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Natural Intelligence In Design

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The ability to design is widespread amongst all people, but some people appear to be better designers than others. This paper addresses what we know about this ‘natural intelligence’ of design ability, and the nature of design activity. Quotations and comments from some acknowledged expert designers are used to reinforce general findings about the nature of design activity that have come from recent design research. The role of sketching in design is used to exemplify some of the complexity of designing. In conclusion, comments are made about the value and relevance of research into artificial intelligence (AI) in design. It is suggested that one aim of research in AI in design should be to help inform understanding of the natural intelligence of design ability.

Keywords: Design behaviour, design cognition, design research, artificial intelligence

This paper is based on the keynote speech delivered by the author to the Conference on Artificial Intelligence in Design (AID98), Lisbon, Portugal, July 1998.

A common joke is to say that ‘the opposite of artificial intelligence is natural stupidity’. In the frustrations of our everyday life, most of us think that designers such as architects, product designers and computer software designers do indeed display considerable evidence of natural stupidity in the results of their work. But in this paper I want to relate the subject of artificial intelligence in design, not to the natural *stupidity*, but to the natural *intelligence* in design that is possessed certainly by good designers, and in fact is possessed to some extent by all of us. My starting point is that people are designers - and some people are very good designers.

Designing is something that all people do; something that distinguishes us from other animals, and (so far) from machines. The ability to design is a part of human intelligence, and that ability is natural and widespread amongst the human population. We human beings have a long history of design ability, as evidenced in the artifacts of previous civilisations and in the continuing traditions of vernacular design and traditional craftwork. The evidence from different cultures around the World, and from designs created by children as well as by adults, suggests that everyone is capable of designing.

But we also know that some people are better designers than others. Ever since the emergence of designers as separate professions, it appears that some people have a design ability that is more highly-developed than other people - either through some genetic endowment or through social and educational development. In fact, some people are very good at designing.

But can a machine design? That of course is the question that concerns researchers in the artificial intelligence of design. It is a question I shall return to, but first let me try to present something about what has been learned about the natural intelligence of design, and especially about some of those people who are very good at designing.

1 Research in design thinking

For almost forty years now there has been a rather embarrassingly slow but nonetheless steady growth in our understanding of design ability - probably the pioneer research paper in this field was the study of engineering designers by Marples in 1960 ¹. Nearly a decade later, we had Eastman’s also pioneering protocol studies of architects ², and in the 1970s we saw the first significant growth of the new field of design research.

I collected some of the early examples of design research together in a book on *Developments in Design Methodology*³, and more recently co-edited another review on *Research in Design Thinking*⁴.

The kinds of methods for researching the nature of design thinking that have been used have included:

- *Interviews with designers*

These have usually been with designers who are acknowledged as having well-developed design ability, and the methods have usually been unstructured interviews which sought to obtain these designers' reflections on the processes and procedures they use - either in general, or with reference to particular works of design. Recent examples include Lawson⁵ and Cross and Clayburn Cross⁶.

- *Observations and case studies*

These have usually been 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 varieties of real, artificially-constructed and even re-constructed design projects have been studied. Recent examples include Candy and Edmonds⁷, Galle⁸ and Valkenburg and Dorst⁹.

- *Protocol studies*

This more formal method has usually been applied to artificial projects, because of the stringent requirements of recording the protocols - the 'thinking-aloud' and associated actions of subjects asked to perform a set design task. Both inexperienced (often student) designers and experienced designers have been studied in this way. Recent examples include Lloyd and Scott¹⁰, Gero and McNeill¹¹, and the Delft Protocols Workshop¹².

- *Reflection and theorising*

As well as the empirical research methods listed above, there has been a significant history in design research of theoretical analysis and reflection upon the nature of design ability. Leading examples are Simon¹³ and Schön¹⁴.

