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Expertise in Professional Design

Nigel Cross

Introduction

Studies of the nature of expert performance in professional design originated in the late 1960s with protocol studies of architects and other design professionals. Primarily, they have been conducted by researchers who are themselves situated within the design professions, and these studies have been an important element in the more general growth of design research. More recently, researchers from fields such as psychology and cognitive science have also begun to make significant contributions to the study of design expertise.

I will review and give examples of the range of research methods that have been applied in developing the understanding of expertise in design. I will then discuss the key aspects of design expertise, and some of its apparent weaknesses, that have been established from these studies. I will briefly comment on some of the observed development of competence within students of design, and conclude with a summary of what we know of the nature of design expertise.

My starting point is that the ability to design is widespread amongst all people, but that some people appear to be better designers than others.

Design Ability

Everyone can – and does – design. We all design when we plan for something new to happen, whether that might be a new version of a recipe, a new arrangement of the living room furniture, or a new layout of a personal web page. 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. So design capability is something inherent within human cognition; it is a key part of what makes us human.

Human beings have a long history of design capability, as evidenced in the artifacts of previous civilisations and in the continuing traditions of vernacular design and traditional craftwork. Everything that we have around us has been designed. Anything that isn't a simple, untouched piece of nature has been designed by someone. The quality of that design effort therefore profoundly affects our quality of life. The ability of designers to produce effective, efficient, imaginative and stimulating designs is therefore important to all of us.

To design and make things are normal activities for humans, and 'design' has not always been regarded as something needing special abilities. Designing used to be regarded as a collective or shared capability, and it is only in fairly recent times that the ability to design has become regarded as a kind of exceptional individual talent. In traditional, craft-based production, the conception, or 'designing', of artifacts is not really separate from making them; that is to say, there is usually no prior activity of drawing or modelling before the activity of making the artifact. For example, a potter will make a pot by working directly with the clay, and without first making any sketches or drawings of the pot. In modern, industrial production, however, the activities of designing and of making artifacts are usually quite separate: the process of making something does not normally start before the process of designing it is complete.

Ever since the emergence of design as a profession, it has appeared that some people have a level of design ability that is more highly developed than in other people. Design ability has been regarded as something that many people possess to some degree, but only a few people have a particularly strong design talent or 'gift'. Of course, we know that some people are better designers than others. In fact, some people are very good at designing, and expertise is acknowledged through peer recognition, established reputations, and awards for innovative, high quality or high performance designs. Although there is so much design activity going on in the world, the ways in which people design were rather poorly understood for rather a long time. However, there are now growing bodies of knowledge about the nature of designing, and about the core features or aspects of design expertise.

Understanding Expertise in Design

The study of expertise in design originated in the late 1960s with studies in architecture, and developed across a variety of other domains such as engineering, product and software design (Cross, 2001). In these studies, participants have been categorised as novice designers (students at various stages of development), experienced designers (professional designers with several years of experience), expert designers (those with well-established reputations for excellence within their profession) or outstanding designers (those with international reputations and records of innovative and exceptional performance, including awards for high quality, or consistently high objective achievements in their field). As well as studies of individuals, there have also been studies of teams. Research methods have included interviewing expert and outstanding designers, ethnographic observation and case studies of professional design activity, experimental studies especially protocol studies of novice and experienced designers, neurological studies and computational attempts to model or simulate expert performance.

Interview studies have focused on designers who are acknowledged as having well-developed or outstanding design expertise, and have been based on conversations or interviews that sought to obtain these designers' reflections on the processes and procedures they use, either in general, or with reference to particular works of design. Observations and case studies have tended to focus 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. Experimental methods have usually been applied to artificial projects, related to the stringent requirements of recording the data. They include asking the participants to conduct a short design task and to 'think aloud' as they respond to the task, and using these statements and the associated actions of the participants as the basis of protocol analysis studies.

An interview study by Davies and Talbot (1987) was conducted with members of the UK-based 'Faculty of Royal Designers for Industry'. This is an élite body of designers, across all domains of design practice, affiliated to The Royal Society for the Encouragement of Arts, Manufactures and Commerce, or the Royal Society of Arts (RSA) as it is more commonly known. Royal Designers for Industry are selected for the honour of appointment to the Faculty on the basis of their records of sustained excellence in design.

