Design cognition: results from protocol and other empirical studies of design activity

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Chapter 5

Design Cognition: Results From Protocol And Other Empirical Studies Of Design Activity

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Abstract

The paper reviews protocol and other empirical studies of design activity, and summarises results relevant to understanding the nature of design cognition from an interdisciplinary, domain-independent overview. Results are presented in three major aspects of design cognition - the formulation of problems, the generation of solutions, and the utilisation of design process strategies. Parallels and comparisons between results are drawn, and a number of issues identified. Many similarities of design cognition across domains of professional practice are found. It seems that the 'intuitive' behavior of experienced designers is often highly appropriate to design tasks, although appearing to be 'unprincipled' in theory.

1. Introduction

For thirty years there has been a slow but steady growth in empirical research studies of design cognition - the pioneering work being the study of architects by Eastman (69, 70). A substantial and varied range of research methods has been adopted and adapted for the investigation of design activity, including the following:

- *Case studies* have usually focused on one particular design project at a time, with observers recording the progress and development of the project either contemporaneously or post-hoc. Both participant and non-participant observation methods have been included, and both real and artificially-constructed design projects have been studied.

- The more formal method of *protocol studies* has usually been applied to artificial projects, because of the stringent requirements of recording the protocols - the 'thinkingaloud' and associated actions of subjects asked to perform a set design task. Both inexperienced (usually student) designers and experienced designers have been studied in this way.

• There have also been a few examples of *performance tests* conducted under controlled, laboratory conditions, in which subjects are required to perform a specialised task, and data on their performance is recorded and analysed. The models for these kinds of tests are the controlled laboratory studies of psychology research.

YEAR	ARCHI-TECTURE	INDUSTRIAL DESIGN	MECHANICAL ENGINEERING	ELECTRONIC ENGINEERING	SOFTWARE DESIGN	VARIOUS/ OTHER
1970	Eastman					
1973	Foz					
1978	Akin					
1979	Lawson					Thomas
1981					Jeffries	
1983	Schön					
1985					Adelson	
1987		Ballay	Stauffer			
1988	Eckersley		Ullman			
1989			Radcliffe			
1990	Chan		Tang		Guindon	
			Visser			
1991	Goldschmidt		Jansson	Colgan		
			Purcell			
1992		Christiaans	Ehrlenspiel		Davies	Goel
					Olson	
1993			Fricke			
1994			Lloyd	Ball		
1995		Dorst				
1997	Suwa					Göker
1998		Valkenburg		McNeill		Smith
1999			Atman			

Summary Chart - Protocol and Other Formal Studies of Design Activity

Of all the empirical research methods for the analysis of design activity, protocol analysis is the one that has received the most use and attention in recent years (Ericsson and Simon, 93). It has become regarded as the most likely method (perhaps the only method) to bring out into the open the somewhat mysterious cognitive abilities of designers. It was given a significant boost by the Delft Design Protocols Workshop of 1994 (Cross et al., 96). It does, though, have some severe limitations, to be noted later.

The chart above summarises the history of the development of this field of the formal study of design activity. This is not an exhaustive chart of all the studies that have been conducted, but is designed merely to indicate the range and timescales of developments, across different design domains.

Although the amount of research in design activity has grown substantially since the mid-1980s, the total amount still is not particularly great, and the results of that research are varied, often based on single or small numbers of subjects, and usually untested by repeat studies. Nevertheless, in this paper I propose to try to pick out some consistent patterns that may be discerned in those results, and to identify issues that are pertinent to the utilisation of the results (for example, in design education) and to further research. I will take a cross-disciplinary, or domain-independent view of the field, and try to integrate results from studies across the various domains of professional design practice.

In analysing design cognition, it has been normal until relatively recently to use language and concepts from cognitive science studies of problem solving behavior. However, it has become clear that designing is not normal 'problem solving' (Cross, 99). We therefore need to establish appropriate concepts for the analysis and discussion of design cognition. For example, designing involves 'finding' appropriate problems, as well as 'solving' them, and includes substantial activity in problem structuring and formulating, rather than merely accepting the 'problem as given'. The first main area in which I will present my interpretations of findings, patterns and issues in design cognition is therefore that of how designers *formulate problems*. The second main area will be how designers *generate solutions*, since that is the over-riding aim and purpose of design activity: to generate a satisfactory design proposal. And the third main area will be the *process strategies* that designers employ, because there has been a lot of interest in design methodology - the understanding and structuring of design procedures - especially in the context of design education.

2. Problem Formulation

It is widely accepted that design 'problems' can only be regarded as a version of ill-defined problems. In a design project it is often not at all clear what 'the problem' is; it may have been only loosely defined by the client, many constraints and criteria may be un-defined, and everyone involved in the project may know that goals may be re-defined during the project. In design, 'problems' are often defined only in relation to ideas for their 'solution', and designers do not typically proceed by first attempting to define their problems rigorously.

One of the concerns in some other areas of design research has been to formulate design problems in *well*-defined ways. This is intended to overcome some of the inherent difficulties of attempting to solve ill-defined problems. However, designers' cognitive strategies are presumably based upon their normal need to resolve ill-defined problems. Thomas and Carroll (79) carried out several observational and protocol studies of a variety of creative problem-solving tasks, including design tasks. One of their findings was that designers' behavior was characterised by their treating the given problems *as though* they were ill-defined problems, for example by changing the goals and constraints, even when they could have been treated as well-defined problems. Thomas and Carroll concluded that: 'Design is a type of problem solving in which the problem solver views the problem or acts as though there is some ill-definedness in the goals, initial conditions or allowable transformations.' The implication is that designers will be designers, even when they could be problem-solvers.

2.1 Goal analysis

This 'ill-behaved' aspect of design behavior has been noted even from the very earliest formal studies. Eastman (70), in the earliest recorded design protocol study (of architectural design), found that: 'One approach to the problem was consistently expressed in all protocols. Instead of generating abstract relationships and attributes, then deriving the appropriate object to be considered, the subjects always generated a design element and then determined its qualities.' That is to say, the designer-subjects jumped to ideas for solutions (or partial solutions) before they had fully formulated the problem. This is a reflection of the fact that designers are solution-led, not problem-led; for designers, it is the evaluation of the solution that is important, not the analysis of the problem.