- *Simulation trials*

A relatively new development in research methodology has been the attempt of AI researchers to simulate human thinking through artificial intelligence techniques. Although AI techniques may be meant to supplant human thinking, research in AI can

also be a means of trying to understand human thinking. Many examples have been included in the proceedings of the series of AI in Design conferences ^{15, 16, 17}.

We therefore have a varied set of methods which have been used for research into design thinking. The set ranges from the more abstract to the more concrete types of investigation, and from the more close to the more distant study of actual design practice. The studies have ranged through inexperienced or student designers, to experienced and expert designers, and even on to forms of non-human, artificial intelligence. All of these methods have helped researchers to develop insights into what I am referring to as the natural intelligence of design - or 'designerly' ways of thinking. Personally, I am particularly interested in what the best, expert designers have to say about design, because they may help us to develop insights into what it means to think, not just like any of us, but like a *good* designer. Therefore I am going to use some quotations from expert, outstanding designers, to illustrate the kinds of things that they say when they are interviewed about design thinking. The examples come from different design domains - architecture, engineering and product design - and I am going to relate what they say to the insights about the nature of good design thinking that the design researchers have begun to compile in recent years.

2 What expert designers say about design

A famous example of early Modern Architecture was the 1930 'Tugendhat House' in Brno, designed by Ludwig Mies van der Rohe. Apparently, according to Mies, the client had approached the architect after seeing some of the rather more conventional houses that he had designed before. Then, Mies said, in an anecdote reported by Simon ¹³, when he showed the surprising new design to the client,

'He wasn't very happy at first. But then we smoked some good cigars, ... and we drank some glasses of a good Rhein wine, ... and then he began to like it very much.'

The difficult lesson that we have to learn from this example, I believe is that *design is rhetorical*. By this, I mean that design is persuasive. You, like me, have probably experienced this for yourself - for example, you go to a car sale, looking for a sensible, modest car, and come away with something that is impractical but beautiful! Perhaps the most famous example worldwide was the design of the Sony Walkman - a product that none of us realised we wanted, until we saw it.

Design is rhetorical also in the sense that the designer, in constructing a design proposal, constructs a particular kind of argument, in which a final conclusion is

developed and evaluated as it develops against both known goals and previously unsuspected implications.

This rhetorical nature of design has been summarised in a comment by the outstanding architect, Denys Lasdun:

‘Our job is to give the client . . . *not* what he wants, but what he never dreamed he wanted; and when he gets it, he recognizes it as something he wanted all the time.’¹⁸

I think that we should try to see through the apparent arrogance in this statement, to the underlying truth that clients do want designers to transcend the obvious and the mundane, and to produce proposals which are exciting and stimulating as well as merely practical. What this means is that design is not a search for the optimum solution to the given problem, but that *design is exploratory*. The creative designer interprets the design brief not as a specification for a solution, but as a kind of partial map of unknown territory (as Jones¹⁹ suggested), and the designer sets off to explore, to discover something new, rather than to return with yet another example of the already familiar.

The vagueness, or slipperiness of the relationship between problem and solution in designing is also conveyed in the comment of the furniture designer Geoffrey Harcourt, discussing how one of his particular designs emerged:

‘As a matter of fact, the solution that I came up with wasn’t a solution to the problem at all.But when the chair was actually put together, in a way it solved the problem quite well, but from a completely different point of view.’
(Quoted by Davies²⁰.)

His comment suggests something of the perceptual aspect of design thinking - seeing the vase rather than the faces, in the well-known ambiguous figure. It implies that *design is emergent* - relevant features emerge in putative solution concepts, and can be recognised as having properties that suggest how the developing solution-concept might be matched to the developing problem-concept. In design, the solution and the problem develop together.

