocative regarding the close link it proposes with imagery. If we are to understand sketching it needs to be tested. The hypothesis seems to assume that there is a one-to-one correspondence between mental imagery and sketching. Do designers mentally capture the image of sketches as they are created? As an example test, can they be distracted after generating a doodle and still reproduce it? Is a large doodle structured in a way similar to images, as a series of possibly overlapping images, as proposed by Kosslyn? The relation of sketching to mental imaging is especially interesting in light of the previously reviewed work indicating that images are necessarily interpreted while drawings need not be. How does interpretation apply to this dynamic process of mental

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[5] The exercise used by Schon and Goldschmidt was originally developed by William Porter and is discussed at length in Schon (88).

and physical image generation? For some further discussion, see Goldschmidt's Chapter this volume[6].

Schon and Goldschmidt have begun to identify a mixed role for mental imaging, its interplay with symbolic or propositional knowledge, and the interaction between imaging and sketching. The processes of design described by Schon and Goldschmidt however are very different from those described by Wright. And these are different from the processes reported in most protocol studies. Are all these approaches equally effective? Further investigation of these questions may allow us to better understand design thinking and how to it can be more easily learned.

3.4. Design Tools as External Representations

The cognitive process by which people learn language and mathematical representations provides a useful perspective on how they *should* learn computer-based design tools. Computer-aided design (CAD) systems are becoming standard tools-of-the-trade for architects and the basic tool for geometric representation by mechanical and other engineers.

The negative side of current CAD systems is the user interface complexity of these tools. Architects and engineers have strongly criticized most CAD drawing and modeling tools because of their complexity and long learning time (Johnson 97, Henderson 99:c6). The complexity of most CAD systems is such that without daily use, constant attention to how to operate it is required. Users must spend mental effort at the user interface of the tool in order to carry out most operations, distracting them from design issues. An important goal of the field of human-computer interaction is to reduce the cognitive cost of computer interfaces so they can be used transparently, with their operations being automated by the user, as in writing and typing. Can this goal be widely achieved for CAD systems also? It would seem to be mandatory if computer-based sketching is to support the role posed by Goldschmidt (94) of augmenting mental imagery. She identifies some criteria for such sketches: economical, fast, ambiguous and easily managed over time. More generally, all general purpose tools that are meant to support design need to be easily learned to the point of automatization. This is an important criterion that explains many of the limitations of current CAD tools.

There has been anecdotal reports that knowledge of form manipulation enhances the ability to generate and interpret form, what architects might call "form literacy". Sculpting and printmaking were basic parts of the Bauhaus curriculum, in support of these assumptions (Dearstyne 86). Do students that have learned well a solid modeling tool, such as Pro-Engineer®, 3D Studio Viz® or Architectural Desktop®, also become familiar with complex shapes, in the way a sculptor does? Do such students gain new ways to conceive of shapes in their heads? Do they learn to carry out sculpting operations in their heads, as might a sculptor? These questions apply to both architects and engineers. A possible benefit of these powerful sculpting tools is that they may allow users to become more knowledgeable in forming, recognizing and interpreting complex shapes. These hypotheses have not yet been tested.

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[6] For a survey of current work in sketching, see Purcell (98).

3.5. Methodological Issues

A variety of approaches have been developed to study imagery and other mental representations. Most have relied on experimental methods. Some seem well suited to studies in design cognition. In an experimental setting, it is desirable to simplify responses of Subjects to simple tests. One often-used procedure asks whether two or three different views of an object are of the same object or different ones. Two example objects are presented in Figure Six. The views may be given simultaneously or sequentially (Cooper 89). The assumption is that answers require the Subject to mentally integrate the two views. Another test is to present two or three orthographic views, then ask Subjects to match their mental image with an isometric view (Cooper, Mumaw, Morrow 84) or carry out operations on the 3D shape. These tests require Subjects to integrate multiple views, then to determine if they are consistent or to carry out other forms of reasoning on the integrated 3D shapes.
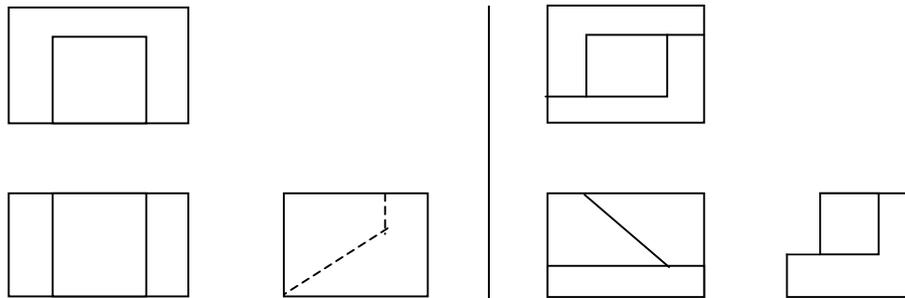
Figure Six: Multiple orthographic views of shapes. Are they consistent or do they describe an impossible shape?

Such experiments must be structured carefully. Other strategies may be used by Subjects to generate responses then 3D integration. Checking the number and location of vertical or horizontal edges or blocks and the order of changes allow differences to be identified, without mentally generating a 3D model. Such a strategy is easily applied to the forms in Figure Six. That is, symbolic operations can be applied to some visual tasks, which defeats their intention and leads to wrong interpretations of the experimental result. It is critical that tests be pre-tested with visually educated users, to assess the different strategies that may be applied.

A reasonable hypothesis regarding mental imaging is that one effect of a design education is to develop student skills in mental imaging. That is, a professional architect or industrial designer should have greater imaging capabilities than a senior design student. A senior student designer should have greater imaging capabilities than a freshman. Similar but possibly less strong effects should occur in engineering education. We know that mental imaging capabilities can be improved with training (Wallace and Hofelich 92, Seel and Dörr 94). However, we currently have no validated measures of the ability to reason and make inferences in a mental representation. The ability to assess student capabilities would be enhanced if we could identify reliable

measures of this mental skill. A commonly used test to assess mental visualization skills in people is the Minnesota Paper Form Board (Likert and Quasha 41), but questions have arisen regarding these and other tests of imaging, because they have not correlated well with individual measures of imaging ability. See Paivio (86) and Intons-Peterson (93a). Perhaps carefully constructed tests that require imaging ability are the best tests for now.

1. what are a, b, c, d in this drawing?
2. how many windows are there?
3. how many people can be seated?
4. the person at the desk can see the faces of how many people?
5. when the door is first opened, can a person at the table see who opens it?
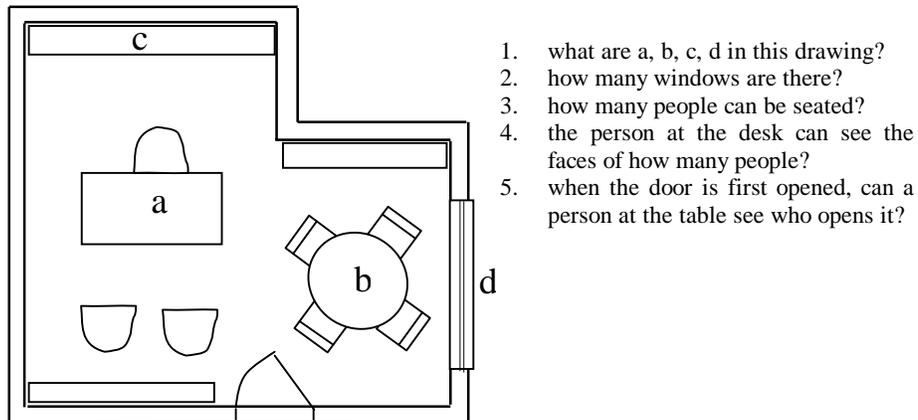
Figure Seven: An architectural drawing and some questions to be asked about it.

