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Expertise in Engineering Design

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Abstract. *Most studies of designer behavior are limited to studies of novice or average-ability designers. We have studied two outstanding, expert designers, and are able to draw some parallels between their design strategies. We note that they both take a systemic view of the design situation, choose to frame their view of the problem in a challenging way, and draw upon first principles to guide both their overall concept and detailed design. Studying expert designers should enable us to identify the seeds of 'best practice'. This should be useful in design practice and in education, for guiding the development of better-than-average designers.*

Keywords: Expertise; Engineering design; Problem framing

1. Introduction

Most studies of designer behavior have been based on novices (e.g. students) or, at best, designers of relatively modest talents; it is easier to obtain such people as subjects for study. However, if studies of designer behavior are limited to studies of rather inexpert designers, then our understanding of design ability will also be limited. Studying expert designers, instead, may give us different, and more appropriate, insights and understanding of design activity, on which to develop models and methods of design.

The reality of design practice seems to be that some individuals have outstanding design abilities, but there have been only a few studies of outstanding designers, such as Lawson's [1] studies of successful architects. In this paper, we report briefly on our own study of an outstanding designer – the racing car designer, Gordon Murray – and we make some comparisons with the strategies of another expert engineering designer, 'Dan', who was a subject of a protocol analysis study. In this comparison, we develop parallels between Dan's design strategies and those of Gordon Murray. We find several striking similarities, which suggest that general lessons may be constructed about the nature of expertise in engineering design.

We find three aspects of design strategy that appear to be used by both Gordon and Dan: (1) taking a 'systemic' approach to the problem; (2) 'framing' the problem in a distinctive way; and (3) designing from 'first principles'. These are all aspects that have been (separately) recommended by design theorists or methodologists from time to time. For instance, Jones [2] recommends a systemic approach; Schön [3] has identified the importance of 'problem framing'; and authors such as French [4] and Pahl and Beitz [5] have stressed the values of 'first principles' as design guides. However, these rather personal insights and recommendations have not, in general, been based on much apparent evidence or empirical study. Our studies therefore lend some credence to such insights, and perhaps offer more confidence about the goals to be attained in skilled, expert design behavior. From such studies and insights, we might attempt to build some generalizable findings about the nature of expertise in design.

2. An Outstanding Designer

Our first study is of an engineering designer who has established a long record as a highly successful and highly innovative designer in a highly competitive environment; that of Formula One racing car design. Gordon Murray became chief designer for the Brabham racing car team as a young man, in 1973. Brabham cars designed by him were driven by Nelson Picquet to win World Championships in 1981 and 1983. In 1987, Gordon Murray moved to the McLaren Formula One team as technical director, and again his car designs, driven by Alain Prost and Ayrton Senna, won World Championships in 1989 and 1990. In some 20 years as a Formula One designer, he established an outstanding reputation not only as a

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successful designer (over 50 race wins), but also as a consistently radical innovator.

Gordon Murray then became technical director of an off-shoot company from the racing team, McLaren Cars Limited, and became responsible for the design and development of a completely new, road-going 'super car' – the McLaren F1, which attracted immense attention for its radical design features. Although not originally designed for racing (but designed to racing principles), GTR versions of the new McLaren F1 were entered in the 1995 Le Mans 24-hour race and came first, third, fourth and fifth. They have continued to have considerable success in GT racing.

Gordon Murray is an example of an 'outstanding' designer – a designer who has achieved extraordinary success throughout a long career. In his case, the measures of his success as a designer are absolute – his achievements have been in a competition field where absolute performance standards are the criteria. We have been able to gain some insight into Gordon Murray's design strategies and approaches through discussion and informal interviews with him. We have reported this in more depth elsewhere [6]. Here, we will refer to the three aspects of his design strategy that we have suggested may offer keys to his design successes: systemic design, framing the problem, and designing from first principles.

2.1. Systemic Design

An example of Gordon's radical design approach was the Brabham team's introduction of planned pit stops during a race, in the 1982 season. This was not a radical innovation in car design *per se*, but reflected a total systems approach to the overall goal of winning each race. At that time, it was not normal to have pit stops as regular, planned parts of the race routine. Pit stops were for emergencies such as changing a punctured or badly-worn tyre.