It is not just that problem-analysis is weak in design; even when problem goals and constraints are known or defined, they are not sacrosanct, and designers exercise the freedom to change goals and constraints, as understanding of the problem develops and definition of the solution proceeds. This was a feature of designer behavior noted by Akin (78) from his protocol studies of architects: 'One of the unique aspects of design behavior is the constant generation of new task goals and redefinition of task constraints.' As Ullman et al. (88) pointed out, from studies in mechanical engineering, only some constraints are 'given' in a design problem; other constraints are 'introduced' by the designer from domain knowledge, and others are 'derived' by the designer during the exploration of particular solution concepts.

The formulation of appropriate and relevant problem structures from the ill-defined problem of a design brief is not easy - it requires sophisticated skills in gathering and structuring information, and judging the moment to move on to solution generation. Christiaans and Dorst (92), from protocol studies of junior and senior industrial design students, found that some students became stuck on information gathering, rather than progressing to solution generation. Interestingly, they found that this was not such a significant difficulty for junior students, who did not gather a lot of information, and tended to 'solve a simple problem', being unaware of a lot of potential criteria and difficulties. But they found that senior students could be divided into two types. The more successful group, in terms of the creativity quality of their solutions, 'asks less information, processes it instantly, and gives the impression of consciously building up an image of the problem. They look for and make priorities early on in the process.' The other group gathered lots of information, but for them 'gathering data was sometimes just a substitute activity for actually doing any design work' (Cross et al., 94).

A similar finding was reported by Atman et al. (99), who found from their protocol analysis studies of engineering students that, for novices (freshmen with no design experience), '. . those subjects who spent a large proportion of their time defining the problem did not produce quality designs.' However, with senior students, Atman et al. did find that attention to 'problem scoping' (i.e., 'adequately setting up the problem before analysis begins', including gathering a larger amount and wider range of problem-related information) did result in better designs. As with the industrial design students, some of the freshmen engineering students, it seemed, simply became stuck in problem-definition and did not progress satisfactorily into further stages of the design process.

2.2 Solution focusing

Many studies suggest that designers move rapidly to early solution conjectures, and use these conjectures as a way of exploring and defining problem-and-solution together. This is not a strategy employed by all problem-solvers, many of whom attempt to define or understand the problem fully before making solution attempts. This difference was observed by Lawson (79), in his experiments on problem-solving behavior in which he compared scientists with architects: 'The scientists were [attempting to] discover the structure of the problem; the architects were proceeding by generating a sequence of high-scoring solutions until one proved acceptable... [The scientists] operated what might be called a problem-focusing strategy... architects by contrast adopted a solution-focusing strategy.' Lawson repeated the experiment with first-year students of science and architecture, and did not find the same difference in problem-solving strategy. It appears to be a difference that grows with education and experience in designing.

Lloyd and Scott (94), from protocol studies of experienced engineering designers, found that a solution-focused approach appeared to be related to the degree and type of previous experience of the designers. They found that more experienced designers used more 'generative' reasoning, in contrast to the deductive reasoning employed more by less-experienced designers. In particular, designers with specific experience of the problem type tended to approach the design task through solution conjectures, rather than through problem analysis. They concluded that 'It is the variable of specific experienceof the problem type that enables designers to adopt a conjectural approach to designing, that of framing or perceiving design problems in terms of relevant solutions.'

2.3 Co-evolution of problem-solution

Designers tend to use solution conjectures as the means of developing their understanding of the problem. Since 'the problem' cannot be fully understood in isolation from consideration of 'the solution', it is natural that solution conjectures should be used as a means of helping to explore and understand the problem formulation. As Kolodner and Wills (96) observed, from a study of senior student engineering designers: 'Proposed solutions often directly remind designers of issues to consider. The problem and solution co-evolve.'

This interpretation of design as a co-evolution of solution *and* problem spaces has also been proposed by others, and has been found by Cross and Dorst (98) in protocol studies of experienced industrial designers. They reported that: 'The designers start by exploring the [problem space], and find, discover, or recognise a partial structure. That partial structure is then used to provide them also with a partial structuring of the [solution space]. They consider the implications of the partial structure within the [solution space], use it to generate some initial ideas for the form of a design concept, and so extend and develop the partial structuring. . . They transfer the developed partial structure back into the [problem space], and again consider implications and extend the structuring of the [problem space]. Their goal . . . is to create a matching problem-solution pair.'

2.4 Problem framing

Designers are not limited to 'given' problems, but find and formulate problems within the broad context of the design brief. This is the characteristic of reflective practice identified by Schön (83) as problem setting: 'Problem setting is the process in which, interactively, we *name* the things to which we will attend and *frame* the context in which we will attend to them.' This seems to characterise well what has been observed of the problem formulation aspects of design behavior. Designers select features of the problem space to which they choose to attend (naming) and identify areas of the solution space in which they choose to explore (framing). Schön (88) suggested that: 'In order to formulate a design problem to be solved, the designer must *frame* a problematic design situation: set its boundaries, select particular things and relations for attention, and impose on the situation a coherence that guides subsequent moves.'

This kind of problem framing has been noted often in studies of architects. Lloyd and Scott (95), from their studies of (mostly senior-student) architects, reported that 'In each protocol there comes a time when the designer makes a statement that summarises how he or she *sees* the problem or, to be more specific, the structure of the situation that the problem presents.' They referred to this 'way of seeing the design situation' as the designer's 'problem paradigm'. As with their earlier studies of engineers, Lloyd and Scott found that the architects who had specific prior experience of the problem type had different approaches from their less-experienced colleagues: the experienced architects' approaches were characterised by strong problem paradigms, or 'guiding themes'. Cross and Clayburn Cross (98) have also identified, from interviews and protocol studies, the importance of problem framing, or the use of a strong guiding theme or principle, in the design behavior of outstanding, expert engineering designers. Darke (79) also reported from interviews with outstanding architects that they used strong guiding themes as 'primary generators' for setting problem boundaries and solution goals.

Schön (88) pointed out that 'the work of framing is seldom done in one burst at the beginning of a design process.' This was confirmed in Goel and Pirolli's (92) protocol studies of several types of designers (architects, engineers and instructional designers). They found that 'problem structuring' activities not only dominated at the beginning of the design task, but also reoccurred periodically throughout the task.

Valkenburg and Dorst (98) have attempted to develop and apply Schön's theory of reflective practice into team design activity, through a study of student industrial designers. In comparing a successful and an unsuccessful design team, Valkenburg and Dorst stressed the importance of the teams' problem framing. They identified five different frames used sequentially by the successful team during the project, in contrast to the single frame used by the unsuccessful team. The unsuccessful team also spent much greater amounts of time on 'naming' activities - i.e. on identifying potential problem features, rather than on developing solution concepts.