The ill-defined nature of design problems means that they cannot be solved simply by collecting and synthesising information, as the architect Richard MacCormac has observed:

‘I don’t think you can design anything just by absorbing information and then hoping to synthesise it into a solution. What you need to know about the problem only becomes apparent as you’re trying to solve it.’ ²¹

MacCormac is saying that all the relevant information cannot be predicted and established in advance of the design activity. The directions that are taken during the exploration of the design territory are influenced by what is learned along the way, and by the partial glimpses of what might lie ahead. In other words, *design is opportunistic*, and so the path of exploration cannot be predicted in advance.

Given the apparently ad hoc and surprise-ful nature of creative design activity, it is not unusual for designers, when talking about design thinking, to refer to the role of ‘intuition’ in their reasoning processes. For instance, the engineering product designer Jack Howe has commented:

‘I believe in intuition. I think that’s the difference between a designer and an engineer... I make a distinction between engineers and engineering designers... An engineering designer is just as creative as any other sort of designer.’
(Quoted by Davies ²⁰.)

This emphasis on ‘intuition’ is perhaps a bit surprising, coming from someone with a reputation for rather severe, rational design work. But I think that the concept of ‘intuition’ is a convenient, shorthand word for what really happens in design thinking. The more useful concept that has been used by design researchers in explaining the reasoning processes of designers is that *design is abductive*: a type of reasoning different from the more familiar concepts of inductive and deductive reasoning, but which is the necessary logic of design - the necessary step from function to form ²².

The thinking processes of the designer seem to hinge around the relationship between internal mental processes and their external expression and representation in sketches. As the engineer-architect Santiago Calatrava has said:

‘To start with you see the thing in your mind and it doesn’t exist on paper and then you start making simple sketches and organising things and then you start doing layer after layer . . . it is very much a dialogue.’ (Quoted by Lawson ⁵.)

Acknowledging the dialogue or ‘conversation’ that goes on between internal and external representations is part of the recognition that *design is reflective*. The designer has to have some medium - which is the sketch - which enables half-formed ideas to be expressed and to be reflected upon: to be considered, revised, developed, rejected and returned to.

Given the complex nature of design thinking, therefore, it hardly seems surprising that the structural engineering designer Ted Happold should have suggested that:

‘I really have, perhaps, one real talent; which is that I don’t mind at all living in the area of total uncertainty.’ (Quoted by Davies ²⁰.)

Happold certainly needed this talent, as a leading member of the structural design team for some of the most challenging buildings in the world, such as the Sydney Opera House and the Pompidou Centre in Paris. The uncertainty of design is both the frustration and the joy that designers get from their activity; they have learned to live with the fact that *design is ambiguous*. Designers will generate early tentative solutions, but also leave many options open for as long as possible; they are prepared to regard solution concepts as necessary, but imprecise and often inconclusive.

One final theme that emerges from conversations with designers is the sense of risk-taking that accompanies creative design. The racing car designer Gordon Murray has said:

‘There are patches of quite - loneliness, really, when you sit there and you think . . . I’m committed to this crazy idea!’ (Quoted by Cross and Clayburn Cross ⁶.)

This comment is from a man whose innovative, Formula One cars for the Brabham and McLaren teams won more than 50 Grand prix races, and three Drivers’ World Championships, and who designed the outstanding McLaren F1 - a road car that also went on to dominate in GT racing in recent seasons. In the face of the uncertainty of original design, there comes a time when the designer has to make a personal commitment. I think we have to acknowledge that *design is risky* - it is not comfortable, and it is not easy. The designers I have quoted above - all of them successful, and acknowledged expert or even outstanding designers - made their reputations by taking risks.

In quoting these designers, and interpreting those quotations in terms of concepts from design research, I have been trying to show two things. Firstly, that although designers themselves do not normally use the kinds of concepts that the researchers use, we are talking about the same experiences and perceptions: we are talking about - hopefully, developing a disciplined conversation about ²³ - the natural intelligence of highly-developed design ability. Secondly, I have wanted to show that this is a difficult conversation: we are not talking about simple activities that can be expressed in simple concepts.

