Expertise in design: an overview

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Expertise in Design: an overview

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Abstract
This is a review paper of the field of research into expertise in design. There has been a growth of empirical and formalised study of designer behaviour, and this paper focuses specifically on expert performance. Some background information from the study of expertise in other fields is introduced. The studies of design expertise that are reviewed refer to expert vs. novice performance, expert designer behaviour and outstanding designers. It seems that expertise in design has some aspects that are siginificantly different from expertise in other fields.

Keywords: design behaviour, design cognition, design process, expertise

The focus of this review paper is the nature of expert performance in design.
The topic of expertise has been receiving increasing attention in the design research community. There has been a rapidly growing development of protocol and other empirical studies of design cognition, amongst which have been studies of expert, or experienced designers, comparisons of the processes of novice and expert designers, and some interview studies on outstanding or exceptional designers. A significant addition to work in this area was the recent Design Thinking Research Symposium on Expertise in Design [1].

1 Expertise

There is, of course, a substantial and long history of work on understanding expertise in some other fields and contexts, including chess, music and sports. From these studies, there is a general view that expertise develops over time as a person matures, but that there comes a point when a peak of performance is reached, and then an inevitable decline begins. This performance peak will be reached at different ages in different fields – for physical sports, it may be around the age of middle-twenties, whereas in mental activities it may not be until much later in life: in the sciences, people seem to produce their best work in their thirties, whilst in the arts it may be in their forties. Some outstanding individuals seem to defy the general picture, and to continue producing great work well into later years. But one aspect that seems agreed from studies of expertise is that it requires a minimum period of practice and sustained involvement before performance reaches an international peer-level of achievement – at least 10 years from first involvement [2].

Expertise is not simply a matter of possessing 'talent', but is the result of a dedicated application to a chosen field. According to Ericsson [3], who is an expert in the study of expertise, 'Superior expert performance is primarily acquired . . . Many thousands of hours of deliberate practice and training are necessary to reach the highest levels of performance'. He comments that 'Most international masters emphasise the role of motivation, concentration, and the willingness to work hard on improving performance.' Ericsson [4] suggests that deliberate practice (i.e. practice deliberately guided towards improvement of performance) is one of the key factors in the acquisition of expertise: 'The attained level of performance of many types of experts, such as musicians, chess players and athletes, is closely related to their accumulated amount of deliberate practice.' Usually, a child may display a certain aptitude or interest, and parents or teachers then encourage and guide their development. But without the dedicated application of the individual, levels of performance will remain modest.

The development of expertise probably passes through different phases. We are all familiar with the concepts of the novice and the expert – and that something happens in the development from one to the other. A novice undergoes training and education in their chosen field, and then at some later point becomes an expert. The accumulation of experience is a vital part of the transformation to expert. For some people, the 'expert' level of achievement is where they remain, perhaps with some continued moderate improvement before reaching their peak and beginning their decline. A few manage to go beyond the level of their peers, into a further phase of development, reaching outstanding levels of achievement and eminence. At the other end of the scale of maturity, at a young age, all of us are introduced to a variety of human activities, whether it be playing football or playing the violin. We all improve a little, but some, as noted above, will begin to practice with a dedication – and probably a joy – that sets them apart. In areas such as sports and music and chess, there are established programmes of training for these neophytes; perhaps the design community also needs to focus some attention on this earliest phase in the development of expertise.

2 Expert vs. novice designers

Novice behaviour is usually associated with a 'depth-first' approach to problem solving, i.e. sequentially identifying and exploring sub-solutions in depth, whereas the strategies of experts are usually regarded as being predominantly top-down and breadth-first approaches. Many of the classic studies of expertise have been based on examples of game-playing (e.g. chess), or on comparisons of experts versus novices in solving routine problems (e.g. physics). These are all well-defined problems, whereas designers characteristically deal with ill-defined problems. Ho [5], in a protocol study of a novice and an expert product designer, found that their problem-solving strategies did not conform with the 'standard' expectations derived from studies in well-defined problem domains. The expert designer used explicit problem decomposing strategies, which the novice appeared not to possess, but both expert and novice used similar, bottom-up, or working-backward, problem solving strategies.