3. Solution Generation

The solution-focused nature of designer behavior appears to be appropriate behavior for responding to ill-defined problems. Such problems can perhaps never be converted to well-defined problems, and so designers quite reasonably adopt the more realistic strategy of finding a satisfactory solution, rather than expecting to be able to generate an optimum solution to a well-defined problem. However, this solution-focused behavior also seems to have potential drawbacks. One such drawback might be the 'fixation' effect induced by existing solutions.

3.1 Fixation

A 'fixation' effect in design was suggested by Jansson and Smith (91), who studied senior student and experienced professional mechanical engineers' solution responses to design problems. They compared groups of participants who were given a simple, written design brief, with those that were given the same brief but with the addition of an illustration of an existing solution to the set problem. They found that the latter groups appeared to be 'fixated' on the example design, producing solutions that contained many more features from the example design than did the solutions produced by the control groups. Jansson and Smith proposed that such fixation could hinder conceptual design if it prevents the designer from considering all of the relevant knowledge and experience that should be brought to bear on a problem. Some designers may be too ready to re-use features of known existing designs, rather than to explore the problem and generate new design features.

Purcell and Gero (91, 93, 96) undertook a series of experiments to verify and extend Jansson and Smith's findings on fixation. They studied and compared senior students in mechanical engineering and in industrial design. Early results suggested that mechanical engineers appeared to be much more susceptible to fixation than did industrial designers; the engineers' designs were substantially influenced by prior example designs, whereas the industrial designers appeared to be more fluent in producing a greater variety of designs, uninfluenced by examples. Purcell and Gero suggested that this might be a feature of the different educational programs of engineers and designers, with the latter being more encouraged to generate diverse design solutions. In a further development of the study, however, Purcell and Gero explored engineers' and designers' responses when the example design was an innovative rather than a routine prior solution. Here they found that engineers became fixated in the traditional sense when shown a routine solution, i.e. incorporating features of the routine solution in their own solutions, but became fixated on the underlying *principle* of the innovative solution, i.e. producing new, innovative designs embodying the same principle. The industrial designers, however, responded in similar ways under both conditions, generating wide varieties of designs that were not substantially influenced by any of the prior designs. Purcell and Gero therefore concluded that the industrial designers seem to be 'fixated on being different', and that 'fixation' in design may exist in a number of forms.

It is not clear that 'fixation' is necessarily a bad thing in design. As mentioned above, Cross and Clayburn Cross (98) have reported that outstanding engineering designers exhibit a form of 'fixation' on their problem frame, or on a guiding theme or principle. Having established the 'frame' for a particular problem, these designers can be tenacious in their pursuit of solution concepts that fit the frame. Similar observations have been reported by Lawson (94) and Darke (79) from their studies of outstanding architects. This tenacious fixation seems to be found often amongst highly creative individuals.

3.2 Attachment to concepts

Another form of 'fixation' that has been found to exist amongst designers is their attachment to early solution ideas and concepts. Although designers change goals and constraints as they design, they appear to hang on to their principal solution concept for as long as possible, even when detailed development of the scheme throws up unexpected difficulties and shortcomings in the solution concept. Some of the changing of goals and constraints during designing is associated with resolving such difficulties without having to start again with a major new concept. For example, from case studies of professional architectural design, Rowe (87) observed that: ‘A dominant influence is exerted by initial design ideas on subsequent problem-solving directions... Even when severe problems are encountered, a considerable effort is made to make the initial idea work, rather than to stand back and adopt a fresh point of departure.’

The same phenomenon was observed by Ullman et al. (88), in protocol studies of experienced mechanical engineering designers. They found that ‘designers typically pursue only a single design proposal,’ and that ‘there were many cases where major problems had been identified in a proposal and yet the designer preferred to apply patches rather than to reject the proposal outright and develop a better one.’ A similar observation was also made by Ball et al. (94), from their studies of senior students conducting ‘real-world’, final-year design projects in electronic engineering: ‘When the designers were seen to generate a solution which soon proved less than satisfactory, they actually seemed loath to discard the solution and spend time and effort in the search for a better alternative. Indeed the subjects appeared to adhere religiously to their unsatisfactory solutions and tended to develop them laboriously by the production of various slightly improved versions until something workable was attained.’

Ball et al. regarded this behavior as indicating a ‘fixation’ on initial concepts, and a reliance on a simple ‘satisficing’ design strategy in contrast to any more ‘well-motivated’ process of optimisation. They found it difficult to account for this apparently unprincipled design behavior. Nevertheless, adherence to initial concepts and a satisficing strategy seem to be normal design behavior. Guindon (90a), in a study of experienced software designers, found that ‘designers adopted a kernel solution very early in the session and did not elaborate any alternative solutions in depth. If designers retrieved alternative solutions for a subproblem, they quickly rejected all but one alternative by a trade-off analysis using a preferred evaluation criterion.’

However, in contrast to the ‘fixation’ findings reported above, in a study of senior industrial engineering students, Smith and Tjandra (98) found that the quality of design solutions produced did appear to be dependent upon a willingness to reconsider early concepts. They experimented with nine groups of four students, undertaking an artificial design exercise based upon two-dimensional configurations of coloured triangles supposed to have different functional properties. Each member of a design team in the exercise played a different role (architect, thermal engineer, structural engineer, and cost estimator). One of Smith and Tjandra’s findings was that ‘The top three designs . . . were the three groups that chose to scrap their initial design and to start afresh with a new design concept.’ The successful players of this particular design game therefore seemed to be ones who were able and willing to overcome the possible fixation on an early concept. Perhaps it is worth emphasising that this study was based on a role-playing game and an artificial 'design' problem far removed from real-world design projects.

3.3 Generation of alternatives

It may be that good designers produce good early concepts that do not need to be altered radically during further development; or that good designers are able to modify their concepts rather fluently and easily as difficulties are encountered during development, without recourse to exploration of alternative concepts. Either way, it seems that designers are reluctant to abandon early concepts, and to generate ranges of alternatives. This does seem to be in conflict with a more 'principled' approach to design, as recommended by design theorists, and even to conflict with the idea that it is the exploration of solution concepts that assists the designer's problem understanding. Having more than one solution concept in play should promote a more comprehensive assessment and understanding of the problem.