In 1982, as part of his thinking about how to make a car lighter in weight, Gordon conceived of running the car with only half the normal, full-race fuel load, and including a pit stop for re-fuelling. Nowadays, Formula One pit stops have been refined down to an incredibly quick norm of about seven seconds actual stopped time, in which time all four wheels are changed and some 100 litres of fuel taken on. The total racing time lost is about 20 seconds. In 1982, a quick pit stop for tyre changes took about 15 seconds of actual stopped time. Gordon calculated that to preserve the advantage gained from from the lighter car he had to get the stopped time in the pit down to about ten seconds, and to reduce the lost racing time to under 26 seconds.

To achieve this, an extraordinary development programme had to be undertaken, under the pressures of Formula One racing. For example, within three weeks, Gordon and his team had thought of, designed, made and tested a high-pressure re-fuelling system. To improve pit-stop procedures, he hired a film crew to film the team practising pit stops, and then played back the film, stopping it to identify difficulties and errors, and devising ways to improve the procedures. Such improvements included details such as re-designing the wheel-nut gun to improve its engagement with the nut. The new systems, the improvements, and the training of the pit team got the actual stopped-time down to under the target of ten seconds.

However, one 'big killer' remained, Gordon told us: 'When you put new tyres on they were cold, and it always took two laps to get back up to speed, and the time you lost in those two laps killed the whole thing. So then I thought, well I know the tyres start working at 70 degrees temperature ... so we designed an oven, a wooden oven with a gas-fired heater, and we heated the tyres up – and ten seconds before the car was coming in we opened the oven door, whipped the tyres out, put them on, and the guy was instantly quick. Now every Grand Prix team has tyre heating; that's where it started'.

The example of the introduction of planned pit stops illustrates how Gordon adopted a total systems approach to the design task: the goal was winning a race over some 60 or 70 laps, which could include bringing the car into the pits during the race if that could be used to convey sufficient advantage. The systemic view of the design task led to a long series of detailed developments and innovations.

2.2. Framing the Problem

At the start of the 1981 season, the Formula One governing body, FISA, had introduced new regulations intended to reduce the 'ground effect' on racing cars. This effect had been pioneered on Lotus cars some three seasons earlier; smooth underbodies, flexible side-skirts and careful aerodynamic design provided a ground-effect downforce which increased the car's grip on the track surface. This meant much higher cornering speeds were possible, and by the 1980 season, people were worried about safety and the *g*-force effects that were being imposed on the drivers. In 1981, FISA set a minimum ground clearance of 6 cm, which they hoped would thereby eliminate or substantially reduce 'ground effect'. But for Gordon this change in the regulations was simply another stimulus to innovation.

Gordon's thinking on this – which he says came as a sudden illumination after a long period of worrying at the problem – was that the authorities had to accept that at some points during a race, any car's ground clearance is going to be less than the 6 cm minimum, simply because of the effects of braking, or roll on corners, etc. Knowing that any driver-operated, mechanical device to alter the ground clearance was illegal, he focused on the physical forces that act on a car in motion. The braking and cornering forces he felt unable to work with because of their asymmetrical effects on the car, but the downforce from air pressure on a moving car will, if the car is correctly designed aerodynamically, push the car down equally over its whole length and width. The design challenge, therefore, was to let the natural downforce push the car down at speed, and then somehow to keep it down when it slowed for corners, but allow the car to return to 6cm ground clearance at standstill. Gordon had therefore 'framed' the problem as one of sustaining a temporary lowering of the car, from natural forces, only whilst it was at racing speeds.

The ingenious solution that he developed incorporated hydro-pneumatic suspension struts at each wheel, connected to hydraulic fluid reservoirs. As the car went faster, the aerodynamic downforce pushed the body lower on its suspension and the hydraulic fluid in each suspension strut was pushed out into the reservoirs. The trick then was to find a way of letting the fluid return to the suspension struts only very slowly when the car slowed down. At cornering speeds, the suspension would stay low, but on slowing down and stopping at the end of the race, the fluid would return from the reservoirs to the suspension struts, giving the required 6 cm ground clearance. Gordon and his team developed such a system, using devices such as organic micro-filters borrowed from medical technology.

The hydro-pneumatic suspension system is an example of radical innovation arising through framing the problem in a new and productive way: how to lower the car and keep it there by natural forces. Like the systemic design approach, it also requires the motivation to follow through a basic idea into finely-detailed implementation.