What many of these outstanding designers suggested is that they find some aspects of their work appear to them to be natural, perhaps almost unconscious, ways of thinking. They believe that this 'intuitive' way of thinking may be something that they inherently possess, or it may be something that they developed through their education. Making decisions, or generating proposals, in the design process is something that they feel relaxed about, and for which they feel no need to seek rational explanations or justifications. But it may be that they are overlooking the experience that they have gathered, and in fact their 'intuitive' responses may be derived from these large pools of experience, and from prior learning gained from making appropriate, and inappropriate, responses in certain situations.

What designers say about what they do can of course be rather biased, or based on partial recall, or limited by their willingness or ability to articulate what are complex cognitive activities. Sometimes, some designers can even seem to be wilfully obscure about how they work, and where their ideas come from. The renowned designer Philippe Starck is known to suggest that design ideas seem to come to him quite magically, as if from nowhere (Carmel-Arthur, 1999). For example, of the design process of his iconic lemon squeezer for the Italian kitchenware manufacturer Alessi, Starck said that, shortly after being set the task, whilst eating squid in a restaurant, "this vision of a squid-like lemon squeezer came upon me..." (Carmel-Arthur, p.13). And so, *Juicy Salif*, the lemon squeezer, was conceived, went into production and on to become a phenomenally successful product in terms of sales (if not necessarily in terms of its apparent function).

But it is possible to construct a less mystical account of the conception of Starck's lemon squeezer. In deconstructing this particular design act, Lloyd and Snelders (2003), utilising what Starck has said about himself in various interviews, what (little) he said about the conception of the lemon squeezer, and in particular the evidence of his very first design sketches for it, which were made on the restaurant placemat. Lloyd and Snelders implied that the 'squid-like' concept was not an inexplicable flash of inspiration, but that it arose rather more prosaically by applying an analogy (that happened to be at hand, in the form of the squid) to the problem that was in the designer's mind (to create a novel form for a lemon squeezer). The utility of this kind of analogy-making is often encountered in accounts of creative thinking (e.g. Boden, 1990). What was particularly striking in this case was Starck's ability to make the mental leap of transposing 'squid' to 'lemon squeezer'. Thereafter, Lloyd and Snelders suggested, Starck, in developing the concept, was doing what many designers do, which is to draw upon a repertoire of precedents, of remembered images and recollections of other objects that helped him to give a more coherent, practicable and attractive form to the concept.

A more direct form of enquiry into understanding what designers do is actually to watch them at work, observing their activities. Bucciarelli (1994) conducted a series of participant-observer studies of engineering design projects in three different companies. Large projects demand an important aspect of design ability, that of reconciling the variety of interests – technical, financial, social, aesthetic, etc. – that inevitably have to coalesce around a major project. In these cases, designing becomes not just a personal, cognitive process, but a shared, social process. The main conclusion that Bucciarelli stressed is how even engineering design, traditionally seen as a strictly technical process, is in reality a social process of interaction and negotiation between the different participants who each bring to bear their own 'object world' – their own specific knowledge and awareness of aspects of the object being designed. The social nature of designing, Bucciarelli suggested, requires acknowledging the inevitability of uncertainty and ambiguity, even within the process of engineering design.

Lawson (1994) suggested that successful designers are good at coping with this uncertainty and ambiguity. From interviews with several outstanding architects, he identified their ability to maintain parallel processes of cognition relevant to the same design job at the same time, for example, working on detail junctions of materials at the same time as on general spatial concepts of a design. Lawson described how the architect Robert Venturi, working on a design for a major extension to the National Gallery in London, maintained one particular line of thought concerned with ideas for relating the circulation system in the new building to that in the older part (issues of the plan, and of floor levels), whilst another was for relating together the external appearances of the new and old parts (issues of the elevation, and of architectural styles). Lawson suggested that Venturi kept these two sets of ideas in progress, both equally important to his design thinking, before resolving them into a single solution.

One way to cope with uncertainty is to try to impose order. Darke (1979) interviewed a number of expert architects, and noticed how they sought to impose order on the rather nebulous problems they faced. Some brought to the problem a personal set of guiding principles that offered starting points, some sought to find starting points in the particularities of the site on which they were to build. In each case, Darke observed how these starting points enabled the designers to limit the problem to something manageable, to provide a narrower focus within which they could work. The designers imposed a limited set of objectives, or an idea about the building form, as a 'primary generator', as Darke called it, a means of instantiating a solution concept. This seems to be a necessary part of the design process, because a solution concept cannot be derived directly from the problem statement; the designer has to add or bring something to it.