Some studies of expertise in fields such as creative writing and computer programming [6, 7], where problems are ill-defined, also suggest that some of the standard results from studies of expertise do not match with results from studies of expertise in creative domains. For example, creative experts will define the given task so that it is problematic – i.e. deliberately treat it as ill-defined – which is contrary to the assumption that experts will generally solve a problem in the 'easiest' way, or certainly with more ease than novices. In some ways, therefore, creative experts treat problems as 'harder' problems than novices do. This was also suggested in observations of expert designers [8].

Education in design has well-established practices that are assumed to help the progression from novice to expert; but there is still precious little real understanding of the differences between novice and expert performance in design, and how to help students move from one to the other. Research questions to address here include: What are the key differences between expert and novice behaviour and cognition? How is the transition made from novice to expert? Can certain educational methods assist the transition more effectively or efficiently?

Christiaans and Dorst [9], from protocol studies of junior and senior industrial design students, found that some students became stuck on information gathering, rather than progressing to solution generation. Interestingly, they found that this was not such a significant difficulty for junior students, who did not gather a lot of information, and tended to 'solve a simple problem', being unaware of a lot of potential criteria and difficulties. But they found that senior students could be divided into two types. The more successful group, in terms of the creativity quality of their solutions, 'asks less information, processes it instantly, and gives the impression of consciously building up an image of the problem. They look for and make priorities early on in the process.' The other group gathered lots of information, but for them 'gathering data was sometimes just a substitute activity for actually doing any design work' [10].

A similar finding was reported by Atman et al. [11], who found from their protocol analysis studies of engineering students that, for novices (freshmen with no design experience), '. . those subjects who spent a large proportion of their time defining the problem did not produce quality designs.' However, with senior students, Atman et al. did find that attention to 'problem scoping' (i.e., 'adequately setting up the problem before analysis begins', including gathering a larger amount and wider range of problem-related information) did result in better designs. As with the industrial design students, some of the freshmen engineering students, it seemed, simply became stuck in problem-definition and did not progress satisfactorily into further stages of the design process. Atman et al. found that, in comparison to the freshmen, senior students gathered more information, considered more alternative solutions, and transitioned more frequently between types of design activities.

In further, longitudinal studies of freshman vs. senior student behaviours, Adams et al. [12] found that changes in individual students' behaviours over time can be quite complex and variable. As well as those for whom there was definite change, some of the students did not appear to change their behaviours at all and some simply spent more time on design projects but without any qualitative behavioural changes. It also appeared that students exhibited different behavioural changes for different types of design projects.

Differences between the behaviour of novice and experienced designers in engineering were studied by Ahmed et al. [13]. They found clear differences between the behaviours of new (graduate) entrants to the engineering design profession and much more experienced colleagues. The novices 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 considered whether it seemed worthwhile to move further into the implementation stage of a design decision. In contrast to the novices’ trial-and-error approach, the experienced designers employed integrated design strategies.

Protocol studies of two novice and two expert designers in the field of weaving design were made by Seitamaa-Hakkarainen and Hakkarainen [14]. They found that the experts integrated the visual and technical elements of weaving, and generally considered them in a parallel way during the design process. Iteration between the ‘composition space’ and the ‘construction space’ was a significant aspect of the experts’ design process; they ‘continuously moved from one design space to another to carry out very detailed processes of search for design solutions.’ In contrast, the novices organised their process around the composition space and only occasionally jumped to the construction space to explore how visual ideas could be realised in weaving.

Kavakli and Gero [15] compared the cognitive performances of a novice and an expert architect, using data from protocol studies. Over a similar time period, there were significant differences in output between the two. Analysis of the expert’s protocol showed 2916 actions, divided into 348 segments of simultaneous cognitive actions, whilst the novice’s showed 1027 actions, with 122 segmements of simultaneous cognitive actions. Thus, the speed of cognitive processes was much higher for the expert, and the expert’s rate of cognitive activity continuously rose throughout the experiment, whilst the novice’s cognitive activity started at a peak and declined continuously. Kavakli and Gero found a structured organisation and systematic expansion in the expert’s cognitive activity, as opposed to an exhaustive search strategy in the novice’s: ‘The expert seems to have control of his cognitive activity and governs his performance in a more efficient way than the novice, because his cognitive actions are well organised and clearly structured.’