Fricke (93, 96), from protocol studies of engineering designers, found that both generating few alternative concepts and generating a large number of alternatives were equally weak strategies, leading to poor design solutions. Where there was 'unreasonable restriction' of the search space (when only one or a very few alternative concepts were generated), designers became 'fixated' on concrete solutions too early. In the case of 'excessive expansion' of the search space (generating large numbers of alternative solution concepts), designers were then forced to spend time on organising and managing the set of variants, rather than on careful evaluation and modification of the alternatives. Fricke identified successful designers to be those operating a 'balanced search' for solution alternatives.

Fricke also found that the degree of precision in the problem as it was presented to the designers influenced the generation of alternative solution concepts. When the problem was precisely specified, designers generated more solution variants; with an imprecise assignment (for the same design task), designers tended to generate few alternative solution concepts. This perhaps indicates that the more active problem-framing required for an imprecise assignment leads more readily to preferred solution concepts. Designers given precise assignments have less scope for problem-framing, and generate a wider range of solution concepts in order to find a preferred concept.

3.4 Creativity

Designers themselves often emphasise the role of 'intuition' in the generation of solutions, and 'creativity' is widely regarded as an essential element in design thinking. Creative design is often characterised by the occurrence of a significant event, usually called the 'creative leap'. Recent studies of creative events in design have begun to shed more light on this previously mysterious (and often mystified) aspect of design.

Akin and Akin (96) studied creative problem-solving behavior first on a classic problem where a form of 'fixation' normally prevents people from finding a solution to the problem: the 'nine-dots' problem. (In this problem, nine dots are arranged in a 3 x 3 square, and subjects are invited to join all nine dots by drawing just four straight lines without lifting pen from paper. Subjects normally assume that they have to draw within the implicit outline of the square, whereas the solution requires extending the lines to new vertices outside of the square.) They then extended their study from the nine-dot problem into a study of a simple architectural design problem, and compared the protocols of a non-architect and an experienced architect in tackling this problem. In these studies, Akin and Akin were looking for cases of the 'sudden mental insight' (SMI) that is commonly reported in cases of creative problem solving. They referred to the 'fixation' effect, such as the implicit nine-dot square, as a 'frame of reference' (FR) that has to be broken out of in order to generate creative alternatives. They suggested that a SMI occurs when a subject perceives their own fixation within a standard FR, and simultaneously perceives a new FR. The new FR also has to include procedures for generating a solution to the problem. The experienced architect possessed such procedural knowledge, whereas the novice did not, and was not able to generate anything other than a very conventional solution. Akin and Akin conclude: 'Realising a creative solution, by breaking out of a FR, depends on simultaneously specifying a new set of FRs that restructure the problem in such a way that the creative process is enhanced. The new FRs must, at a minimum, specify an appropriate *representational* medium (permitting the explorations needed to go beyond those of the earlier FRs), a design *goal* (one that goes beyond those achievable within the earlier FRs), and a set of *procedures* consistent with the representation domain and the goals.'

This seems to be similar to Schön's concept of a 'frame' which permits and encourages the designer to explore new design 'moves' and to reflect on the discoveries arising from those moves. But 'frames' can clearly be negative conceptual structures, when they are inappropriate 'fixations', as well as positive, creative structures.

Akin and Akin's conclusions also resonate with the study by Cross (97) of the 'creative event' that occurred in a protocol study of teamwork in industrial design. About half-way through the design session, one of the designers rather suddenly proposed that a concept for the device they were designing could be that 'maybe it's like a little vacuum-formed tray'. This was the first time in the team's activity that a 'tray' had been mentioned, but it immediately focused the team's attention and quickly became adopted as the basic concept for their solution. It appears to be the equivalent of a 'sudden mental insight', offering a new, creative 'frame of reference' meeting Akin and Akin's criteria, above. Cross suggested that the 'tray' concept should be seen not in terms of a 'creative leap', but in terms of a 'bridge' between the problem space and the solution space: 'During the design process, partial models of the problem and solution are constructed side-by-side . . . But the crucial factor, the "creative leap", is the bridging of these two partial models by the articulation of a concept (the "tray" idea in this example) which enables the models to be mapped onto each other. The "creative leap" is not so much a leap across the chasm between analysis and synthesis, as the throwing of a bridge across the chasm between problem and solution. The "bridge" recognisably embodies satisfactory relationships between problem and solution.'

It may be also that 'creative leaps' or 'sudden mental insights' are not so personal and idiosyncratic as has been promoted before. In protocol studies of experienced industrial designers, Cross and Dorst (98) observed that all nine subjects reported *the same* 'creative breakthrough'. All nine linked together the same pieces of available information and used this as a basis for their solution concept. All nine appeared to think that this was a unique personal insight.

3.5 The role of sketching

Several researchers have investigated the ways in which sketching helps to promote creativity in design thinking. Sketching helps the designer to find unintended consequences, the surprises that keep the design exploration going in what Schön and Wiggins (92) called the 'reflective conversation with the situation' that is characteristic of design thinking. Goldschmidt (91) called it the 'dialectics of sketching': a dialogue between 'seeing that' and 'seeing as', where 'seeing that' is reflective criticism and 'seeing as' is the analogical reasoning and reinterpretation of the sketch that provokes creativity. Goel (95) suggested that sketches help the designer to make not only 'vertical transformations' in the sequential development of a design concept, but also 'lateral transformations' within the solution space: the creative shift to new alternatives. Goel referred especially to the ambiguity inherent in sketches, and identified this as a positive feature of the sketch as a design tool.

It is not just formal or shape aspects of the design concept that are compiled by sketching; they also help the designer to identify and consider functional and other aspects of the design. Suwa, Purcell and Gero (98) suggested that sketching serves at least three purposes: as an external memory device in which to leave ideas as visual tokens, as a source of visuo-spatial cues for the association of functional issues, and as a physical setting in which design thoughts are constructed in a type of situated action. Although the above studies refer mostly to sketching in architectural design, Ullman et al. (90) also studied and emphasised the importance of sketching in mechanical engineering design, as have Kavakli et al. (98) and McGown et al. (98) in respect of product design. Verstijnen et al. (98) studied differences between skilled sketchers (industrial design students) and unskilled sketchers, and concluded that it was the skilled sketchers who benefited from the externalisation of mental imagery.