Early attempts at analysing expert design behaviour tended to borrow language and concepts from cognitive science studies of problem solving behaviour. However, gradually it became clear that designing is not 'normal' problem solving. Goel and Pirolli (1992), even from within a conventional cognitive science paradigm of problem solving, successfully established designing as distinct from non-design problem-solving.

However, design ability seems to be a natural part of human cognition, and there is evidence that such deep-seated strategies and competencies can be impacted and even lost through neurological damage in the brain. One of these cases was reported by Goel and Grafman (2000), who studied an architect who had had a seizure, associated with a meningioma tumour in his right prefrontal cortex. Before his attack, this person had practiced successfully as an architect. Through protocol analysis studies, Goel and Grafman compared this architect's post-attack design ability with that of a healthy, matched control person (another architect with similar education and design experience), on being given a relatively simple task of re-designing a laboratory space. Both participants began by making a survey drawing of the existing laboratory and its furniture. The healthy control architect then produced a coherent series of sketches, beginning with abstracted considerations of circulation and organisation, then developing proposals and refining the preferred one. The neurological patient produced three separate, basic and incomplete proposals, finishing with a 'final proposal' that was still inadequate and incomplete.

The differences in the thinking processes of the two individuals became clear in graphs of the amount of time each devoted to different cognitive activities, as revealed by their think-aloud comments made during the experiments. The control architect focused initially on 'problem structuring', with periodical returns to this. He then moved to 'preliminary design' and on to 'refinement' and 'detailing'. His graph clearly showed a controlled but complex pattern of activities, with overlap and quick transitions between activities. In contrast, the patient spent a huge amount of time on attempting 'problem structuring', and only small amounts of time on 'preliminary design' and 'refinement'.

The experimenters reported that the patient understood the task, his architectural knowledge base was still intact, and he used it quite skilfully during the problem-structuring phase. However, he was unable to make the transition from problem structuring to problem solving, and simply could not perform the relatively simple design task. This unhappy case exposed some of the considerable complexity that there is in design thinking, and evidence that the normal brain has high-level cognitive functions that control or process activities that are essential aspects of design expertise.

One neuroscience study (Alexiou et al., 2009; Gilbert et al., 2009) investigated the neurological bases of design cognition using fMRI brain imaging techniques, with a mixed group of participants with varying experience in design. The researchers set the experiment participants a simple design task, involving the layout of furniture within a conference room, but two different versions of the problem task were given to different participant groups. One version was formulated as a well-defined problem solving task, with specific constraints to be satisfied, such as 'the two tables must face each other'. The other, less-defined and more design-like version, gave qualitative requirements, such as achieving a 'spacious room' and a layout that 'enables cooperation'. The findings suggested that the two conditions, problem solving and designing, involve distinct cognitive functions associated with distinct brain networks, with the design condition associated with greater activity in right dorsolateral prefrontal cortex compared to the non-design condition. Such studies tend to confirm the view within the design studies community that there are particular, 'designerly' ways of knowing, thinking and acting (Cross, 2006), associated with identifiable, key aspects of design expertise.

Key Aspects of Expertise in Design

Conventional wisdom about the nature of expertise in problem solving seems often to be contradicted by the behaviour of expert designers. For example, expert designers challenge problem 'rules' and often tackle the problem in a 'difficult' way. Studies of design activity suggest that these unconventional features of design behaviour actually may be the most effective and relevant to the intrinsic nature of designing.

Unlike 'normal' problem solving, 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. So it is not unreasonable that in approaching a new project expert designers do not proceed by first attempting to define the problem rigorously. However, they do appear to have a number of characteristic key strategies or approaches for dealing with the given problems.

Problem Framing

Designers are not limited to 'given' problems, but find and formulate problems within the broad context of the design brief. Processes of structuring and formulating the problem are frequently identified as key features of design expertise. The concept of 'problem framing' seems to capture best the nature of this activity. Successful, experienced and – especially – outstanding designers are 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.

This is also a more general characteristic of professional reflective practice identified by Schön (1983) 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" (p. 40). This seems to characterise well what has been observed of the problem formulation aspects of design behaviour. 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 (1988) 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" (p. 182). This kind of problem framing has been noted often in studies of architects. Lloyd and Scott (1995), from their studies of 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" (p. 397). They referred to this 'way of seeing the design situation' as the designer's 'problem paradigm'. In common also with their studies of engineers (Lloyd and Scott, 1994), they 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 (1998) 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 behaviour of expert and outstanding engineering designers.