3 Expert behaviour in design

Clearly, part of the development of expertise lies in the accumulation of experience. Something that distinguishes experts from novices is that the experts have been exposed to a large number of examples of the problems and solutions that occur in their domain. But a key competency of an expert is the ability mentally to stand back from the specifics of the accumulated examples, and form more abstract conceptualisations pertinent to their domain of expertise. Experts are believed to be able to store and access information in larger cognitive ‘chunks’ than novices can, and to recognise underlying principles, rather than focussing on the surface features of problems.

One problem-solving strategy used by expert designers seems to be different from that employed by other kinds of problem solvers, who usually attempt to define or understand the problem fully before making solution attempts. 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 [16], from protocol studies of experienced engineering designers, found that this solution-focused approach (identified by Lawson [17]) 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.'

This kind of 'problem setting' is a characteristic of reflective practice identified by Schön [18]: 'Problem setting is the process in which, interactively, we *name* the things to which we will attend and *frame* the context in which we will attend to them.' This seems to characterise well what has been observed of the problem formulation aspects of expert designer 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 [19] 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.'

Schön [19] also pointed out that 'the work of framing is seldom done in one burst at the beginning of a design process.' This was confirmed in Goel and Pirolli's [20] 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.

The occurence of problem framing activities has been noted often in studies of architects. Lloyd and Scott [21], from studies of (mostly senior-student) architects, reported that 'In each protocol there comes a time when the designer makes a statement that summarises how he or she *sees* the problem or, to be more specific, the structure of the situation that the problem presents.' They referred to this 'way of seeing the design situation' as the designer's 'problem paradigm'. As with their studies of engineers, Lloyd and Scott found that the architects who had specific prior experience of the problem type had different approaches from their less-experienced colleagues: the experienced architects' approaches were characterised by strong problem paradigms, or 'guiding themes'. This approach was also identified in expert architects by Darke [22], who referred to their use of guiding principles or 'primary generators'.

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 [23] observed that: ‘A dominant influence is exerted by initial design ideas on subsequent problem-solving directions . . . Even when severe problems are encountered, a considerable effort is made to make the initial idea work, rather than to stand back and adopt a fresh point of departure.’

The same phenomenon was observed by Ullman et al.[24], in protocol studies of experienced mechanical engineering designers. They found that ‘designers typically pursue only a single design proposal’, and that ‘there were many cases where major problems had been identified in a proposal and yet the designer preferred to apply patches rather than to reject the proposal outright and develop a better one.’ A similar observation was also made by Ball et al. [25], from their studies of senior students conducting ‘real-world’, final-year design projects in electronic engineering: ‘When the designers were seen to generate a solution which soon proved less than satisfactory, they actually seemed loath to discard the solution and spend time and effort in the search for a better alternative. Indeed the subjects appeared to adhere religiously to their unsatisfactory solutions and tended to develop them laboriously by the production of various slightly improved versions until something workable was attained.’

Ball et al. regarded this behaviour as indicating a ‘fixation’ on initial concepts, and a reliance on a simple ‘satisficing’ design strategy in contrast to any more ‘well-motivated’ process of optimisation. They found it difficult to account for this apparently unprincipled design behaviour. Nevertheless, adherence to initial concepts and a satisficing strategy seem to be normal expert design behaviour. Guindon [26], in a study of experienced software designers, found that ‘designers adopted a kernel solution very early in the session and did not elaborate any alternative solutions in depth. If designers retrieved alternative solutions for a subproblem, they quickly rejected all but one alternative by a trade-off analysis using a preferred evaluation criterion.’

Designers tend to use solution conjectures as the means of developing their understanding of the problem. Since ‘the problem’ cannot be fully understood in isolation from consideration of ‘the solution’, it is natural that solution conjectures should be used as a means of helping to explore and understand the problem formulation. As Kolodner and Wills [27] observed, from a study of senior student engineering designers: ‘Proposed solutions often directly remind designers of issues to consider. The problem and solution co-evolve.’

This interpretation of design as a co-evolution of solution *and* problem spaces has also been proposed by others, and has been found by Dorst and Cross [28] 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.'