4. Process Strategy

An aspect of concern in design methodology and related areas of design research has been the many attempts at proposing systematic models of the design process, and suggestions for methodologies or structured approaches that should lead designers efficiently towards a good solution. However, most design in practice still appears to proceed in a rather ad-hoc and unsystematic way. Many designers remain wary of systematic procedures that, in general, still have to prove their value in design practice.

4.1 Structured process

It is not clear whether learning a structured, systematic process actually helps designers. One study that has suggested that a systematic approach might be helpful to students was that of Radcliffe and Lee (89). They studied senior students of mechanical engineering, working in small-groups (2-4) on a design project. In analysing the results, Radcliffe and Lee computed linear regression analyses of the subjects' design process sequence in comparison to an idealised, structured process of seven stages. They found that more 'efficient' processes (following closer to the supposed 'ideal') correlated positively with both quantity and quality of the subjects' design output: 'There was a positive correlation between the quality or effectiveness of a design and the degree to which the student follows a logical sequence of design processes.'

Fricke (93, 96) also studied a number of mechanical engineers, of varying degrees of experience and with varying exposures to education in systematic design processes. He found that designers following a 'flexible-methodical procedure' tended to produce good solutions. These designers worked reasonably efficiently and followed a fairly logical procedure, whether or not they had been educated in a systematic approach. In comparison, designers with too-rigid adherence to a methodical procedure (behaving 'unreasonably methodical'), or with very un-systematic approaches, produced mediocre or poor design solutions. It seems that, with or without an education in systematic design, designers need to exercise sophisticated strategic skills.

The occurrence of some relatively simple patterns of design process activity has often been suggested from anecdotal knowledge. For example, there has been a broad assumption that designing proceeds in cycles of analysis-synthesis-evaluation activities. Although such patterns of design process activity frequently have been proposed or hypothesised, there has been little empirical confirmation. McNeill et al. (98) were able to confirm some of these basic patterns, in a study of electronics engineers, using subjects with varying degrees of experience, from senior students to very experienced professionals. They were able to confirm that, 'In addition to the short-term cycles [of analysis-synthesis-evaluation], there is a trend over the whole design episode to begin by spending most of the time analysing the problem, then mainly synthesising the solution and finishing by spending most time on the evaluation of the solution.' They also confirmed a supposed progression through the design process from first considering required functions, then structure of potential solutions, and then the behavior of those solutions. Their general, if unsurprising conclusion was that: 'A designer begins a conceptual design session by analysing the functional aspects of the problem. As the session progresses, the designer focuses on the three aspects of function, behavior and structure, and engages in a cycle of analysis, synthesis and evaluation. Towards the end of the design session, the designer's activity is focused on synthesising structure and evaluating the structure's behavior.'

4.2 Opportunism

In contrast to studies that confirm the prevalence and relevance of fairly structured design behavior, there have also been some reports from studies that have emphasised the 'opportunistic' behavior of designers. This emphasis has been on designers' deviations from a structured plan or methodical process into the 'opportunistic' pursuit of issues or partial solutions that catch the designer's attention. For example, Visser (90) made a longitudinal study of an experienced mechanical engineer, preparing a design specification. The engineer claimed to be following a structured approach, but Visser found frequent deviations from this plan. 'The engineer had a hierarchically structured plan for his activity, but he used it in an opportunistic way. He used it only as long as it was profitable from the point of view of cognitive cost. If more economical cognitive actions arose, he abandoned it.' Thus Visser regarded reducing 'cognitive cost' - i.e. the cognitive load of maintaining a principled, structured approach - as a major reason for abandoning planned actions and instead delving into, for example, confirming a partial solution at a relatively early stage of the process.

From protocol studies of three experienced software system designers, Guindon (90b) also emphasised the 'opportunistic' nature of design activities. Guindon stressed that 'designers frequently deviate from a top-down approach. These results cannot be accounted for by a model of the design process where problem specification and understanding precedes solution development and where the design solution is elaborated at successively greater levels of detail in a top-down manner.' Guindon observed the interleaving of problem specification with solution development, 'drifting' through partial solution development, and jumps into exploring suddenly-recognised partial solutions, which were categorised as major causes of 'opportunistic solution development'. Guindon also referred to 'cognitive cost' as one possible explanation for such behavior: 'Designers find it advantageous to follow a train of thought temporarily, thus arriving at partial solutions at little cognitive cost.'

Ball and Ormerod (95) criticised a too-eager willingness to emphasise 'opportunism' in design activity. In their studies of expert electronics engineers they found very few deviations from a top-down, breadth-first design strategy. But they did find some significant deviations occurring, when designers made a rapid depth-first exploration of a solution concept in order to assess its viability. Ball and Ormerod did not regard such occasional depth-first explorations as implying the abandonment of a structured approach. Instead, they suggested that expert designers will normally use a mixture of breadth-first and depth-first approaches: 'Much of what has been described as opportunistic behavior sits comfortably within a structured top-down design framework in which designers alternate between breadth-first and depth-first modes.' Ball and Ormerod were concerned that 'opportunism' seemed to imply unprincipled design behavior, 'a non-systematic and heterarchical process' in contrast to the assumed ideal of a systematic and hierarchical process. However, rather than regarding opportunism as unprincipled design behavior, Guindon had suggested it might be inevitable in design: 'These deviations are not special cases due to bad design habits or performance breakdowns but are, rather, a natural consequence of the ill-structuredness of problems in the early stages of design.'

4.3 Modal shifts

An aspect of cognitive strategy that emerges from several studies is that, especially during creative periods of conceptual design, designers alternate rapidly in shifts of attention between different aspects of their task, or between different modes of activity. Akin and Lin (95), in their protocol study of an experienced engineering designer, first identified the occurrence of 'novel design decisions' (NDDs). These, in contrast to routine design decisions, are decisions that are critical to the development of the design concept. Akin and Lin also segmented the designer's activities into three modes: drawing, examining and thinking. Then, allowing for some implicit overlap or carry-over of the designer's attention from one segment to another, they represented the designer's activities in terms of single-, dual- or triple-mode periods. They found a significant correlation between the triple-mode periods and the occurrence of the NDDs: 'Six out of a total of eight times a novel design decision was made, we found the subject alternating between these three activity modes (examining-drawing-thinking) in rapid succession.' Akin and Lin are cautious about drawing any inference of causality, concluding only that 'Our data suggest that designers explore their domain of ideas in a variety of activity modes . . . when they go beyond routine decisions and achieve design breakthroughs.'