An example test figure is shown in Figure Seven. To test if students are able to read drawings, the questions can be asked with the drawing present. More challenging is to present the drawing and ask students to study it until they can remember it, then take it away and ask the questions. I propose that they can only be answered by carrying the image of the drawing in ones head.

A more general question regarding mental representations is "at what point of learning any external representation does it become available for internal representation and support mental reasoning?" With repeated practice, "reading" an external representation becomes easier and eventually becomes transparent, allowing automatic interpretation. In roughly parallel fashion, practice allows us to gain the ability to mentally use the representation and to carry out simple mental operations. Do these two capabilities—automatic reading of a representation and the ability to mentally reason in the representation—come into being at the same time as complementary capabilities, or does one precede the other? It would be valuable to determine this relation, if it exists. If they took place together, then testing could use one capability as a surrogate for the other.

In summary, the development of expertise in the use of both internal and external representations is one of the hallmarks of design education. At the time of introduction to a new representation, people are very aware that they are learning something new. As their familiarity grows, using the representation becomes easier and its application more confident. Still later it becomes routinized; we might say it has become a skill. At some point, it becomes automatized and we are hardly aware of the representation and are

able to focus on its semantic content. During this time, the ability to use the representation internally, in ones thinking, grows. As the representational skills advance, new skills are based on them. These may be based on reading the representation or manipulating it, and/or interpreting various results. It is likely to involve mapping between the representation and other knowledge, held for example verbally or mathematically. This seems to be the point where design expertise can emerge. The development of the lower level representational skills is a prerequisite for the high level reasoning and for the actions required of effective designers.

Hopefully, we can learn how such skills are built up and the critical links required in developing such a lattice of skills. Research in mental imagery in cognitive psychology allows us to frame many questions of relevance to various design fields. I propose that it offers an practical foundation for future work in design cognition.

Now I turn to review another important issue in design education, the structuring of a design context.

4. Structuring of Design Contexts and Recalling Relevant Design Features

An important aspect of any design task, recognized in both engineering and architecture, is the structuring of the design context. This can be characterized in different ways: for example, as Simon's ill-defined property, distinguishing design from other forms of problem-solving; as Winograd's contextual "situatedness" or as the development of Schon's "design world". Described in more engineering terms, designers are assumed to be able to interpret a design problem readily into a set of performance or behavioral requirements of the technical system (to use Hubka and Eder's term (88)). That is, all descriptions of design characterize within their own vocabulary the important subtask of formulating an understanding of the context of the design situation, of the function and behaviors important to a successful design, to identify relations and dependencies, whether technical, user-defined, cultural, climatic or economic, and the class of materials, features, construction methods, or other entities the design is to be composed from.

Students in both engineering and architecture have some base knowledge of their field when they begin it, gained from living in buildings and visiting many others, or in engineering, gained from working on cars, computers or other machines. Previous learning, from personal reading or school, has also added to their mental "store".

Architectural education is assumed to incrementally build up a rich memory structure for young architecture students through studios, courses in architectural history and field trips, all considered essential to their education. Together these courses present a historical/cultural view of buildings, their function and response to context, as well as details of their form and aspects of their experiential qualities. The architectural curriculum is organized to structure the diversity of individual experience and to

develop a shared way to attend to architectural experiences[7]. The encoding of architectural knowledge is a complex, multi-modal structure, mixing perceptual memories—visual, auditory, kinesthetic, possibly smell—combined with historical, critical assessment, and other propositional knowledge. In later studio projects, students are expected to be able to identify precedents and analogies with their work, as a way to explain and justify it.

A component of engineering design education is the design project, where students scope out and specify a product to design, in response to some given set of functions (often nonsense functions, such as catapulting an egg some distance and catching it without breaking). In this type of experience, students are expected to gain skills in abstractly defining a structure of functions and composing a mechanical system that supports them. If the project is done well, they will learn a vocabulary to identify different functions, various structures that respond to the functions and gain experience in composing structures. They will learn to identify the critical behavioral parameters, tune those parameters, and so forth. They may also learn to consider secondary functions, such as maintenance, safety, pollution that are important to successful designs in modern society (Ullman 92).

In both architectural and engineering design, the form vocabularies from which designs are composed are very large. For example in mechanics there are many types of mechanisms; in architecture, there are many building types, each with their own set of prototypes. It is not practical for students to become deeply familiar with all types while in school. Rather they generally gain experience in the meta-capability of how to effectively learn and use such taxonomies by examining one taxonomy or a small number. It is assumed that students will later know how to learn the detailed information about a particular design class when it is needed in practice. However, in both fields, consideration should be given as to whether the structuring of this knowledge is done effectively and the general skills appropriately conveyed. This applies to both the structuring of the data, taxonomically or otherwise, and its application and use.

Problem structuring capabilities are an important part of design education of all types. Protocol studies have shown that problem definitions generated by different designers are highly varied. My set of early room layout protocols varied by a 3:1 ratio in terms of relevant criteria generated (Eastman 69,70). In this case, the criteria were based on the same explicitly given information, suggesting that differences in previous experience, the encoding of that experience and/or differential abilities to recall relevant experiences were influential in producing the results. The Subject that generated more than twice as many criteria than the other three Subjects tested offered an insight. After collecting the protocol, I asked him how he was able to identify so many criteria. Paraphrasing his answer, "Whenever I look at a design, I consider it from a basic set of issues.

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[7] One can question from this perspective the effectiveness of the heavy weight put on required history courses. Because the context of historical buildings is so different from current ones, many architecture students receive little analysis of current building types, such as shopping malls, government buildings, airports, high-rise offices, schools or hospitals.

Bathrooms and stairs are the places in residences where most accidents occur. Also, cleaning of a bathroom is a major issue. A bathroom is difficult to keep clean and any reduction of cleaning problems should be attractive to purchasers. I apply these criteria as well as my experience whenever I review some design. That is, I look at new designs from an analytic point of view." This designer had a strategy for encoding design information whenever he looked at example designs. He used this richly encoded information when new design problems arose. This suggests that some designers have trained themselves to experience designs in a specialized way, so that they gain more useful design information from a given experience. This anecdotal description from a designer, who later became well-known industrial designer, suggests that design recall is a complex interaction between structuring experience, reflection about design knowledge and later recall in new design situations.

4.1. Recall of design information

Psychology provides an abstract interpretation of retrieval processes. The associations between information, regardless of modality, are thought to be the basis for recall. The term *activation* is used to identify the strength of associations. Only associations above a certain activation level enter consciousness. On the learning side, conscious attention to an association increases its activation level. However, associations that are experienced but not consciously attended to also increase the activation level, but to a lesser degree. Other influences on recall are the number and uniqueness of cues used to recall some piece of information, and the number of times the association has been used in recall (reviewed in Glass and Holyoak 83:c 7).

At the simplest level, naming a phenomenon or feature allows it to be recalled more easily (Barsalou 93). Architecture and the various branches of engineering have both developed specialized vocabularies to describe important concepts. Names typically denote an individual item or a class of similar items, providing associations with other similar concepts. It also has been hypothesized that imagery is a necessary component for classification, which allows naming (Intons-Peterson 93). That is, classification occurs through the matching of an image with the phenomena being classified. .If this is the case, then people who are good imagers, as architects are proposed to be, should also be good classifiers. This symmetry seems to support the idea that the name-image relation supports multiple means to recall information.