Schön (1988) pointed out that "the work of framing is seldom done in one burst at the beginning of a design process" (p. 182). This was confirmed in Goel and Pirolli's (1992) 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 re-occurred periodically throughout the task.

Solution Conjecturing

Experience within a problem domain enables designers to move quickly to identifying a problem frame and proposing a solution conjecture. This appears to be a feature of design cognition that comes with experience in designing. Generating a wide range of alternative solution concepts is frequently recommended by theorists and educationists but appears not to be normal in expert 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.

The solution-focused nature of designing was first noted by Lawson (1979) in comparisons of problem solving behaviour by scientists and architects. Subsequently, many studies of expert design behaviour suggest that designers move rapidly to early solution conjectures, and use these conjectures as a way of exploring and defining problem-and-solution together. Lloyd and Scott (1994), from their protocol analysis studies of experienced engineering designers, found that this 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" (p. 140).

This aspect of design expertise has been noted even from the very earliest formal studies. Eastman (1970), in the earliest recorded design protocol study (of experienced architects), 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" (p. 27). That is to say, the designers jumped to ideas for solutions (or partial solutions) rather than attempting first to fully formulate 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. As Ullman, Dietterich and Stauffer (1988) pointed out, from their protocol studies of experienced mechanical engineering designers, 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.

Co-evolving 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.

Creative design is not a matter of first fixing the problem and then searching for a satisfactory solution concept; instead, it seems more to be a matter of developing and refining together both the formulation of the problem and ideas for its solution, with constant iteration of analysis, synthesis and evaluation processes between the two 'spaces' of problem and solution. As Kolodner and Wills (1996) observed, from a study of engineering designers: "Proposed solutions often directly remind designers of issues to consider. The problem and solution co-evolve" (p. 390). The concept of 'co-evolution' was introduced in computer modelling of design processes by Maher (1994), and has been developed to describe how designers develop aspects of both the problem and the solution together in conceptual stages of the design process.

In this interpretation of design as a co-evolution of both solution and problem, the designer's attention oscillates between the two, forming partial, related structurings within the problem and solution spaces. Dorst and Cross (2001) observed this behaviour 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" (pp. 434-435).

Wiltschnig, Christensen and Ball (2013) extended the study of co-evolution from laboratory studies of individual designers into team design processes in professional engineering design practice. They found that co-evolution was significantly present in such practice, identifying episodes of co-evolution that demonstrated elements from within the problem space being intimately linked with solution generation activity. These episodes revealed close links between co-evolution and creative processes, and they concluded that "the evidence points to co-evolution episodes as being the creative engine of everyday design practice" (p. 539).

During a co-evolutionary design process, partial models of the problem and solution are constructed side-by-side, as it were. But the crucial factor, often regarded as a 'creative leap', is the bridging of these two partial models by the articulation of a concept that enables the models to be mapped onto each other. Cross (1997) argued that, in design, the creative event is not so much a 'creative leap' from problem to solution as the building of a 'bridge' between the problem space and the solution space by the identification of a key concept. The development of a satisfactory bridging concept or conjecture embodies constructive relationships between problem and solution. It is the recognition of such a satisfactory concept that provides the illumination of the creative 'flash of insight'. The interdependent development of problem and solution spaces, and the recognition of a satisfactory bridging concept for a problem-solution pair are considered key features that characterise creative design as a process of exploration rather than search. Creative design involves a period of exploration in which problem and solution spaces are evolving and are unstable until (temporarily) fixed by an emergent problem-solution pair.

A related aspect of cognitive strategy that emerges from some studies is that, especially during creative periods of conceptual design, expert designers alternate rapidly in shifts of attention between different aspects of their task, or between different modes of activity. Akin and Lin (1996), in a protocol study of an expert engineering designer, first identified the occurrence of a sequence of novel design decisions. 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 novel design decisions, where the designer was alternating between these three activity modes (examining-drawing-thinking) in rapid succession. Akin and Lin were 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" (p. 59).