I don't want to imply that designing is mysterious and obscure; but I do want to show that it is complex. Although everyone can design, designing is one of the highest forms of human intelligence. So converting this highly developed natural intelligence into forms of artificial intelligence is a very difficult challenge!

3 The role of sketching in design

In order to explore the complexity of design thinking a little more deeply, I would like to consider how and why designers use one of the particular tools that helps them to think - the tool of sketching. The use of sketches is clearly an important part of the natural processes of designing, but trying to understand just what this importance is, is something that has only relatively recently become a subject of more careful consideration and analysis by design researchers. (See the recent special issue of *Design Studies* on this subject ²⁴.)

I have already used a quotation from Santiago Calatrava to the effect that sketching is fundamental, as a kind of 'dialogue' situation for the designer.

Figure 1 shows some of Calatrava's sketches for a project for the Cathedral of St John, New York.

Figure 1

But why is it necessary for designers to draw at all? One obvious reason is that the end point of the design process usually requires a drawing, or a set of drawings, that provide a model of the object - the building or the product - that is to be made by the builder or manufacturer. That is the designer's goal - to provide that model. If, given the brief for a new product, the designer could immediately make that final model, then there would really be no need for a design process at all - the designer would simply read the brief and then prepare the final drawings.

Perhaps that is the goal of some AI research: to construct a machine that takes the design brief as input and gives the design drawings (or probably some other form of data for manufacture) as output. But human beings don't seem to be able to do that. A design process is necessary in which the final drawings are gradually, and sometimes rather arduously approached through a series of other drawings that we call sketches. As the engineering designer Jack Howe said, about how to start a design project, or how to proceed when stuck, 'I draw *something* - even if it's "potty" - the act of drawing seems to clarify my thoughts.' ²⁰ Trying to understand what goes on in that

sketching-and-thinking process should give us some insights into the nature of the design process.

Drawing and sketching have been used in design for a long time - certainly since long before the Renaissance, but it is the period since that time that has seen a massive growth in the use of drawings, as designed objects have become more complex and more novel. Many of Leonardo da Vinci's drawings of machines show one of the key aspects of drawings, in terms of their purpose of communicating to someone else how a new product should be built, and also how it should work. Some of Leonardo's design drawings also show how a drawing can be not only a communication aid, but also a thinking and reasoning aid. Tzonis ²⁵ has discussed how Leonardo's sketches for the design of fortifications show how he used sight-lines and missile trajectories as lines to set up the design of the fortifications, and how cognitive processes were assisted by drawing. In such drawings (Figure 2) we see how the sketch can help the designer to consider many aspects at once - we see plans, elevations, details, trajectory lines, all being drawn together and thus all being thought about, reasoned about, all together.

Figure 2

Similar kinds of drawing and thinking can also be seen in more contemporary sketches, such as those of the architect Alvar Aalto (Figure 3). Apparently Aalto would sometimes use random drawing marks as stimuli to the development of ideas for building forms. But in these design sketches we see him, like Leonardo, drawing plans and elevations and sections together, and making calculations alongside the sketches.

Figure 3

The architect Richard MacCormac has said, 'I use drawing as a process of criticism and discovery' ⁵. The concepts that are drafted in design sketches are there to be criticised, not admired; and they are part of the activity of discovery, of exploration, that is the activity of designing. Sketches by another architect, James Stirling (Figure 4), again show plans and sections being drawn and considered together, and also 3-D representations of the emerging building, as the designer generates alternative versions, and criticises them, and continues the voyage of discovery.

Figure 4

One might ask, why is it not done, simply to produce the one drawing, the one solution? Well, because a large number of alternative solutions are possible, and because (as Marples ¹ pointed out all that time ago) the nature of the design problem can only be found by exploring it through some alternative solution proposals.

This critical, reflective dialogue through sketching is just as relevant in high-performance engineering design as it is in architectural design. The racing car designer Gordon Murray says that he does lots of thumb-nail sketches, in which he ‘talks’ to himself by annotating them with criticisms such as ‘too heavy’, and ‘stupid’ or ‘rubbish’ ⁶.