The rich cognitive structures into which design information is encoded, are assumed to facilitate recall. The benefits of such structures were verified by Mäntylä, who ran tests showing significant increases in recall as a result of developing multiple associations and distinctive access cues (Mäntylä 86). There is a well-developed body of research identifying various factors to improve recall (Kihlstrom 96). However, most emphasize encoding strategies and duplicating as far as possible the multiple cues existing during the encoding.

While we could go down a path of design cognition research that examines individual encoding and retrieval processes, it is not apparent that this path will lead to enhancement of understanding how people learn effective strategies for recalling information while designing. Recall implies finding something in memory that is

already stored there. But structuring a design context is much more complex than recalling the right "fact" at the right time and seems to require more complex processes.

When an architect learns about a building, the kind of memory structure defined earlier gets recalled. Relations are defined with that knowledge to existing knowledge. If someone asks "what other buildings are like the New York Guggenheim Museum?", one looks for properties of the Guggenheim and searches for other buildings with those properties. If someone says that the Guggenheim is like a circular car park (not a very attractive association), this association is built from two different relations: a spiral circulation path and a cylindrical form. Mentally constructing such associations, finding common properties or processes in different phenomena, is called forming an *analogy*. Analogies have been an area of study in psychology for some time (Duncker 45, Gick and Holyoak 80, Gentner 89).

The classic analogy is described by Duncker (45) as the radiation problem—of how to destroy a tumor with radiation without destroying surrounding tissue. The source case tells of a general who instead of attacking a fortification straight on, disperses his soldiers all around the fort and has them attack from all angles. The attack succeeds because the soldiers in the fort did not see that an army was attacking them. From this example can you find how to solve the radiation problem? In this perspective, analogy is an example of memory retrieval, accessing indirectly related design information and making a new association. Once the association has been made, the analogy is no longer of interest; it is the making of the association that is the critical cognitive event.

Rowe cites the following examples of the use of analogy in architecture, drawn from the architectural literature: the roof of Le Corbusier's Ronchamp Chapel being shaped like a crabshell, the form of FL Wright's Unitarian Church shaped like hands folded in prayer, and Utzon's Sydney Opera House shaped like sails on a yacht (Rowe 87:p. 82). Engineers' use of functional analysis, that is decomposing a complex system into its individual functions, then using the functions to identify alternative mechanisms that might be used, is considered a form of analogical reasoning by Chi, Feltovich and Glaser (81). A number of studies of the use of analogies have been made in other fields (Vosniadou and Ortony 89).

An analogy arises when some relations in one situation can be adapted to address a problem in a quite different situation. An analogy is defined as a likeness relation, as in A:B as to C:D (shown in Figure Eight). It involves an abstraction taken from one situation and applied to another. Analogies are different from similes and metaphors: similes are of the form "A is like B", where A and B have some properties in common; metaphors are an unconventional way of describing one thing in reference to another, based on some common semantics. Analogies involve relations that have some correspondence in two situations or things, called the *source* and the *target*. The source is the information from which the relation is extracted and the target is the information to which it is applied. Analogy is considered to consist of the following processes: (1) abstracting some significant relations of the target, (2) recalling or abstracting the relations of candidate sources, (3) making an inductive association between the target relations and those of some source (the A::B mapping), (4) identifying other relevant

source properties or relations that can be mapped from the source to the target in a similar way that resolves a problem or unknown (the C::D mapping) (Vosniadou 1989).
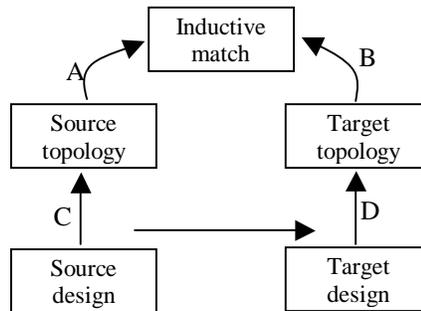
Figure Eight: The structure of analogical reasoning.

Analogies can be made by children as well as by adults (Holyoak, Jun, and Billman 1984). What is different are the relations by which analogies are identified. Analogical relations are described as being "shallow" or "deep". Shallow analogies are those made based on the perceptual or surface features of the two phenomena, such as their color or shape. Deep analogies are based on abstractions of the phenomena, such as their topological structure or function. Some refer to these correspondingly as iconic and structural analogies. The architectural analogies described by Rowe, reported earlier for Le Corbusier, Wright and Utzon, are all iconic analogies. Some people do not consider associations without relevant abstractions to be analogies, but similes.

Engineering involves the application of complex analogies. A high level goal is to identify and apply an appropriate math model characterizing a design's behavior. Errors arise if the wrong math model is applied, or its parameters used incorrectly. The application of an appropriate mathematical model to a design or aspect of a design is a multi-step process. The process has different contexts, requiring different actions. The pure synthesis process is the easier. A mechanism is selected and its associated mathematical model is applied; performance requirements are defined and design parameters selected or derived to meet them. In other cases, however, the design has already been generated, possibly in response to other behaviors or criteria, and the design generated must be analyzed from a particular behavioral perspective. This kind of real-world application of engineering concepts has been cited as a common weakness of student engineers.

This process is another version of the analogy process described above (Chi, Feltovich and Glaser 81). The association of a math model to a design involves two abstractions: of the existing design and of the candidate source mechanisms. The relation between the math model and the target abstraction is part of the initial learning. For lack of a known terminology, I call the source and target abstraction the source and target *topologies*. The topologies are needed to match the design with an appropriate math model. Once matched the corresponding math model can be applied.

Different representations of the topology of a model can be used in learning mechanisms and their math models: in words defining relations and properties or graphically as diagrams. A third alternative is that the second abstraction is not needed and that students can identify the appropriate mapping from the math model. Are there differences in the ability of students to apply mathematical models of behavior, based on the topology representations used in teaching the mechanisms? Studies of primary school students show that pictorial information is a more effective medium for presenting analogies than words or kinesthetic actions (Gineste 94). In engineering, are diagrams or word descriptions more effective than the math models alone, for students learning and application of what they know?

In previous decades, most engineering curricula included lab courses, where empirical studies were undertaken, verifying the relations between the behavior expressed in the mathematical model and the measured behavior of physical objects or mechanisms. By measuring the object, students directly experienced the relation between the model parameters and the physical object. They also learned the correspondence between the physical object and the mechanism topology. This part of engineering has been dropped from many curricula. It may have had unseen value, showing clearly the relation between mechanisms and associated parameters of a math model.

Analogy is an important form of recall process widely used in design. There have been only a few studies of its use in design and its range of use has not been well documented. Architects seem to become more adept at applying analogy as they become more expert (Casakin and Goldschmidt 99). Is this a tacit result of their design education? Or is it a filtering that eliminates aspiring designers that cannot form analogies? Can analogy use be enhanced by specific training? Some information may support the forming of analogies better than other information. What topological abstractions are most useful when the intention is to identify the correct behavioral model using analogy? Analysis of a specific mechanism or building from many perspectives and behaviors demonstrates how a mechanism has many associated abstractions. Such studies of an object are sometimes used in design. They would seem to be one way to show students how to abstract a design to generate more possibilities of analogical transfer.

4.2. Studies in Recall and the Use of Analogy

Comparing and studying designer's methods for recalling relevant design information can be studied using protocol analysis (Eastman 69, Dwarakanath and Blessing 96). In these cases, the original encoded information in memory is not known, but protocol studies can identify differences in recall and highlight interesting cases. But in order to gain a deeper understanding, more targeted studies seem required.