Several of these features of expert designer behaviour were confirmed and clarified by Suwa, Gero and Purcell (2000) from a protocol study of an experienced architect. They concentrated on the occurrence of 'unexpected discoveries' during the design process – that is, those instances when a designer perceives something 'new' in a previously-drawn element of a solution concept – and related these to the 'invention' of further issues or requirements within the design problem. They found a strong bi-directional correlation between unexpected discoveries and the invention of issues and requirements. Suwa, Gero and Purcell suggested that their findings provided empirical evidence both for the co-evolution of problem space and solution space and for designing as a 'situated' act – that is, designers invent design issues or requirements in a way situated in the environment in which they design. Their analysis also confirmed the importance of rapid alternation between different modes of activity, facilitated by external representations: "drawing sketches, representing the visual field in the sketches, perceiving visuo-spatial features in sketches, and conceiving of design issues or requirements are all dynamically coupled with each other" (p. 564).

Representations

A key tool to assist design cognition is the use of representations, including the traditional form of the 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.

One obvious purpose of sketching and drawing 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 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.

It seems that designing is difficult to conduct by purely internal mental processes; the designer needs to interact with an external representation. The activity of sketching, drawing or modelling provides some of the circumstances by which designers put themselves into the design situation and engage with the exploration of both the problem and its solution. There is a cognitive limit to the amount of complexity that can be handled internally; sketching provides a temporary, external store for tentative ideas, and supports the on-going 'dialogue' that the designer conducts between problem and solution.

Several researchers have referred to the ways in which sketching helps to assist cognition in design thinking. Sketching helps the designer to find unintended consequences, the surprises that keep the process of design exploration going in what Schön and Wiggins (1992) called the 'reflective conversation with the situation' that is characteristic of design thinking. Goldschmidt (1991) 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 (1995) 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 (1998) 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, Wood and Craig (1990) also studied and emphasised the importance of sketching in mechanical engineering design, as have others in respect of various domains of design practice. The critical, reflective dialogue through sketching seems to be relevant in all forms of design.

Clearly the use of external representations is something important in the design process. One reason is that sketches enable designers to handle different levels of abstraction simultaneously. As various studies have shown, during design activity expert designers are thinking about the overall concept and at the same time thinking about detailed aspects of the implementation of that concept. Obviously not all of the detailed aspects are considered early on, because if the designers could do that, they could go straight to the final set of detailed drawings. So they use sketches 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 may be 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. 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.

Another key benefit of design sketches is that they assist problem structuring through solution attempts. Designers' sketches incorporate not only drawings of tentative solution concepts but also numbers, symbols and texts, as designers relate what they know 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. Perhaps crucially, sketches in design promote the recognition of emergent features and properties of the solution concept.

Precedents

In a co-evolutionary process of exploration, how do designers identify or construct partial structures within the problem and solution spaces? From protocol studies, Dorst and Cross (2001) suggested that expert designers seek to gather pieces of related information within the problem space. Expert designers appear to have a search strategy, pursuing a quasi-standard set of questions, and actively seeking or creating patterns within the data. They also have a store of knowledge of solution precedents, either from their own previous experience or from a broad knowledge of the domain in which they practice. Somewhat like chess players, expert designers seem to recognise patterns in problem situations and draw upon knowledge of precedents that enable them to build conceptual bridges between the problem and solution spaces. However, in designing, unlike chess playing, it is not possible simply to reproduce previous solutions; the new design in some way has to be original.

In developing a knowledge-based computational model of design, Oxman (1990) considered the apparent paradox of how knowledge of precedents, which by definition are examples of the old, can be used to help generate proposals for the new. She suggested that a fundamental factor is the classification of prior solutions in terms of more abstract and generalised knowledge, the ability to progress from iconic sources to generic types. When designers study prior examples, therefore, it is not simply to copy them, but to abstract general principles of how to resolve similar situations. This is not the use of precedent in the form of a rule, or a normalised prior solution, but to adapt and extract from it in order to reach a creative re-interpretation.

So a key competency of an expert designer, like other experts, is the ability mentally to stand back from the specifics of accumulated examples, and form more abstract conceptualisations pertinent to their domain of expertise. Experts are able to store and access information in larger cognitive chunks than non-experts, and to recognise underlying principles, rather than focussing on the surface features of problems. Lawson (2004) suggested that designers use knowledge of precedents that they have abstracted into solution chunks, or 'schemata'. A typical design schema for an architect might be a way of organising internal space, such as around an atrium, or for an industrial designer might be grouping together different functional parts of a product.

Lawson also suggested that, like chess masters, expert designers have repertoires of 'gambits', or ways of proceeding, of entering into and opening up the problem situation. These can be guiding principles or the use of techniques such as geometrical formulations. Some designers use the same or similar 'gambits' frequently, developing them into recognisable personal design styles.