So what might we learn from looking at these examples of what designers sketch, and considering their own comments about why they make sketches? One thing that is clear is that sketches enable designers to *handle different levels of abstraction simultaneously*.

Clearly this is something important in the design process. We see that designers think about the overall concept and at the same time think about detailed aspects of the implementation of that concept. Obviously not *all* of the detailed aspects, because if they could do that, they could go straight to the final set of detailed drawings. So they use the sketch to identify and then to reflect upon *critical* details - details that they realise will hinder, or somehow significantly influence the final implementation of the detailed design. This implies that, although there is a hierarchical structure of decisions, from overall concept to details, designing is not a strictly hierarchical process; in the early stages of design, the designer moves freely between different levels of detail.

The identification of critical details is part of a more general facility that sketches provide, which is that they *enable identification and recall of relevant knowledge*. As Richard MacCormac said, ‘What you need to know about the problem only becomes apparent as you’re trying to solve it.’ There is a massive amount of information that *may* be relevant, not only to *all* the possible solutions, but simply to *any* possible solution. And any possible solution in itself creates the unique circumstances in which these large bodies of information *interact*, probably in unique ways for any one possible solution. So these large amounts of information and knowledge need to be brought into play in a selective way, being selected only when they become relevant, as the designer considers the implications of the solution concept as it develops.

Because the design problem is itself ill-defined and ill-structured, another key feature of design sketches is that they *assist problem structuring through solution attempts*. We have seen that sketches incorporate not only drawings of tentative solution concepts but also numbers, symbols and texts, as the designer relates what he knows of the design problem to what is emerging as a solution. Sketching enables exploration of the problem space and the solution space to proceed together, assisting the designer to converge on a matching problem-solution pair. It enables exploration of constraints and requirements, in terms of both the limits and the possibilities of the problem and solution spaces.

Finally, as several design researchers have pointed out, sketches in design *promote the recognition of emergent features and properties* of the solution concept. They help the designer to make what Goel ²⁶ called ‘lateral transformations’ in the solution space: the creative shift to new alternatives. They assist in what Goldschmidt ²⁷ called the ‘dialectics of sketching’, the 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, again, provokes creativity. And sketches help the designer to find the unintended consequences, the surprises that keep the exploration going in what Schön ²⁸ called the ‘reflective conversation with the situation’ that is characteristic of design thinking.

In all these ways, and in some more that I’m sure we have still to realise, sketching helps design thinking. In design, drawing is a kind of intelligence amplifier, just as writing is an intelligence amplifier for all of us when we are trying to reason something out. Without writing, it can be difficult to explore and resolve our own thoughts; without drawing, it is difficult for designers to explore and resolve their thoughts. Like writing, drawing is more than simply an external memory aid; it enables and promotes the kinds of thinking that are relevant to the particular cognitive tasks of design thinking. We have seen, through considering the role of sketching in design, confirmation of the aspects of design thinking I identified earlier, such as the exploratory, opportunistic and reflective nature of design thinking.

4 Can a machine design?

Let me finally turn from understanding how human designers think, from natural intelligence in design to artificial intelligence in design: from how humans think to how machines might think.

It seems that AI-in-design research can be aimed either at *supporting* design (through interactive systems that aid the designer's creativity) or at *emulating* design (that is, through developing computational machines that design). Where the goal is to develop interactive systems that support designers, then knowledge of the human designer's cognitive behaviour obviously is of fundamental importance, because the users of the interactive systems (that is, designers) must be able to use them in ways that are cognitively comfortable. So the systems must be designed on the basis of models of the cognitive behaviour of the system users.