Most uses of protocol analysis in design have been to study the generation of a design from scratch. However, more constrained and structured forms of design study can be fruitful. Crismond (97) used an adaptation of a protocol study that elicits rich insight into how information is recalled and used. His adaptation involves a task structure called "investigate-and-redesign". It was developed to be a less time-consuming and

quicker means to assess design skills, than the more common design-and-redesign tasks. It provides a rich means to assess what information is available and how it is used. The investigate-and-redesign task structure consists of six sequential activities:

(1) The Subject investigates a set of existing products, all with the same function, handling and studying them, what Hawkins (74) referred to as "messing-about" The Subjects assessed the product's function and identified its features.
(2) Subjects were asked to rank each product, using their own criteria, assessed by studying the tools directly, but not using them.
(3) They were then asked to use each product and to reflect upon what they had learned. Subjects ranked the items again, so as to note any changes in the rankings.
(4) They were asked to list features of an ideal device.
(5) Subjects were asked to design an experiment or user study, that would allow assessment of one or more products, as a way to learn what an ideal product might be.
(6) Last, Subjects were asked to design an improved product. This could be an incremental improvement of one of the products or a completely new product.

The two sets of tools to be redesigned—three nutcrackers and three jar openers—relied of physics principles for their functioning. The individual design samples were selected because of their novelty and potential unfamiliarity to the Subjects. They included technical (mostly mechanical), aesthetic and cultural considerations in their design.

The Subjects used in this study consisted of three groups. One group was of naïve designers from special high schools or colleges with special curricula in design. These Subjects were selected for their reputation for being good designers. The second group, called "novice designers," were senior design students at well known universities, all of whom were recommended by their professors as being excellent designers. The last group involved experts. They were all experienced professional designers, inventors or design teachers. Most of this last group held patents and had multiple commercial designs to their credit. All studies were videotaped with two Subjects working together, to facilitate verbalization. Each session covered the six activities and lasted two hours. Twenty-five pairs of Subjects participated.

With existing designs as context, investigate-and-redesign scaffolds a space of designs and uses and potentially users, offering a motivating and grounded exercise. Among the insights about information use that Crismond found were:
- experts used analogies more than novices and naïve designers; they used deep analogies between the given object and other objects to determine the object's function ("looks like a clamp", "this is wrench-like", "just the same as a car-jack");
- each device involved principles of physics that partially determined how well they functioned (mechanical advantage gained from levers or screws); few naïve or beginning designers recognized these principles, while the experts recognized and applied them immediately;
- features of the product were poorly related to their function by naïve designers, while done richly, both qualitatively and quantitatively, by expert designers;

- all three groups discovered new secondary functions of the products during their use that were not identified by looking at it (some nutcrackers propensity to scatter nut shells rather than hold them: p 90-91), the need to grip the jar as well as the lid in an opener (p.252-3);
- naïve designers identified important features only while using it, while expert designers identified features during first examination of the product and used the features to infer the product's intended use;
- naïve designers identified design principles that were primarily derived from a user-perspective ("easy to use") while novice and expert designers identified criteria that were principles based ("I want to multiply the force");
- expert designers considered different user groups, such as arthritic users versus a professional chef (p.232-3); naïve designer's primary user were themselves;
- in redesign, naïve designers predominantly work from an existing design and try to improve it; they also directly transferred aspects of an existing good design to reapply; those with more experience attempted to integrate abstract principles from multiple designs (p 118,127);
- making connections—between form and function, between high-level values and their low-level embedding in a product, between a mathematical model or physical principle and product features, application of an analogy to a product—were common in expert designers and rare or missing in naïve designers (p.276-7);
- drawings were generally used as a scaffold to represent a device, used by experts and only a few novice designers; the drawings were used to support a dialogue with the design, as described by Schon and Wiggins (92), that extended their thinking about it (p. 278);
- for all groups, there were instances of ideas being recalled during one aspect of design, but forgotten and not applied later (p119-120).

Crismond's task structure elicited clear information showing how expert designers studied products using a variety of methods: taking them apart and putting them back together, testing cause-and-effect relationships, estimating forces and then testing them, studying how the product was assembled and predicting failure points. These allowed them to identify and recall a range of subtle criteria for the design of the household objects. Some expert designer's emphasized situated technology concepts, such as adjustment, discrete versus continuous, force concentration, portability, simplicity, while others relied on more science-based concepts, such as mass-force-acceleration, mechanical advantage, and distance-velocity-time relations. The experts used both vocabularies for describing products, their function and assembly, allowing them to identify design issues not recognized by the less experienced designers. The protocols articulated the expert's emphasis on keeping the design space open and not fixating early on any particular class of solution and to ask different questions to gain insight into the space of possible designs (Crismond 97:p255-7).

Crismond's investigate-and-redesign task structure elicited information that allows better understanding how Subjects recall and use design information. Asking about the designs initially, before their function is known, accessed the Subject's knowledge about the artifact world, about forms and their relation with functions. Later, when the Subjects used the products, criteria changed as a result of their experience. Asking the Subjects to define the features and criteria for an ideal product of the given type, elicited

information about how the Subject has mentally linked functions and criteria with values. Last, re-design encouraged Subjects to recall from their own repertoire of mechanisms and to study their integration capabilities. The investigate-and-redesign task structure allowed a rich range of information to be elicited from Subjects with three levels of expertise. It should be applied to a range of designs, studying recall and use of information in a variety design domains.

Another study providing insight into recall was undertaken by Hernan Casakin (97). His Ph.D. thesis focused on the application of visual analogies in design. He was interested in whether they played a role in all types of design problems, or more so in ill-defined problems then well-defined problems. He was also interested in the differences in the use of analogies by beginning designers in comparison to experts.

Casakin's experiments consisted of timed design exercises (10-15 minutes), focusing on the development of one of several different design concepts. Five design tasks were used: two well-defined and three ill-defined. The well-defined design tasks were a staircase and a parking garage; the ill-defined design tasks were a viewing terrace, a prison, a dwelling. Here, ill-defined indicates a design task where the general form of the solution is open, while a well-defined task is one where the general form of the solution is fixed. All design tasks had an associated context and specification. Three groups of Subjects were tested: beginning architecture students, advanced students and practicing architects.

Three different experiments were given.
  (1) a design task with visual displays and explicit instructions to use analogy
  (2) a design task with visual displays but *no* explicit instruction to use analogy
  (3) a design task with no visual displays and no instructions to use analogy (control condition)

Each Subject was given two design tasks, one well-defined and one ill-defined. Between 35 and 52 subjects participated in each of the three experiments, divided fairly evenly among the three experience levels. When visual displays were provided, these consisted of seventeen to twenty photographs, diagrams and sketches laid out roughly in a grid on a 1 x 0.7 meter board. The diagrams were both examples within the task design domain, as well as from other domains, as well as from science and art. They were selected separately for each of the five different design tasks to be loosely relevant, plus a few random fillers. The instruction to use analogy was given verbally, asking Subjects to consider the displays and to use them in forming analogies to derive a solution. The design sessions were video taped and Subjects were asked to think aloud.

Three independent judges at a foreign university made the evaluations and their scores averaged. The well-defined design tasks were scored on a binary scale, 0 for an incorrect solution and 1 for a correct one. The ill-defined tasks were scored on a 1 to 5 scale, separately for both design idea and for the solution. 1 or 2 meant that the design requirements were not met, and 3 to 5 were used to grade satisfactory designs. The reliability of judges' scores were assessed and found to be highly consistent.