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

Fricke [29], from protocol studies of engineering designers, found that both generating few alternative concepts and generating a large number of alternatives were equally weak strategies, leading to poor design solutions. Where there was 'unreasonable restriction' of the search space (when only one or a very few alternative concepts were generated), designers became 'fixated' on concrete solutions too early. In the case of 'excessive expansion' of the search space (generating large numbers of alternative solution concepts), designers were then forced to spend time on organising and managing the set of variants, rather than on careful evaluation and modification of the alternatives. Fricke identified successful designers to be those operating a 'balanced search' for solution alternatives.

There have also been some reports from studies that have emphasised 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. For example, Visser [30] made a longitudinal study of an experienced mechanical engineer, preparing a design specification. The engineer claimed to be following a structured approach, but Visser found frequent deviations from this plan. 'The engineer had a hierarchically structured plan for his activity, but he used it in an opportunistic way. He used it only as long as it was profitable from the point of view of cognitive cost. If more economical cognitive actions arose, he abandoned it.' Thus Visser regarded reducing 'cognitive cost' – i.e. the cognitive load of maintaining a principled, structured approach – as a major reason for abandoning planned actions and instead delving into, for example, confirming a partial solution at a relatively early stage of the process.

From protocol studies of three experienced software system designers, Guindon [31] also emphasised the 'opportunistic' nature of design activities. Guindon stressed that 'designers frequently deviate from a top-down approach. These results cannot be accounted for by a model of the design process where problem specification and understanding precedes solution development and where the design solution is elaborated at successively greater levels of detail in a top-down manner.' Guindon observed the interleaving of problem specification with solution development, 'drifting' through partial solution development, and jumps into exploring suddenly-recognised partial solutions, which were categorised as major causes of 'opportunistic solution development'. Guindon also referred to 'cognitive cost' as one possible explanation for such behaviour: ‘Designers find it advantageous to follow a train of thought temporarily, thus arriving at partial solutions at little cognitive cost.’

Ball and Ormerod [32] criticised a too-eager willingness to emphasise ‘opportunism’ in design activity. In 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.’ 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 had suggested it might be inevitable in design: ‘These deviations are not special cases due to bad design habits or performance breakdowns but are, rather, a natural consequence of the ill-structuredness of problems in the early stages of design.’

An 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 [33], in their protocol study of an experienced engineering designer, first identified the occurrence of ‘novel design decisions’ (NDDs). These, in contrast to routine design decisions, are decisions that are critical to the development of the design concept. Akin and Lin also segmented the designer’s activities into three modes: drawing, examining and thinking. Then, allowing for some implicit overlap or carry-over of the designer’s attention from one segment to another, they represented the designer’s activities in terms of single-, dual- or triple-mode periods. They found a significant correlation between the triple-mode periods and the occurrence of the NDDs: ‘Six out of a total of eight times a novel design decision was made, we found the subject alternating between these three activity modes (examining-drawing-thinking) in rapid succession.’ Akin and Lin are cautious about drawing any inference of causality, concluding only that ‘Our data suggest that designers explore their domain of ideas in a variety of activity modes . . . when they go beyond routine decisions and achieve design breakthroughs.’

Several of these features of expert designer behaviour were confirmed and clarified by Suwa, Gero and Purcell [34] 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: ‘Not only did unexpected discoveries become the driving force for the invention of issues or requirements, but also the occurrence of invention, in turn, tended to cause new unexpected discoveries.’ This helps to explain the opportunistic nature of design activity, as the designer pursues issues and requirements in an evolving solution concept. Suwa, Gero and Purcell suggest that their findings provide empirical evidence both for the co-evolution of problem space and solution space and for designing as a ‘situated’ act – that is, that designers invent design issues or requirements in a way situated in the environment in which they design. Their analysis also confirms the importance of rapid alternation between different modes of activity: ‘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.’

4. Outstanding designers

The reality of design practice seems to be that some individuals have outstanding design abilities. Highly creative or talented individuals become successful and highly-regarded designers, with international reputations both within and beyond their professional peer groups. However, many studies of designer behaviour have been based on novices (usually students) or, at best, designers of relatively modest talents. This is because it is easier to obtain such people as subjects for study. But if studies of designer behaviour are limited to studies of rather inexpert designers, then our understanding of design abilty will also be limited. Studying outstanding or exceptional designers may give us different, and more relevant, insights and understanding of design expertise.