But reference to human designers' cognitive behaviour is perhaps inevitable in all branches of AI research, because it is the results of human behaviour that set the standards for design performance against which to assess the progress of the computational machines, just as chess-playing machines are matched against human chess masters. The highest standards of design performance that are (currently) available to us are those provided by the most creative human designers.

However, perhaps the goals of developing either interactive design systems or autonomous design machines are not the only goals of this research field. For some, an intrinsic goal is to further our understanding of human cognitive behaviour by attempting to model or emulate it in computational terms. Asking 'Can a machine design?' can be a research strategy for gaining insights into how designers think.

Again, we might make the analogy with computational modelling of chess playing. Surely the highest goals of such modelling are not simply to produce machines that can (in some sense) 'play' chess, or fatuously to replace all human chess players by machines? The goals of computational chess-playing must include developing our understanding of the nature of the 'problem' of the chess game itself, and of the nature of the human cognitive processes which are brought to bear in chess playing and in the resolution of chess problems. In such ways we could further our understanding of ourselves.

At least, that has always been my assumption about the value of having machines do things that human beings do for fun, whether that is playing chess, or designing. But John Casti, of the Santa Fe Institute, has come to a rather disturbing conclusion about the lessons that have been learned from chess-playing machines. In his recent book, *The Cambridge Quintet*²⁹, Casti imagines some conversations on computation and artificial intelligence between Turing, Wittgenstein, Schrödinger, Haldane and Snow. In a postscript, Casti refers to the 1997 defeat of the world chess champion, Garry

Kasparov, by the computer program Deep Blue II, and he quotes Kasparov as saying, 'I sensed an alien intelligence in the program.'

Casti then goes on to come to the rather surprising, and depressing conclusion that 'we have learned almost nothing about human cognitive capabilities and methods from the construction of chess-playing programs'.

So, in AI-in-design research, will we be forced to come to the same conclusion, that 'we have learned almost nothing about human cognitive capabilities and methods from the construction of designing programs'? Will designers rather nervously contemplate the 'alien intelligence' of the designing programs? Will we have built machines that can design, but also have to bring ourselves to Casti's view of the 'success' of chess-playing machines: 'the operation was a success - but the patient died!'

Perhaps Casti is being unduly pessimistic. One thing that we have learned from chess-playing programs is that the brute force of computation actually can achieve performances that outmatch human performance in a significant area of human cognitive endeavour. And surely researchers of computer chess-playing have learned something of the cognitive strategies of human chess players, even though their programs do not 'think' like humans?

What is the point of having machines do things that human beings not only can do perfectly well themselves, but also actually enjoy doing? Like playing chess, people *enjoy* designing - and, I believe, people are *very good* at designing. If, as Casti says, the building of chess-playing computer programs really has taught us 'almost nothing about human cognitive capabilities', then the research and programming efforts have been almost useless.

It seems to me that the kind of AI research that emulates human cognitive activities should address the question, 'What are we learning from this research about how people think?' Some of the AI-in-design research should attempt to tell us something about how designers think. Through AI-in-design research, I think we can hope to learn some things about the nature of human design cognition through looking at design from the computational perspective.

And of course, there is something else as well. Instead of machines that do things that people enjoy doing, and are good at doing, we want machines to do things that are arduous and difficult for human beings to do. We also want machines to do things that are not merely arduous or difficult for human beings to do, but to do things that

human beings simply cannot do unaided. So rather than just emulate human abilities, some of our design machines should also do things that designers cannot do.