2.3. Designing from First Principles

Gordon Murray insists on keeping experience 'at the back of your mind, not the front', and to work from first principles when designing. For instance, in designing a component such as a suspension wishbone, he says 'it's all too easy, and the longer you're in design the easier it is, to say I know all about wishbones, this is how it's going to look because that's what wishbones look like'. But to make a step forward in design, to look for ways of making it much better and much lighter, then you have to go right back to first principles such as load-path analysis. It reflects an attitude of constantly assuming you are engaged in innovative design, rather than routine design.

As one example of his approach to designing from first principles, Gordon referred to a small, and perhaps seemingly insignificant part of the McLaren F1 – the steering column. 'Conventionally, it would have been, right, steering columns are typically three-quarter-inch solid steel bars'. He explained how this conventional solution arises because the column not only has to carry torsional forces from the resistance to the turning wheels, but also bending loads from the driver leaning on it whilst getting in and out of the car. It also has conventional points of support, is mounted in rubber bushes to reduce noise, and it ends up being encased in a plastic housing for reasons of appearance and convenience. But it does not provide the sort of direct steering feel that a racing car has.

So Gordon decided to apply racing design principles to the steering column, starting by separating the needs to carry both torque and bending loads. However you design the steering column itself, you still need a cover to house electrical cables and to mount switches. So he reasoned that 'if you've got to have that anyway, why not use the insect principle where the skeleton's on the outside, and make that the structure that takes all the bending forces?' This thinking led to the design of an 'exo-skeleton' structural cover, with the steering column itself as an aluminium tube of just 1mm wall thickness; 'it's only taking torque and it weighs nothing'. With other detail design changes, the steering system is now lighter but stronger than a conventional solution, and also has the right racing feel.

The steering column design process therefore stemmed from considering first principles – separating the torque and bending loads – and from an imaginative breakthrough – using the housing cover for structural purposes as well as appearance.

3. An Expert Designer

We propose to compare the design strategies of the outstanding designer, Gordon Murray, with those of a designer who, though not such an internationally famous, outstanding designer, is nontheless a successful, experienced designer. 'Dan' was videorecorded whilst he 'thought aloud' during a 2-hour experimental session in which he was asked to design 'a carrying/fastening device that would enable you to fasten and carry a backpack on a mountain bicycle'. Our observations of Dan's design strategy are therefore based on the artificial situation of a controlled, protocol analysis experiment. Full details of the experiment (and other analyses of Dan's design activity, from several different points of view) are reported in the proceedings of the *Delft Design Protocols Workshop* [7].

Dan is an engineering designer with more than 20 years experience of designing both mechanical and electro-mechanical machines, and robotic systems and devices. He was one of the earliest designers of modern robotic devices, and he has won several design awards from ASME. He is an accomplished, expert designer. The design task set in the experiment was, however, a novel task for Dan. In the following analysis of Dan's strategy, quotations are taken from the transcript of his 'think aloud' comments, preceded by the timestamp for the quotation. The substantive experimental session began at timestamp 00.15minutes.

3.1. Rapidly Gaining Experience

A distinctive feature of the strategy followed by Dan was the time and effort he put into gaining an overview of the potential solution space; his aim appeared to be to determine the most feasible section of that solution space in which to begin work. This was a deliberate strategy, which he explained in 'think-aloud' comments such as:

> (00.21)
> there's no sense in starting from scratch if you can start at square two instead of square one
> (00.27)
> my general philosophy is don't try to reinvent the state of the art if it already exists

The early part of Dan's strategy is concerned with getting 'up to speed' – with informing himself of the nature of similar, rival products to that which he is designing, with identifying a section of the solution space where he is likely to generate an acceptable solution, and therefore with avoiding starting to work in areas that are likely to be unfruitful.

This strategy of 'starting from square two', i.e. building on the experience of others, might appear to be borrowing from old ideas rather than initiating a new design. However, what Dan was doing seemed to be more like immersing himself as rapidly as possible in the domain of expertise relevant to the (for him) novel design task that he had been set. He was prepared to devote rather a lot of time to this – some 30 minutes were spent on gathering this kind of information, and a further 15 minutes were spent confirming and coming to the conclusion that the best location for the carrying device would be over the rear wheel of the bicycle. So at least 45 minutes of the 2-hour design session were spent getting up to speed, so that he would hit the ground running when he did start actual design work.