For the well-defined tasks, the overall results were as one would expect; the beginning students had very low-levels of correct designs (between 7 and 54%), while the advanced students had generally higher levels (between 17 and 57%); professional architects had the most correct designs (between 18 and 83%). The figures are the range over the three different experiments, with the highest scores achieved when displays are provided and the instruction given to use analogies. The lowest scores were where neither were available —the control condition. For the well-defined tasks, the visual displays significantly helped all three groups; the addition of the analogy instruction further improved the number of correct design results. The benefit resulting from the instruction to use analogy, however, was small for the professional architects and not statistically significant. This can be interpreted to mean either that their experience and the availability of the visual displays led them to use analogy without any instruction to do so, or alternatively that routine processes dominated their activities, resulting in them ignoring the use of analogy instruction. The benefits of the visual displays alone were also not statistically significant for the beginning or advanced students. That is, they seemed not yet ready to adapt or apply the visual materials to their designs, even though some of the visual materials were from the same design domain. The instruction to use analogy was necessary for the beginning students to make significant improvements.

TOTAL DESIGN		Beginning students	Advanced students	Architects
Analogy required Displays provided	Mean	3.463	3.734	3.984
	SD	1.036	.838	.537
No analogy required Displays provided	Mean	2.621	2.939	3.236
	SD	.758	1.029	.740
No analogy required Displays not provided	Mean	2.227	2.580	2.809
	SD	.689	.797	.822

Figure Nine: Means and standard deviations from the three experiments for the three Subject groups, scored for their total designs (1 to 5 scale) from (Casakin 97).

The ill-defined design tasks were scored on a 1-to-5 scale, requiring a different form of analysis from the well-defined tests. Total design scores are shown in Figure Nine. Using unpaired T-Tests, the results, evaluating whether the effects of an instruction to use analogy versus having visual display but no instruction, were significant for all user groups, with <.002 or less probability. However, the results are surprising for the professional architects, since there were not parallel to the results for well-defined problems. The effective use of the visual information by practicing architects was not apparent without explicit instruction, for ill-defined problems. For the evaluation whether visual displays alone (without instruction) helped designers versus having no displays or instructions, the results for all user groups were positive, with <.092 or less p. That is, the evaluation scores for each group improved significantly when there was access to the visual displays. A third evaluation was made whether level of expertise was significant in whether designers were able to take advantage of the visual displays.

The results were again positive, with significant increases in evaluation scores from beginners to advanced students, and also from advanced students to practitioners.

Additional tests were made to assess the relation between level of expertise and the use of analogy and visual displays. For students, it was found that the availability of displays with the analogy instruction provides a significant benefit for both tasks, but larger for ill-defined problems than well-defined ones. This result may be partially explained because it seemed that beginning architects treated the well-defined problems as being as difficult as the ill-defined ones; they did not have the routines available for solving these structured tasks. Also, beginning students seemed to not take advantage of the potential help offered by visual displays alone and only used them when instructed to do so—which led to significantly improved designs. This suggests that there is an educational opportunity to improve student design capabilities through the use of visual analogical displays. The benefits gained by professional architects were positive, but small and statistically insignificant when comparing their results for well-defined and ill-defined design tasks. This indicates that experienced architects solve both problem types the same way; both may be defined using analogies, or a familiar method may be utilized for solving both types of tasks, ignoring the instruction. Which of these two cases is the correct one needs to be determined [8]. These results are also reviewed and interpreted in Goldschmidt's chapter in this volume.

The task structure used by Casekin was different from most studies of analogy. Rather than studying the learning of specific analogies, these tests consisted of testing the more general issue of whether applying analogies was beneficial for solving a design task. The results support the general premise that analogies benefit problem solving, but leaves for future refinement the details regarding what operations designers use in carrying out the forming of analogies (but see Gineste 94, Vosniadou 89).

In the given experiments, the visual materials were available during the design time; recall from long term memory was not required for the source. A time lapse between seeing the visual materials and doing the design should indicate a decay rate in the benefit of the visual materials over time. How would the results of the design evaluations vary if the materials were studied earlier, a few hours, a day, or a week earlier? By putting a gap between the study period and the design task, encoding in long term memory and recall strategies come into play. This would allow understanding of the use of visual analogy in various different design situations. It may also allow us to learn better how design information may be abstracted when it is experienced to later facilitate analogies.

The analogies studied by Casekin were presented visually, suggesting the visual images were all processed iconically, as "shallow" analogies. However, some displays included compositional information and may have been used in a more structural or "deep" way. An extension of Casekin's work would be to determine whether successful applications of analogy relied on structural relations. Possibly the failure of beginning students was

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[8] Another partial review of Casekin's thesis is given in Casakin and Goldschmidt (99).

because they did not know how to generate such analogies and attempted to rely on iconic ones.

As a last example study, I consider one from area outside of design, but that has implication for design expertise. In a study of medical expertise carried out by Feltovich, Johnson et al (84), they presented charts of cardiology cases to two groups, fourth year medical students and cardiologists with at least twenty years experience. The Subjects studied the cases and reported aloud their thoughts about the case. They then compared the two sets of Subjects. Medical students proposed diagnoses on a few symptoms, sometimes combining symptoms with inappropriate diseases (factual errors) and in other cases weighting symptoms either too heavily or lightly (judgmental errors). The experts did not associate symptoms with specific diseases, but with classes of disease. They evaluated symptoms relative to a large set of plausible diseases and explicitly considered potential alternatives. From the results of the study, Feltovich and his colleagues construed that medical students are familiar with a few limited prototypical cases of a disease, not the range of possible variations. Expert memories not only included knowledge of more diseases, but how to assess alternatives.

In medicine, symptoms are abstractions of individual cases and much of the work of making analogies has been undertaken communally within the domain. Thus the study dealt more with the content of the doctor's knowledge.

In some ways, the diagnosis of a disease from symptoms is similar to selecting a mechanism for a set of functions, or selecting an appropriate typological class for a building design. Designer should be able to recall various mechanisms not as individual solutions but as classes that respond to the given functions. They also should be able to distinguish between various typologies of buildings or mechanisms, based on detailed criteria, such as site conditions, cost, construction time, spatial differences for the building and based on such criteria as costs, fabrication, assembly and maintenance for the mechanism selection. Expertise is involved in how various typologies are evaluated and how subclasses are discriminated. This suggests another line of research exploring how designers use their knowledge in design contexts that could potentially generate valuable results.

The two main studies reported here both allow for fresh ways of looking at memory and recall in design. They control for previous knowledge in different ways. The Crismond study (97) sought to explicate the previous knowledge used by designers with different experience levels. Casakin (97) provided visual materials during the design task, but had to deal with the uncertainty that experienced architects already possessed the information provided (the displays and/or the instructions).

How does the relevant context and criteria for a design get identified and applied? The studies here begin to document in a rich way what is retrieved, and through extensive information about general knowledge, suggest how expert designers carry out these tasks in relation to beginning ones. While probing the range and extent of a designer's knowledge is difficult, these studies begin to cast a light onto their contents and organization.

5. Summary

The purpose of this chapter has been to identify some new issues of importance for design education and to point to psychology literature that suggests how these issues may be studied. I have attempted to delve deeply into two issues of interest. One is the use of mental imagery in the development of a design and its relation to external representations. I have assumed that both effective use of external representations also and learning them to the point that they can be effectively used internally as mental representations are basic skills that support more advanced work in all design fields. By understanding how this learning takes place and how different representations interact, we may come to understand the process by which these representation-dependent capabilities are built up, both within school and during professional experience.

The other area I have investigated is the interplay between personal experience and recall of design-relevant information. The experience may have been in the guise of education or more personal first-hand experience. Recall in design pertains not so much to factual recall as to responding to contextual conditions, accessed through the use of analogy and other complex associations. There is good evidence that outstanding designers both process their experiences differently from non-designers, and then use their experience in unique and powerful ways. Better understanding of their use of such experiential information resources may help in the education of designers that are more competent and creative, and better able to build upon and utilize their experience.