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Figure captions

Figure 1 *Santiago Calatrava: sketches for a project for the completion of the Cathedral of St John, New York*

Figure 2 *Leonardo Da Vinci: design studies for fortifications*

Figure 3 *Alvar Aalto: sketches for the Maison Carré, Bazoche, France*

Figure 4 *James Stirling: sketches for the Fogg Museum, Cambridge, Mass., USA*

References

1. **Marples, D** *The Decisions of Engineering Design*, Institute of Engineering Designers, London, 1960
2. **Eastman, C** 'On the analysis of intuitive design processes' in Moore, G. T. (ed.) *Emerging Methods in Environmental Design and Planning*, MIT Press, Cambridge, Ma., USA, 1970
3. **Cross, N (ed.)** *Developments in Design Methodology*, Wiley, Chichester, 1984
4. **Cross, N, Dorst, K and Roozenburg, N (eds.)** *Research in Design Thinking*, Delft University Press, Delft, The Netherlands, 1992

5. **Lawson, B** *Design In Mind*, Butterworth-Heinemann, Oxford, 1994
6. **Cross, N and Clayburn Cross, A** 'Winning by design: the methods of Gordon Murray, racing car designer' *Design Studies*, vol 17, no 1, pp. 143-170, 1996
7. **Candy, L and Edmonds, E** 'Creative design of the Lotus bicycle' *Design Studies*, vol. 17, no. 1, pp. 71-90, 1996
8. **Galle, P** 'Design rationalisation and the logic of design: a case study' *Design Studies*, vol. 17, no.3, pp. 253-275, 1996
9. **Valkenburg, R and Dorst, K** 'The reflective practice of design teams' *Design Studies*, vol. 19, no. 3, pp. 249-272, 1998
10. **Lloyd, P and Scott, P** 'Discovering the design problem' *Design Studies*, vol. 15, no. 2, pp. 125-140, 1994
11. **Gero, J and McNeill, T** 'An approach to the analysis of design protocols' *Design Studies*, vol 19, no 1, pp. 21-61, 1998
12. **Cross, N, Christiaans, H and Dorst, K (eds.)** *Analysing Design Activity*, Wiley, Chichester, 1996
13. **Simon, H** *The Sciences of the Artificial*, MIT Press, Cambridge, Ma., USA, 1981
14. **Schön, D** *The Reflective Practitioner*, Basic Books, New York, USA, 1983
15. **Gero, J and Sudweeks, F (eds.)** *Artificial Intelligence in Design 98*, Kluwer, Dordrecht, The Netherlands, 1998
16. **Gero, J and Sudweeks, F (eds.)** *Artificial Intelligence in Design 96*, Kluwer, Dordrecht, The Netherlands, 1996
17. **Gero, J and Sudweeks, F (eds.)** *Artificial Intelligence in Design 94*, Kluwer, Dordrecht, The Netherlands, 1994
18. **Lasdun, D** 'An architects' approach to architecture' *RIBA Journal*, vol. 72, no. 4, 1965

19. **Jones, J C** *Design Methods*, Wiley, Chichester, 1981
20. **Davies, R** 'A Psychological Enquiry into the Origination and Implementation of Ideas', *MSc Thesis*, Dept. of Management Sciences, UMIST, Manchester, 1985
21. **MacCormac, R** *Design Is...* (Interview with N. Cross), BBC/Open University TV broadcast, 1976
22. **Roozenburg, N** 'On the pattern of reasoning in innovative design' *Design Studies*, vol. 14, no. 1, pp. 4-18, 1993
23. **Cross, N** 'Design research: a disciplined conversation' *Design Issues* (forthcoming)
24. **Purcell, T (ed.)** *Design Studies*, vol. 19, no. 4, 1998
25. **Tzonis, A** *Invention Through Analogy: lines of vision, lines of fire*, Architectural Knowledge Systems, Faculty of Architecture, Delft University of Technology, Delft, The Netherlands, 1992
26. **Goel, V** *Sketches of Thought*, MIT Press, Cambridge, Ma., USA, 1995
27. **Goldschmidt, G** 'The dialectics of sketching' *Creativity Research Journal*, vol 4, no 2, pp. 123-143, 1991
28. **Schön, D and Wiggins, G** 'Kinds of seeing and their functions in designing' *Design Studies*, vol. 13, no. 2, pp 135-156, 1992
29. **Casti, J** *The Cambridge Quintet*, Little, Brown, London, 1998