Lawson [35] made a series of interview and observational studies of outstanding architects. He found many similarities in their ways of working, and also some differences. For example, some of the architects prefer to generate a range of alternative solution concepts, whilst others will focus on a narrow range or just one concept. Something they all seem to have is an ability to work along ‘parallel lines of thought’ – that is, to maintain an open-ness, even an ambiguity, about features and aspects of the design at different levels of detail, and to consider these levels simultaneously, as the designing proceeds. Lawson suggests that ‘a degree of bravery is required to allow these lines of thought to remain parallel rather longer than might seem reasonable to the inexperienced designer.’ He also concludes that ‘one simple message’ that recurred from his studies was ‘the extremely demanding standards set by the designers themselves’. Outstanding expertise is fuelled by personal commitment.

Many findings in Lawson’s studies of outstanding architects resonate with those from studies of outstanding designers in the fields of engineering and product design by Cross [36]. Cross reported protocol and interview studies with three outstanding designers, and drew conclusions on the common aspects of their design strategies. Firstly, all three designers either explicitly or implicitly relied upon ‘first principles’ in both the origination of their concepts and in the detailed development of those concepts. Secondly, all three designers explored the problem space from a particular perspective in order to frame the problem in a way that stimulated and pre-structured the emergence of design concepts. In some cases, this perspective was a personal one that the designers seem to bring to most of their designing. Finally, it appeared from these three examples that creative design solutions arise especially when there is a conflict to be resolved between the designer’s own high-level problem goals (their personal commitment) and the criteria for an acceptable solution established by client or other requirements.

From the analysis of the case studies, there appeared to be similar aspects to the creative strategies adopted by all three outstanding designers. However, although there are similarities in creative strategies across domains, this does not necessarily mean that experts can successfully switch practice between domains. Ericsson and Lehmann [37] found that the superior performance of experts is usually domain-specific, and does not transfer across domains. Extensive training within a domain still seems to be crucial to professional expertise. More studies of expert and exceptional designers might lead to a more informed consensus about how design skills are exercised by experts, and on the nature of expertise in design.

5. Conclusions

Expert designers appear to be ‘ill-behaved’ problem solvers, especially in terms of the time and attention they spend on defining the problem. However, this seems to be appropriate behaviour, since some studies have suggested that over-concentration on problem definition does not 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 and prioritising criteria.

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.

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

Generating a wide range of alternative solution concepts is an aspect of design behaviour which is recommended by theorists and educationists but appears not to be normal practice for expert designers. Most expert designers become readily attached to single, early solution concepts and are reluctant to abandon them in the face of difficulties in developing these concepts into satisfactory solutions. This might appear to be a weak feature of design behaviour, which may be susceptible to change through education. However, trying to change the ‘unprincipled’ and ‘ill-behaved’ nature of conventional design activity may be working against aspects that are actually effective and productive features of design expertise. 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.

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

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

In this review paper I have concentrated mainly on protocol and similar formalised methods of study, and I have therefore omitted a range of other kinds of studies that also have relevant and important contributions to make to the understanding of design expertise. Protocol analysis has some severe limitations as a research method for investigating design activity – for instance, it is extremely weak in capturing non-verbal thought processes, which are so important in design work [38]. Protocol analysis offers a valuable but highly specific research technique, capturing a few aspects of design cognition in detail, but failing to encompass many of the broader realities of designing in context. 'Designing in Context' was the topic of the Design Thinking Research Symposium held in Delft in 2001, with papers featuring in a special issue of *Design Studies* [39]. Other kinds of study, which attempt to capture a broader view, include detailed observation of industrial practice, such as Badke-Schaub and Frankenberger [40] and Busby [41], and ethnographic methods, such as Bucciarelli [42]. Ethnographic approaches to the study of engineering design was also the topic of a special issue of *Design Studies* [43].

The range and number of studies surveyed in this paper suggest that the field of studies of expertise in design is growing, and a variety of similar observations and a number of common issues have been identified. In many cases, the issues remain unresolved, and there is therefore still considerable work to be done to establish a robust and reliable understanding of expertise in design.

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