This chapter has made an initial attempt to integrate recent results in cognitive psychology with studies of design cognition and to pose both questions and identify research methods that may allow issues of design learning to be further illuminated. The survey presented has been motivated by the desire to move beyond understanding *what* designers do, as largely studied in protocol analyses over the last thirty years, to understanding *how* designers achieve their results. Of course there is no one answer to the question "how", in the same way that there may not be any one design solution to a given design context. Rather we are still interested in the range of effective processes designers use, how those processes operate and the skills that expert designers bring to bear in their work.

The approach to studying design and the kinds of knowledge it seeks is a continuation of the cognitive psychology tradition of information processing theories of thinking. It however recognizes the huge layer of knowledge based on previous cultural, social, interpersonal as well as formal knowledge about the world and how this knowledge is heavily drawn upon in reasoning during design. I have attempted to broaden the range of information and experience that can be included in the study of design cognition, in response to the criticism that design cognition has not addressed the situational richness that embodies design expertise. It will hopefully be possible to broaden our objective knowledge about design thinking and at the same time address the individualistic, cultural and social aspects that have been raised as counter-positions to the previous work.

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BIBLIOGRAPHY

Akin Ö, (1978) How do architects design? in *Artificial Intelligence and Pattern Recognition in Computer-Aided Design*, Latombe J-C, ed. North Holland Press, New York, pp. 65-104.

Akin Ö, (1986) *Psychology of Architectural Design*, Pion Press, London.

Alexander C, (1964) *Notes on the Synthesis of Form*, Harvard University Press, Cambridge, MA.

Atman C, Chimka J, Bursic K, Nachtmann H, (1999) A comparison of freshman and senior engineering design processes, *Design Studies* 20:3 (March), pp. 131-152

Ballesteros S, (1994) Cognitive Approaches to Human Perception: introduction, in Ballesteros S, ed. *Cognitive Approaches to Human Perception*, Lawrence Erlbaum, Hillsdale NJ, pp.1-20

Ballay J, (1987) An experimental view of the design process, in *System Design: Behavioral perspectives on designers, tools and organizations*, Rouse W, and Boff K, eds. North-Hollans Press, NY, pp 65-82

Barsalou L, (1993) Flexibility, structure, and linguistic vagary in concepts: manifestation of a compositional system of perceptual symbols, in Collins A, Gathercole S, Conway M, Morris P, ed. *Theories of Memory*, Lawrance Erlbaum Associates, Hillsdale NJ, pp. 29-102

Baya V, and Leifer L, (1996) Understanding Information Management in Conceptual Design, in Cross N, Christiaans H, Dorst K, eds. *Analyzing Design Activity*, John Wiley and Sons, Chichester, pp. 151-168.

Baykan C, (1996) Design Strategies, in Cross N, Christiaans H, Dorst K, eds. *Analyzing Design Activity*, John Wiley and Sons, 1996 Chichester pp. 133-150.

Bregman A, (1995) Demonstrations of auditory scene analysis: the perceptual organization of sound, Auditory Perception laboratory, McGill University, Montreal, (digital disc and manual)

Brereton M, Cannon D, Mabogunje A, and Liefer L, (1996) Collaboration in design teams: How social interaction shapes a product, in Cross N, Christiaans H, Dorst K, eds. *Analyzing Design Activity*, John Wiley and Sons, 1996 Chichester pp. 319-342

Candy L, and Edmonds E, (1996) Creative design of the Lotus bicycle, *Design Studies*, 17:1, pp.71-90

Casakin H, (1997) *The Role of Analogy and Visual Displays in Architectural Design*, Ph.D. thesis, Technion – Isreal Institute of Technology, September

Casekin H, and Goldschmidt G, (1999) Expertise and the use of visual analogy: implications for design education, *Design Studies* 20:2 (March) pp. 153-175.

Chambers D, (1993) Images are both depictive and descriptive, in *Imagery, Creativity and Discovery: A cognitive perspective*, Roskos-Ewoldsen B, Intons-Peterson M, and Anderson R, eds. North-Holland Press, Amsterdam, pp. 77-98

Chambers D, and Reisberg D, (1985) Can mental images be ambiguous? *Journal of Experimental Psychology: Human perception and performance*, 11, pp.317-328

Chi MTH, Feltovich P, and Glaser R, (1981) Categorization and representation of physics problems by experts and novices, *Cognitive Science* 5, pp. 121-152

Chi MTH, (1997) Quantifying Qualitative Analyses of Verbal Data: A Practical Guide, *The Journal of the Learning Sciences*, 6(3), p. 271-315, Lawrence Erlbaum Associates, Inc.

Craik F, and Lockhart R, (1972) Levelsd of processing:A framework for memory research, *Journal of Verbal Learning and Verbal Behavior*, 11: pp. 671-684

Crismond D, (1997) *Investigate-and-Redesign as a Context for Learning and Doing Science and Technology: a study of naïve, novice and expert high school and adult designers doing product comparisons and redesign tasks*, Dr.Ed. thesis, Harvard Graduate School of Education, Cambridge

Cooper L, and Shepard R, (1973) Chronometric studies of the rotation of mental images, in Chase W, ed. *Visual Information Processing*, Academic Press, N Y, pp. 75-176

Cooper L, (1989) Mental models of the structure of visual objects, in Shepp B, and Ballesteros S, *Object Perception: structure and process*, Lawrence Erlbaum Associates, NJ, pp. 91-119

Cross N, and Cross A, (1996) Observations of teamwork and social processes in design, in Cross N, Christiaans H, Dorst K, eds. *Analyzing Design Activity*, John Wiley and Sons, Chichester, pp. 291-318

Crowder R, (1993) Systems and principles in memory theory: another critique of pure memory, in Collins A, Gathercole S, Conway M, Morris P, ed. *Theories of Memory*, Lawrance Erlbaum Associates, Hillsdale, pp. 139-162

Davies S, (1995) Effects of Concurrent Verbalization on Design Problem Solving, *Design Studies*, pp. 102-116

Dearstyne H, (1986) *Inside the Bauhaus*, Rizzoli, NY

Denis M. (1996) Imagery and the Description of Spatial Configurations, in de Vega M, Intons-Peterson M, Johnson-Laird P, Denis M, Marchark M, *Models of Visuospatial Cognition*, Oxford University Press, 1996, pp. 128-197

Downing F, (1987) Imagery and the structure of design inquiry, *Journal of Mental Imagery*, 11:1, pp. 61-86

de Vega M, Marschark M, Intons-Peterson M, Johnson-Laird P, Denis M, (1996) Represent-ations of Visuospatial Cognition: A Discussion, in de Vega M, Intons-Peterson M, Johnson-Laird P, Denis M, *Models of Visuospatial Cognition*, Oxford University Press, 1996, pp. 198-226

Dorst K, (1997) *Describing Design: a comparison of paradigms*, Ph.D. thesis TU Delft, 1997

Duncker K, (1945) On problem-solving, *Psychological Monographs*, 58, pp.270

Dwarakanath S, and Blessing L, (1996) Ingredient of the Design Process: a comparison between group and individual work, in Cross N, Christiaans H, Dorst K, eds. *Analyzing Design Activity*, John Wiley and Sons, Chichester, pp. 93-116

Eastman C, (1969) Cognitive processes and ill-defined problems: a case study from design, *Proceedings Joint International Conference on Artificial Intelligence*, Walker D, and Norton L, eds. ACM, Washington D.C.