Apparent Weaknesses

Several studies have shown that the normal practices of expert designers can exhibit certain features that might be regarded as weaknesses in their methods or approaches. One particular weakness appears to be 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 (1987) 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" (p. 36). The same phenomenon was observed by Ullman, Dietterich and Stauffer (1988), 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" (p. 47).

This apparent weakness may be associated with the 'cognitive cost' of developing new design concepts, but might also be a positive aspect of expert behaviour, related to the establishment of a 'problem frame'. Cross and Clayburn Cross (1998) reported that expert designers can be tenacious in their pursuit of solution concepts that fit the frame, or guiding theme or principle that they adopted. Crilly (2015) suggested that experienced designers draw on their knowledge of prior projects but seek to maintain a balance between openness and a persistence in pursuing a solution concept.

Another weakness has been suggested where details of known previous design solutions are carried over, perhaps inappropriately and even unconsciously, into new solutions. This 'fixation' effect in design was suggested by Jansson and Smith (1991), who studied experienced 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' by 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.

Purcell and Gero (1992, 1996) 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. Their results suggested that the engineering students appeared to be much more susceptible to fixation than did the industrial design students; 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 programmes 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 either an innovative or 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 seemed to be fixated on 'being different'.

Many further studies have been made of the use of examples to induce either fixation or inspiration. Sio, Kotovsky and Cagan (2015) conducted a meta-analysis of such studies and concluded that being presented with examples can have a negative effect on the variety of ideas generated but a positive effect on the novelty and quality of ideas. They suggested that "the presence of examples can modify the search strategy from a broad one to a focused one. Although this narrows the scope of search, it allows a more in-depth exploration, and in turn, improves solution quality" (p. 91). These results are generally controlled experiments to investigate particular effects, whereas in practice, designers can choose and use examples, or precedents, more deliberately.

An interview study of expert designers by Crilly (2015) focused on trying to understand their awareness of and attitudes towards fixation. He concluded that fixation is a real problem in a variety of ways in professional design practice, but that expert designers are aware of these problems and they take steps to address them, including discussion with colleagues and the building of models and prototypes. Cross and Clayburn Cross (1998) suggested that, in innovative design, expert designers are aware of the need to "keep experience at the back of [their] mind, not the front" (p. 148), and work from first principles, rather than copying a standard solution.

Another apparent weakness in expert design behaviour emerged from some studies that recorded the 'opportunistic' behaviour 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. Visser (1990) conducted a longitudinal study of an experienced mechanical engineer pursuing a design project. The engineer claimed to be following a structured approach, but Visser found frequent deviations from this plan, observing that "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" (p. 276). 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 analysis studies of three experienced software system designers, Guindon (1990) 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" (p. 326). Guindon observed the co-evolution approach of interleaving problem specification with solution development, 'drifting' through partial solution development, and jumps into exploring suddenly-recognised partial solutions, which she categorised as major causes of 'opportunistic solution development'. She also referred to cognitive cost as one possible explanation for such behaviour.

Ball and Ormerod (1995) 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 behaviour sits comfortably within a structured top-down design framework in which designers alternate between breadth-first and depth-first modes" (p. 148). Ball and Ormerod were concerned that 'opportunism' seemed to imply unprincipled design behaviour, 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 behaviour, Guindon (1990) 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" (p. 307). So it may be that we should not equate 'opportunistic' with 'unprincipled' behaviour in design, but rather that we should regard 'opportunism' as a characteristic of expert design behaviour.

These examples do seem to suggest some weak features in expert design behaviour. 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 design expertise.

Developing Expertise in Design

Education in design has well-established practices, predominantly project- and studio-based learning, that are assumed to help students develop in a progression from novice towards expert; but these are not very well understood, and certainly not well researched, documented and explained. There is still rather limited understanding of the differences between novice and expert performance in design, and in particular how to help students move from one to the other.

In studies of problem solving, novicebehaviour is usually associated with a depth-first approach, whilst the strategies of experts are usually regarded as exhibiting predominantly breadth-first approaches. Differences of this nature were found between the behaviour of novice and experienced designers by Ahmed, Wallace and Blessing (2003). They found clear differences between the behaviours of new (graduate) entrants to the engineering profession and much more experienced engineers. The new entrants used trial-and-error techniques of generating and implementing a design modification, evaluating it, then generating another, and so on through many iterations. Experienced engineers were observed to make a preliminary evaluation of their tentative decisions before implementing them and making a final evaluation. They used the foresight they had gained from experience to consider whether it seemed worthwhile to move further into the implementation stage of a design decision.