Some studies of student designers have also noted the apparent importance of frequent shifts of attention or activity mode in influencing either the creativity or overall quality of the design concepts produced. For example, in their protocol studies of junior and senior students of industrial design, Cross et al. (94) segmented the students' activities into the three modes of gathering information, sketching and reflecting. They suggested that the more successful students (in producing creative design concepts) were those who showed evidence of rapid alternation between the activity modes. Also, Atman et al. (99), from their study of freshmen and senior engineering design students, suggested that overall quality of design concepts was related to rapid alternation of activities, which they measured as transitions between design steps such as gathering information, generating ideas and modelling.

4.4 Novices and experts

Novice behavior is usually associated with a ‘depth-first’ approach to problem solving, i.e. sequentially identifying and exploring sub-solutions in depth, whereas the strategies of experts are usually regarded as being predominantly top-down and breadth-first approaches. But this may be too simplistic a view of the reality of process strategy in design. Ball and Ormerod’s (95) comments about top-down, structured approaches *vs.* ‘opportunism’ have been noted above. They concluded that ‘it would be surprising if it is practicable for expert designers to adopt a purely breadth-first or depth-first approach. Indeed, a flexible mixture of modes is a more psychologically realistic control structure for expert design.’ They suggested that, whilst a depth-first approach minimises cognitive load, a breadth-first approach minimises commitment and optimises design time and effort. Those suggestions would also quite reasonably reflect the respective concerns and strategies that we might expect of novices and experts.

Many of the classic studies of expertise have been based on examples of game-playing (e.g. chess), or on comparisons of experts versus novices in solving routine problems (e.g. physics). These are all well-defined problems, whereas designers characteristically deal with ill-defined problems. Some studies of expertise in fields such as creative writing and computer programming (Holyoak (91); Adelson and Solway (88)) where problems are more ill-defined, do suggest some parallels with observations of expert designers. These studies suggest that some of the ‘standard’ results from studies of expertise do not match with results from studies of expertise in creative domains. For example, creative experts will define the given task so that it is problematic - i.e. deliberately treat it as ill-defined - which is contrary to the assumption that experts will generally solve a problem in the ‘easiest’ way, or certainly with more ease than novices. In some ways, therefore, creative experts treat problems as ‘harder’ problems than novices do. Creative experts are also reported as solving similar tasks from first principles each time, rather than recalling previous solutions. Cross and Clayburn Cross (98) have suggested that such features of creative expertise can be seen in the strategies of outstanding expert designers.

Göker (97) compared novices and experts performing design-related problem solving tasks - the computer-simulated construction of ‘machines’ from catalogues of parts, to achieve certain objectives. A particularly unusual aspect of this study was the experimental method, based on the use of electro-encephalograph (EEG) records. Göker found that experts (subjects skilled in the use of the computer simulation) used more of the visuo-spatial regions of their brains than did the novices, who used more of their brain regions associated with verbal-abstract reasoning. The implication is that experts do not ‘reason’ towards a design concept in an abstract way, but rely more on their experience and on visual information.

5. Conclusions

In this paper I have surveyed the growth of empirical studies of design cognition, and attempted to draw out some of the issues that have emerged in such studies. I have taken a cross-disciplinary view, and looked for comparisons across the different domains of professional design practice. There has been a number of striking similarities identified in design activity, independent of professional domain, suggesting that design cognition is indeed a domain-independent phenomenon.

I have concentrated on protocol and similar formalized methods of study, and I have therefore omitted a wide range of other kinds of studies that also have relevant and important contributions to make to the understanding of design cognition and the nature of design activity. Protocol analysis has some severe limitations as a research method for investigating design activity - for instance, it is extremely weak in capturing non-verbal thought processes, which are so important in design work (Lloyd et al., 95). Dorst and Cross (97) concluded from the Delft Design Protocols Workshop that protocol analysis provides a very valuable but highly specific research technique, capturing a few aspects of design thinking in detail, but failing to encompass many of the broader realities of design in context. Other kinds of study, which attempt to capture a broader view, include detailed observation of industrial practice, such as Frankenberger and Badke-Schaub (98), and ethnographic methods, such as Bucciarelli (94). There has also been valuable historical work, such as Ferguson's (92) study of the role of drawing in engineering, and significant theoretical contributions to identifying fundamental aspects of design reasoning and logic, such as Roozenburg (93).

The range and number of studies surveyed in this paper suggest that the field of empirical studies of design activity is continuing to grow, and a number of shared issues has been identified. In many cases, these issues remain unresolved, and there is therefore still considerable work to be done to establish a robust and reliable understanding of design cognition.

5.1 Summary: problem formulation

• *Goal analysis*

Designers appear to be 'ill-behaved' problem solvers, in that they do not spend much time and attention on defining the problem. However, this seems to be appropriate behavior, since some studies have suggested that over-concentration on problem definition does not lead to successful design outcomes. It appears that successful design behavior is based not on extensive problem analysis, but on adequate 'problem scoping' and on a focused or directed approach to gathering problem information and prioritising criteria. Setting and changing goals are inherent elements of design activity.

- *Solution focusing*

Designers are solution-focused, not problem-focused. This appears to be a feature of design cognition which comes with education and experience in designing. In particular, experience in a specific problem domain enables designers to move quickly to identifying a problem 'frame' and proposing a solution conjecture

- *Problem/solution co-evolution*

The concept of 'co-evolution' of both the problem and its solution has been proposed to describe how designers develop both aspects together in conceptual stages of the design process. The designer's attention oscillates between the two, forming partial structurings of the two 'spaces' of problem and solution. Designing appears to be an 'appositional' search for a matching problem-solution pair, rather than a propositional argument from problem to solution.

- *Problem framing*

Processes of structuring and formulating the problem are frequently identified as key features of design activity. The concept of 'problem framing' perhaps seems to capture best the nature of this activity. Successful, experienced and - especially - outstanding designers are repeatedly found in various studies to be pro-active in problem framing, actively imposing their view of the problem and directing the search for solution conjectures.

5.2 Summary: solution generation

- *Fixation*

'Fixation' seems to be double-edged feature of design activity, in that it can lead to conservative, routine design or - perhaps only when exercised by outstanding designers - to creative, innovative design. There may be differences between educational programs of engineers and industrial designers (and probably architects) which lead engineers more readily to fixate on features of prior design solutions.