Eastman C, (1970) On the analysis of intuitive design processes, in Moore G, ed. *Emerging Methods in Environmental Design and Planning*, , MIT Press Cambridge MA. pp. 21-37

Emkin L, (1995) The threat of computers to engineering education, invited lecture, *Computers in Civil Engineering Conference*, Atlanta GA

Ericsson K, Simon H, (1984) *Protocol Analysis: Verbal reports as data*, MIT Press, Cambridge MA.

Ericsson K, and Charness N, (1994) Expert performance: Its structure and acquisition, *American Psychologist*, 49, pp. 725-747

Farah M, Soso M, Dasheiff R, (1992) Visual angle of the mind's eye before and after unilateral occipital lobectomy, *Journal of Experimental Psychology: Human Perception and Performance*, 18, pp. 241-246

Feltovich P, Johnson P, Moller J, Swanson D, (1984) LCS: The role and development of medical knowledge in diagnostic expertise, in Clancey W, and Shortliffe E, eds. *Readings in Medical Artificial Intelligence*, Addison-Wesley, Reading MA, pp. 275-319

Finke R, (1990) *Creative Imagery: discover and, invention in visualization*, Erlbaum, Hillsdale NJ

Fodor J, (1975) *The Language of Thought*, Crowell, NY.

Foos P, (1980) Constructing cognitive maps from sentences, *Journal of Experimental Psychology: Human Learning and Memory*, 6, pp. 51-78.

Fox P, Mintun M, Raichle M, Meizin F, Allman J, Van Essen D, (1986) Mapping human visual cortex with positron emission tomography, *Nature* 323, pp. 806-809

Feigenbaum E, and Feldman J, eds. (1963) *Computers and Thought*, McGraw-Hill, NY.

Gentner D, (1989) The mechanisms of analogical learning, in Vosniadou S, and Ortnony A, (eds.) *Similarity and Analogical Reasoning*, Cambridge University Press, Cambridge, pp. 199-239

Gick M, and Holyoak K, (1980) Analogical problem-solving, *Cognitive Psychology*, 12, pp. 306-355

Gineste M, (1994) visualized analogies and memory for new information in first graders, in *Comprehension in Graphics*, Schnotz W and Kulhavy R, eds. North-Holland Press, Amsterdam, pp. 251-268

Glass A, and Holyoak K, (1986) *Cognition*, 2nd Ed. Random House NY.

Goel A, Gomez A, Grue N, Murdock W, Recker M, and Govindaraj T, (1996) Design Explanations in Interactive Design Environments,in Gero J, ed. *Proc. Fourth International Conference on AI in Design*, Palo Alto, June 1996.

Goel, V, (1995) *Sketches of Thought*, MIT Press, Cambridge, Mass.

Goldschmidt G, (1991) The dialectics of sketching, *Creativity Research Journal*, 4:2, pp. 123-143

Goldschmidt G, (1994) On Visual Design Thinking: the vis kids or architecture, *Design Studies*, 15:2, pp 158-174

Greenwood D, (1982) *Product Engineering Design Manual*, Kreiger, Malabar FL.

Gregg L, and Steinberg E, (1980) *Cognitive Processes in Writing*, Erlbaum, Hillsdale NJ

Günther J, Ehrlenspiel K, (1999) Comparing Designers From Practice and Designers with Systematic Design Education, *Design Studies*, 20:5, pp. 439-451

Günther J, Frankenburger E, and Auer P, (1996) Investigation of Individual and Team Design, in Cross N, Christiaans H, Dorst K, eds. *Analyzing Design Activity*, John Wiley and Sons, 1996 Chichester, pp. 117-132.

Harris G, (1997) Development of taste perception and appetite regulation, in *Infant Development: Recent advances*, Bremner G, Slater A, Butterworth G, eds. Psychology Press, Hove UK

Harrison S, and Minneman S, (1996) A Bike in Hand: A study of 3-D objects in design, in Cross N, Christiaans H, Dorst K, eds. *Analyzing Design Activity*, John Wiley and Sons, 1996 Chichester, pp. 417-436

Hawkins J, (1974) Messing about in science, in *The Informed Vision: Essay on learning and human nature*, Agathon Press, NY

Heidegger M, (1962) *Being and Time* (translated by J. Macquarrie and E. Robinson, Harper and Row, NY

Henderson K, (1999) *On Line and On Paper: Visual representations, visual culture and computer graphics in design engineering*, MIT Press, Cambridge

Hewitt M, (1985) Representational forms and modes of conception: An approach to the history of architectural drawing, *Journal of Architectural Education*, 39:2 (Winter) pp. 2-9

Holyoak K, Jun E, and Billman D, (1984) Development of analogical problem-solving skill, *Society for Research in Child Development*, 55, pp. 2042-2055

Hubka V and Eder W, (1988) *The Theory of Technical Systems*, Springer-Verlag Berlin.

Intons-Peterson M, (1993) Imagery and Classification, in Collins A, Gathercole S, Conway M, Morris P, ed. *Theories of Memory*, Lawrance Erlbaum Associates, Hillsdale, pp. 211-240

Intons-Peterson M, (1993a) Imagery's role in creativity and discovery, in *Imagery, Creativity and Discovery: A cognitive perspective*, Roskos-Ewoldsen B, Intons-Peterson M, and Anderson R, eds. North-Holland Press, Amsterdam, pp. 1-38

Intons-Peterson M, (1996) Integrating the components of imagery, in de Vega M, Intons-Peterson M, Johnson-Laird P, Denis M, Marchark M, *Models of Visuospatial Cognition*, Oxford University Press, 1996, pp. 20-89

Johnson-Laird P, (1996) Images, Models and Propositional Representations, in de Vega M, Intons-Peterson M, Johnson-Laird P, Denis M, Marchark M, *Models of Visuospatial Cognition*, Oxford University Press, 1996, pp. 90-127

Johnson S, (1997) What's in a representation: why do we care and what does it mean?: Examining the evidence from psychology, *Representation and Design: ACADIA97 Conference Proceedings*, pp. 5-16

Kihlstrom J, (1996) Memory Research: the convergence of theory and practice, in Herrman D, McEvoy C, Hertzog C, Hertel P, and Johnson M, eds. *Basic and Applied Memory Research: practical applications*, Vol. 1, Erlbaum, Mahwah NJ, pp. 5-26.

Kosslyn S, (1980) *Image and the Mind*, Harvard University Press, Cambridge MA.

Kosslyn, S, (1996) *Image and the Brain*, MIT Press, Cambridge MA.

Kosslyn S, Brunn J, Cave K, Wallach R, (1984) Individual differences in mental imagery ability: A computational analysis, *Cognition* 18, pp. 195-243

Krauss R, Myer J, Danielson S, and Lewis R, (1970) Design: a case history, in Moore G, ed, *Emerging Methods in Environmental Design and Planning*, MIT Press, Cambridge, MA, pp.11-20

Langacker R, (1986) An Introduction to Cognitive Grammar, *Cognitive Science*, 10, pp. 1-40

Lawson B (1997) *How Designers Think: The Design Process Demystified*, Architectural Press, Oxford

Likert R, and Quasha W, (1941) *Revised Minnesota Paper Form Board (Series AA)*, The Psychological Corporation, NY

Lindemann P, and Wright C, (1998) Skill Acquisition and Plans for Actions: Learning to write with your other hand, in Osherson D, general editor, *An Invitation to Cognitive Science:* Scarborough D, and Sternberg S, eds. *Methods, Models and Conceptual Issues Vol. 4*, MIT Press, pp. 523-584

Lloyd P, Lawson B, Scott P, (1996) Can verbalization reveal design cognition? in Cross N, Christiaans H, Dorst K, eds. *Analyzing Design Activity*, John Wiley and Sons, 1996 Chichester, pp. 437-461