Developing greater expertise generally means developing a broader and more complex understanding of what has to be achieved, and this is also common in developing design expertise. For example, studies of novice (graduate student) and expert designers in the field of woven textiles found that the novices concentrated on the visual composition task and only occasionally moved to construction issues to explore how the visual ideas could be realised in the weaving. In contrast, the experts integrated both the visual and the technical elements of weaving, and generally considered them in a parallel way during the design process (Seitamaa-Hakkarainen and Hakkarainen, 2001).

Christiaans and Dorst (1992) found, from protocol analysis studies of junior and senior industrial design students, that some students became stuck on information gathering, rather than progressing to solution generation. 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 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" (p. 135). This is the activity of problem framing. The other group gathered lots of information, but for them, the activity of naming, or simply gathering data, was sometimes just a substitute activity for actually doing any design work.

In studies of junior versus senior student design behaviours, Adams, Turns and Atman (2003) found that changes in individual students' behaviours over the three or four years of their studies were quite complex and variable. Although there were identifiable changes in behaviour for many of the students, some did not appear to change their behaviours at all and some seniors simply spent more time on the given design projects but without any qualitative behavioural changes. It also appeared that some students exhibited different behavioural changes for different types of design projects; they were perhaps on the cusp of development from beginners to more competent practitioners, showing more sensitivity to different problem situations.

The development of expertise passes through different stages. Something happens in the development from novice to expert, involving a progression through different levels of ability. Thus a novice undergoes training and education in their chosen field, enters into practice, achieves some competence, and then at some later point becomes regarded as an expert. In all fields, the accumulation of experience is a vital part of the transformation to expert.

Dreyfus and Dreyfus (2005) outlined a five-stage general model of skill acquisition and the development of expertise: Novice; Advanced Beginner; Competence; Proficiency; Expertise. Lawson and Dorst (2009) expanded this model to fit the development of expertise in design. They inserted a student 'beginner' phase between novice and advanced beginner, acknowledging that most people can be 'novice designers'. Also, the graduate student may have reached a level of competence, but probably is still an 'advanced beginner' and needs much more practice and experience to become an expert. For most designers, the expert level of achievement is where they remain, perhaps with some continued moderate improvement. But some progress beyond the peak level of their peers, and enter into a further phase of development, reaching outstanding levels of achievement and eminence. They can even develop into 'visionaries' who introduce completely new concepts and constructs to the profession.

Conclusion

Many of the classic studies of expertise have been based on examples of game-playing (such as chess), or on comparisons of experts versus novices in solving routine problems (e.g. in physics). These studies are generally examples of solving well-defined problems, whereas designers characteristically deal with ill-defined problems, where there is no definitive formulation of the problem, there are no rules of how to operate, and no single or verifiably correct solution. Some of the standard results from studies of expertise do not match with results from studies of expertise in creative domains such as design. For example, creative experts might reformulate the given task so that it is more 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.

Expert designers appear to be 'ill-behaved' problem solvers, e.g. in that they do not devote extensive time and attention to defining the problem. However, it seems that this may well be appropriate behaviour, since some studies have suggested that over-concentration on problem definition does not necessarily lead to successful design outcomes. It appears that successful design behaviour is based not on extensive problem analysis, but on adequate 'problem scoping' and on a focused or directed approach to gathering problem information, prioritising criteria and generating solution concepts. Setting and changing goals, rather than sticking to the problem as given, are inherent elements of design activity.

Expert designers perform in ways akin to other professionals operating in fields of naturalistic decision making (Klein, 1999), dealing with practical situations of uncertainty, inadequate information and unclear goals. Klein suggested that experts in these situations make 'recognition-primed' decisions: "They understand what types of *goals* make sense (so the priorities are set), which *cues* are important (so there is not an overload of information), what to *expect* next (so they can prepare themselves and notice surprises), and the *typical ways of responding* in a given situation. By recognising a situation as typical, they also recognise a *course of action* likely to succeed" (p. 24). This description is very similar to how we have seen that designers operate. Like other professional decision makers, expert designers do not work from 'intuition' but have recognisable and appropriate strategies for dealing with their ill-defined problems, as research in understanding design expertise has shown.

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