- *Attachment to concepts*

Designers become readily attached to single, early solution concepts and are reluctant to abandon them in the face of difficulties in developing these concepts into satisfactory solutions. This seems to be a weak feature of design behavior, which may be susceptible to change through education. However, trying to change the 'unprincipled' and 'ill-behaved' nature of conventional design activity may be working against aspects that are actually effective and productive features of intuitive design cognition.

- *Generation of alternatives*

Generating a wide range of alternative solution concepts is another aspect of design behavior which is recommended by theorists and educationists but appears not to be normal design practice. Generating a very wide range of alternatives may not be a good thing: some studies have suggested that a relatively limited amount of generation of alternatives may be the most appropriate strategy.

- *Creativity*

Creative thinking has tended to be regarded as mysterious, but new explanatory descriptions of creativity in design are beginning to emerge from empirical studies. In particular, it no longer seems correct to promote the key feature of creative design as dependent upon an intuitive, heroic ‘creative leap’ from problem to solution. Problem framing, co-evolution, and conceptual bridging between problem space and solution space seem to be better descriptors of what actually happens in creative design.

- *Sketching*

The key ‘tool’ to assist design cognition remains the traditional sketch. It seems to support and facilitate the uncertain, ambiguous and exploratory nature of conceptual design activity. Sketching is tied-in very closely with features of design cognition such as the generation and exploration of tentative solution concepts, the identification of what needs to be known about the developing concept, and especially the recognition of emergent features and properties. Studies of the role of sketching have all emphasised its inherent power as a design aid.

5.3 Summary: process strategy

- *Structured process*

Following a reasonably-structured process seems to lead to greater design success. However, rigid, over-structured approaches do not appear to be successful. They key seems to be flexibilty of approach, which comes from a rather sophisticated understanding of process strategy and its control.

- *Opportunism*

‘Opportunistic’ behavior sounds like another feature of the characteristically ‘unprincipled’, ‘ill-behaved’ activity of designers. As with some other aspects of intuitive design behavior, it may be that we should not equate ‘opportunistic’ with ‘unprincipled’ behavior in design, but rather that we should regard ‘opportunism’ as characteristic of expert design behavior. The ‘cognitive cost’ of apparently more principled, structured behavior may actually be higher than can be reasonably sustained, or can be justified by quality of outcome.

• *Modal shifts*

It has been noticed in some studies that creative, productive design behavior seems to be associated with frequent switching of types of cognitive activity. There is no clear explanation for this observation, but it may be related to the need to make rapid explorations of problem and solution in tandem.

• *Experts and novices*

Conventional wisdom about the nature of problem-solving expertise seems often to be contradicted by the behavior of expert designers. In design education we must therefore be very wary about importing models of behavior from other fields. Empirical studies of design activity have frequently found 'intuitive' features of design behavior to be the most effective and relevant to the intrinsic nature of design. Some aspects of design theory, however, have tried to develop counter-intuitive models and prescriptions for design behavior. We still need a much better understanding of what constitutes expertise in design, and how we might assist novice students to gain that expertise.

References

Adelson B and Solway E (1985) The Role of Domain Experience in Software Design, *IEEE Transactions on Software Engineering* **11**: 1351-1360

Adelson B and Solway E (1988) A Model of Software Design, *The Nature of Expertise,* M Chi R Glaser and M Farr (ed), Erlbaum, Hillsdale, NJ

Akin Ö (1978) How do Architects Design? *Artificial Intelligence and Pattern Recognition in Computer Aided Design,* J C Latombe (ed), IFIP/North-Holland, New York

Akin Ö and Akin C (1996) Frames of Reference in Architectural Design: analysing the hyper-acclamation (Aha!) *Design Studies* **17**(4): 341-361

Akin Ö and Lin C (1995) Design Protocol Data and Novel Design Decisions *Design Studies* **16**(2): 211-236

Atman C Chimka J et al (1999) A Comparison of Freshman and Senior Engineering Design Processes *Design Studies* **20**(2): 131-152

Ball L J Evans J et al (1994) Cognitive Processes in Engineering Design: a longitudinal study *Ergonomics* **37**(11): 1753-1786

Ball L J and Ormerod T (1995) Structured and Opportunistic Processing in Design: a critical discussion *International Journal of Human-Computer Studies* **43**: 131-151

Ballay J (1987) An Experimental View of the Design Process, *System Design: Behavioral Perspectives on Designers, Tools and Organisations,* W B Rouse and K B Roff (ed), North-Holland, New York

Bucciarelli L (1994) *Designing Engineers*, MIT Press, Cambridge, Ma

Chan C-S (1990) Cognitive Processes in Architectural Design Problem Solving *Design Studies* **11**(2): 60-80

Christiaans H and Dorst C (1992) Cognitive Models in Industrial Design Engineering: a protocol study, *Design Theory and Methodology - DTM92,* D L Taylor and D A Stauffer (ed), American Society of Mechanical Engineers, New York

Colgan L and Spence R (1991) Cognitive Modelling of Electronic Design, *AI in Design 91,* J Gero (ed), Butterworth-Heinemann, Oxford, UK

Cross N (1997) Creativity in Design: analyzing and modeling the creative leap *Leonardo* **30**(4): 311-317

Cross N (1999) Natural Intelligence in Design *Design Studies* **20**(1): 25-39

Cross N Christiaans H and Dorst K (1994) Design Expertise Amongst Student Designers *Journal of Art and Design Education* **13**(1): 39-56

Cross N Christiaans H and Dorst K (ed) (1996) *Analysing Design Activity*, John Wiley & Sons, Chichester, UK

Cross N and Clayburn Cross A (1998) Expertise in Engineering Design *Research in Engineering Design* **10**(3): 141-149

Cross N and Dorst K (1998) Co-evolution of Problem and Solution Spaces in Creative Design: observations from an empirical study, *Computational Models of Creative Design IV,* J Gero and M L Maher (ed), University of Sydney, NSW, Australia

Darke J (1979) The Primary Generator and the Design Process *Design Studies,* **1**(1): 36-44

Davies S and Castell A (1992) Contextualizing Design: narratives and rationalization in empirical studies of software design *Design Studies* **13**(4): 379-392

Dorst K and Dijkhuis J (1995) Comparing Paradigms for Describing Design Activity *Design Studies* **16**(2): 261-274

Eastman C M (1969) Cognitive Processes and Ill-defined Problems: a case study from design *International Joint Conference on Artificial Intelligence*, Washington, DC

Eastman C M (1970) On the Analysis of Intuitive Design Processes, *Emerging Methods in Environmental Design and Planning,* G T Moore (ed), MIT Press, Cambridge, Ma