Maier NRF, (1931) Reasoning in humans II: The solution of a problem and its appearance in consciousness, *J. Comparative Psychology*, 12, pp.181-194; reprinted in Wason P, and Johnson-Laird P, (1968) *Thinking and Reasoning*, Penguin Modern Psychology, Baltimore MD. pp.17-27

Mäntylä T, (1986) Optimizing cue effectiveness: recall of 500 and 600 incidentally learned words, *Journal of Experimental Psychology: Learning, Memory and Cognition*, 12, pp. 66-71

Massaro D, (1998) Models for reading letters and words, in Osherson D, general editor, *An Invitation to Cognitive Science:* Scarborough D, and Sternberg S, eds. *Methods, Models and Conceptual Issues Vol. 4*, MIT Press, pp. 301-364

Miller A, (1984) *Imagery in Scientific Thought: Creating 20th century physics*, Birkhauser, Boston

Newell A, (1969) Heuristic Programming: Ill-structured Problems, in Julius Aronofsky, ed. *Progress in Operations Research*, Vol. 3, John Wiley & Sons, pp. 360-414

Newell A, and Simon H, (1972) *Human Problem Solving*, Prentice Hall, Englewood Cliffs, NJ

Paivio A, (1971) *Imagery and Verbal Processes*, Holt, Rinehart and Winston, NY

Paivio A, (1986) *Mental Representations: A dual coding approach*, Oxford University Press, UK

Pahl G, and Beitz W, (1996) *Engineering Design*, Springer-Verlag, London

Peterson M, (1993) The ambiguity of mental images: insights regarding the structure of shape memory and its function in creativity, in Roskos-Ewoldsen, Intons-Peterson M, and Anderson R eds. *Imagery, Creativity and Discovery: a cognitive approach*, Elsevier, Amsterdam, pp.151-186

Purcell T, ed. (1998) Special Issue on Sketching and Drawing in Design, *Design Studies*, 19:4

Purcell T, Gero J, et al, (1996) The Data in Design Protocols: The Issue of Data Coding, Data Analysis in the Development of Models of the Design Process, in Cross N, Christiaans H, Dorst K, eds. *Analyzing Design Activity*, John Wiley and Sons, 1996 Chichester, pp. 225-252

Pylshyn Z, (1973) What the mind's eye tells the mind's brain: a critique of mental imagery, *Psychological. Bulletin* 80, pp. 1-24

Radcliffe D, (1996) Concurrency of actions, ideas and knowledge displays within a design team, in Cross N, Christiaans H, Dorst K, eds. *Analyzing Design Activity*, John Wiley and Sons, 1996 Chichester, pp. 343-364

Reisberg D, and Logie R, (1993) The ins and outs of working memory: Overcoming the limits on learning from imagery, in Roskos-Ewoldsen, Intons-Peterson M, and Anderson R eds. *Imagery, Creativity and Discovery: a cognitive approach*, Elsevier, Amsterdam, pp.39-76

Reitman W, (1964) Heuristic Decision Procedures, Open Constraints, and the Structure of Ill-defined Problems, in *Human Judgments and Optimality*, Shelly M, and Bryan G, eds. Wiley, N Y, pp.282-315

Robbins E, (1994) *Why Architects Draw*, MIT Press, Cambridge MA

Sachs A, (1999) 'Stuckness' in the design studio, *Design Studies*, 20:2, pp. 195-210

Schon D, (1983) *The Reflective Practitioner*, Basic Books, NY

Schon D, (1988) Designing: Rules, types and worlds, *Design Studies*, 9:3, pp. 181-190

Schon D, (1992) Designing as Reflective Conversation with the Materials of a Design Situation, *Research in Engineering* Design, 3, pp. 131-147

Schon D and Wiggins G, (1992) "Kinds of seeing and their functions in designing, *Design Studies*, 13:2, pp 135-156

Seel N, and Dörr G, (1994) The supplementation of mental images through graphics: instructional effects on spatial visualization skills of adults, in *Comprehension in Graphics*, Schnotz W and Kulhavy R, eds. North-Holland Press, Amsterdam, pp. 271-290

Shepard R, and Feng C, (1972) A Chronometric Study of Mental Paper Folding, *Cognitive Psychology*, 3, pp.228-243

Shepard R, (1978) *Mind Sights*, Freeman, NY

Shepp B, (1989) On perceiving objects: holistic versus featural properties, in Shepp B, and Balllesteros S, *Object Perception: Structure and Process*, Lawrence Erlbaum Associates, NJ, pp. 203-233

Simon H, (1969) *The Sciences of the Artificial*, MIT Press, Cambridge MA

Simon H, (1973) The structure of ill-structured problems, *Artificial Intelligence*, 4, pp.181-203

Simon H, (1976) The information storage system called 'Human Memory' in Rosenzweig M, and Bennett E, eds. *Neural Mechanisms of Learning and Memory*, MIT Press, pp. 79-96

Suh N, (1990) *The Principles of Design*, Oxford University Press, Oxford

Tafel E, (1979) *Apprentice to Genius: Years with Frank Lloyd Wright*, McGraw-Hill Book Co.

Takeda H, Yoshioka M, Tomiyama T, and Shimomura Y, (1996) Analysis of Design Protocol by Functional Evolution Process Model, in Cross N, Christiaans H, Dorst K, eds. *Analyzing Design Activity*, John Wiley and Sons, 1996 Chichester, pp. 187-210

Talmy L (1988) Force Dynamics in Language and Cognition, *Cognitive Sciences,* 12, pp. 49-100

Trousse B, and Christiaans H, (1996) Design as a Topos-based Argumentative Activity: A protocol analysis study, in Cross N, Christiaans H, Dorst K, eds. *Analyzing Design Activity*, John Wiley and Sons, 1996 Chichester, pp.365-388

Ullman D, (1992) *The Mechanical Design Process*, McGraw-Hill, NY.

Ullman D, Herling D and Sinton A, (1996) Analysis of Protocol Data to Identify Product Information Evolution and Decisionmaking Process, in Cross N, Christiaans H, Dorst K, eds. *Analyzing Design Activity*, John Wiley and Sons, 1996 Chichester, pp.169-185

Ulusoy Z, (1999) To design versus to understand design: the role of graphic representations and verbal expressions, *Design Studies* 20:2 (March) pp. 123-130.

von der Weth R, (1999) Design Instinct? — the development of individual strategies, *Design Studies* 20:3, pp 453-463

Visser W, (1996) Use of Episodic Knowledge and Information in Design Problem Solving, in Cross N, Christiaans H, Dorst K, eds. *Analyzing Design Activity*, John Wiley and Sons, 1996 Chichester, pp.271-290

Viviana P, and Cenzato M, (1985) Segmentation and coupling in complex movements, *J. Experimental Psychology: Human Perception and Performance* 11, pp. 828-845

Vosniadou S, (1989) Similarity and analogical reasoning: a developmental perspective, in Vosniadou S, and Ortnony A, (eds.) *Similarity and Analogical Reasoning*, Cambridge University Press, Cambridge, pp. 199-239

Vosniadou S, and Ortnony A, eds.(1989) *Similarity and Analogical Reasoning*, Cambridge University Press, Cambridge

Winograd T, and Flores F, (1987) *Understanding Computers and Cognition: A new foundation for design*, Ablex Corporation, Norwood NJ

Wallace B, and Hofelich B, (1992) Process generalization and the prediction of performance on mental imagery tasks, *Memory and Cognition*, 20, pp. 695-704

Ward T, Finke R, Smith S, (1995) *Creativity and the Mind: discovering the genius within*, Plenum Press, NY

Wright F L, (1928) Concept and Plan, *The Architectural Record*, January-February