Eckersley M (1988) The Form of Design Processes: a protocol analysis study *Design Studies* **9**(2): 86-94

Ehrlenspiel K Dylla N et al (1992) Experimental Investigation of Individual Processes in Engineering Design, *Research in Design Thinking,* N Cross K Dorst and N Roozenburg (ed), Delft University Press, Delft, The Netherlands

Ericsson K A and Simon H A (1993) *Protocol Analysis: Verbal Reports as Data*, MIT Press, Cambridge, Ma

Ferguson E (1992) *Engineering and the Mind's Eye*, MIT Press, Cambridge, Ma

Foz A (1973) Observations on Designer Behavior in the *Parti DMG-DRS Journal: Design Reseach and Methods* **7**(4): 320-323

Frankenberger E and Badke-Schaub P (1998) Integration of Group, Individual and External Influences in the Design Process, *Designers - The Key to Successful Product Development,* E Frankenberger P Badke-Schaub and H Birkhofer (ed), Springer, London, UK

Fricke G (1993) Empirical Investigations of Successful Approaches When Dealing With Differently Précised Design Problems *International Conference on Engineering Design ICED93*, Heurista, Zürich

Fricke G (1996) Successful Individual Approaches in Engineering Design *Research in Engineering Design* **8**: 151-165

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

Goel V and Pirolli P (1992) The Structure of Design Problem Spaces *Cognitive Science* **16**: 395-429

Göker M H (1997) The Effects of Experience During Design Problem Solving *Design Studies* **18**(4): 405-426

Goldschmidt G (1991) The Dialectics of Sketching *Creativity Research* **4**(2): 123-143

Guindon R (1990a) Knowledge Exploited by Experts During Software System Design *I J Man-Machine Studies* **33**: 279-304

Guindon R (1990b) Designing the Design Process: exploiting opportunistic thoughts *Human-Computer Interaction* **5**: 305-344

Holyoak K J (1991) Symbolic Connectionism: toward third-generation theories of expertise, *Toward a General Theory of Expertise: prospects and limits,* K A Ericsson and J Smith (ed), Cambridge University Press, Cambridge, UK

Jansson D G and Smith S M (1991) Design Fixation *Design Studies* **12**(1): 3-11

Jeffries R Turner A et al (1981) The Processes Involved in Designing Software, *Cognitive Skills and their Acquisition*, J R Anderson (ed), Lawrence Erlbaum Associates, Hillsdale, NJ

Kavakli M Scrivener S et al (1998) Structure in Idea Sketching Behavior *Design Studies* **19**(4): 485-517

Kolodner J L and Wills L M (1996) Powers of Observation in Creative Design *Design Studies* **17**(4): 385-416

Lawson B (1979) Cognitive Strategies in Architectural Design *Ergonomics* **22**(1): 59-68

Lawson B (1994) *Design In Mind*, Butterworth-Heinemann, Oxford, UK

Lloyd P Lawson B and Scott P (1996) Can Concurrent Verbalisation Reveal Design Cognition? *Design Studies* **16**(2): 237-259

Lloyd P and Scott P (1994) Discovering the Design Problem *Design Studies* **15**(2): 125-140

Lloyd P and Scott P (1995) Difference in Similarity: interpreting the architectural design process *Planning and Design* **22**: 383-406

McGown A Green G et al (1998) Visible Ideas: information patterns of conceptual sketch activity *Design Studies* **19**(4): 431-453

McNeill T Gero J et al (1998) Understanding Conceptual Electronic Design Using Protocol Analysis *Research in Engineering Design* **10**(3): 129-140

Olson G M Olson J S et al (1992) Small Group Design Meetings: an analysis of collaboration *Human-Computer Interaction* **7**: 347-374

Purcell A T and Gero J (1991) The Effects of Examples on the Results of Design Activity, *Artificial Intelligence in Design AID91,* J S Gero (ed), Butterworth-Heinemann, Oxford, UK

Purcell T and Gero J (1996) Design and Other Types of Fixation *Design Studies* **17**(4): 363-383

Purcell A T Williams P et al (1993) Fixation Effects: do they exist in design problem solving? *Environment and Planning B: Planning and Design* **20**(3): 333-345

Radcliffe D and Lee T Y (1989) Design Methods Used by Undergraduate Engineering Students *Design Studies* **10**(4): 199-207

Roozenburg N (1993) On the pattern of reasoning in innovative desig *Design Studies*, 14(1): 4-18

Rowe P (1987) *Design Thinking*, MIT Press, Cambridge, Ma

Schön D A (1983) *The Reflective Practitioner*, Temple-Smith, London, UK

Schön D A (1988) Designing: rules, types and worlds *Design Studies* **9**(3): 181-190

Schön D and Wiggins G (1992) Kinds of Seeing and their Functions in Designing *Design Studies* **13**(2): 135-156

Smith R P and Tjandra P (1998) Experimental Observation of Iteration in Engineering Design *Research in Engineering Design* **10**(2): 107-117

Stauffer L Ullman D et al (1987) Protocol Analysis of Mechanical Engineering Design *International Conference on Engineering Design ICED87*, ASME, New York

Suwa M Purcell T and Gero J (1998) Macroscopic Analysis of Design Processes Based on a Scheme for Coding Designers' Cognitive Actions *Design Studies* **19**(4): 455-483

Suwa M and Tversky B (1997) What do Architects and Students Perceive in Their Design Sketches? *Design Studies* **18**(4): 385-403

Tang J C and Leifer L (1990) An Observational Methodology for Studying Group Design Activity *Research in Engineering Design* **2**:209-219

Thomas J C and Carroll J M (1979) The Psychological Study of Design *Design Studies* **1**(1): 5-11

Ullman D G Dietterich T G et al (1988) A Model of the Mechanical Design Process Based on Empirical Data *A I in Engineering Design and Manufacturing* **2**(1): 33-52

Ullman D G Wood S et al (1990) The Importance of Drawing in the Mechanical Design Process *Computers and Graphics* **14**(2): 263-274

Valkenburg R and Dorst K (1998) The Reflective Practice of Design Teams *Design Studies* **19**(3): 249-271

Verstijnen I M Hennessey J M et al (1998) Sketching and Creative Discovery *Design Studies* **19**(4): 519-546

Visser W (1990) More or Less Following a Plan During Design: opportunistic deviations in specification *I J Man-Machine Studies* **33**: 247-278