Most of this early information was gathered from a potential rival company already making bicycle luggage carriers. Dan gathered information from the company's catalog and from a telephone call to the company. The catalog information was scanned for general principles – the weight and cost limits of the rival products, and their mounting positions on the bicycle – as indicated in these comments:

> (00.28)
> aha, so he has a series of front mounting racks and rear racks, and he sells these things at between . . thirty dollars and fifty dollars
> (00.29)
> his frames weigh between . . 480 grams and . . 650 grams
> (00.30)
> he has more rear racks than front racks . . they are all frames that mount over the wheel

The telephone call was also used to gather general principles and expert advice about the preferred location on the bicycle for carrying a backpack. Dan commented as follows about what he learned from the telephone call:

> (00.44)
> I learned a few things; I learned about the fact that people originally thought that it was bad to have it on the front but if you keep the backpack pretty low on the front it's OK, high up is bad; on the rear the issues are related to heel clearance and thigh clearance, and he feels that keeping it as low as possible is good

So Dan appeared to be searching not for prior design examples *per se*, but for the criteria (such as weight and cost) that his design will have to match, and for experience that would guide the major design decision of whereabouts on the bicycle to locate the carrying device. In this way, Dan rapidly developed valuable, surrogate expertise in this novel design domain.

3.2. Systemic Design

As an expert designer, Dan also displayed aspects of his design approach that can be compared with those of an outstanding designer such as Gordon Murray. Firstly, Dan developed a systemic view of the problem he had been set. Very early in the session, reading the design brief, he made a comment that suggested he saw something special about the design problem:

> (00.19)
> it is to attach to a bicycle, a mountain bike and to me that makes it different

Dan was also able to draw on personal experience that helped him to formulate some of the implicit requirements for a good design solution:

> (00.26)
> having used a backpack on a bike in the past and having ridden over many mountains, unfortunately not on a mountain bike but I can imagine that the situation is similar, I learned very early on that you want to keep it as low as possible

He also drew upon personal experience to confirm that the preferred location for the backpack would be on the rear wheel rather than the front wheel:

> (00.51)
> my first thought is hey the place to put it is back here; there's another advantage by the way of having it in the back I can see immediately, and that is it's off the side in the front, and you're on a mountain bike trail and you hit something you're out of control in the front wheel
> (00.52)
> downhill work on mountain bikes, I know you want to keep your weight back rather than forwards

Dan's personal experience of biking with a backpack led him to identify an issue that only someone who has had such experience might be aware of:

> (00.55)
> when I biked around Hawaii as a kid that's how I mounted my backpack . . and I have to admit if there's any weight up here this thing does a bit of wobbling, and I remember that as an issue

So the systemic view that Dan formed of the problem was that of the total task that encompasses the dynamic system of the rider plus bicycle plus backpack, and the issues of control of the bicycle that arise in the situation of riding over rough terrain with a heavy backpack attached to the bicycle. This is a different situation to that of everyday, smooth-surface, level-grade riding, and it accentuates the needs to position the backpack low and to the rear. The view that Dan had of the design task was significantly different from a view that might be formed from considering the bicycle and backpack in a static situation, or without considering the effects on the rider's ability to control the bicycle with a mounted backpack. Dan's understanding of the dynamic situation therefore enabled him to formulate a systemic view of the design task.

3.3. Framing the Problem

The second aspect of Dan's approach that can be compared with that of Gordon is how he 'framed' the problem. From a systemic overview of the total dynamic situation of rider + bicycle + backpack, Dan identified stability as a key issue. Quite early in the session, commenting on the prototype design that had been developed earlier by other designers, he surmised about the user-evaluation report on this prototype that:

> (00.22)
> it probably . . says the backpack's too high or something like that, and that bicycle stability's an issue

Dan therefore seemed to frame the problem as 'how to maintain stability', given that a heavy packpack had to be carried over the rear wheel of the bicycle, and given his experience of the 'wobbling' that can occur in the riding situation. This problem-framing and his prior experience led him to conclude that he must design a rigid carrying device:

> (00.59)
> the biggest thing that I remember in backpack mounting is that it's got to be rigid, very rigid

He then developed this viewpoint into the requirement that the structural members of any carrying device must be stiff:

> (01.06)
> making the carrier stiff enough for holding the backpack, that seems to be a big issue

So, at about halfway through the session, Dan had arrived at a framing of the problem which directed him to design a stiff, rigid carrier, mounted as low as possible over the rear wheel. Soon after, a secondary framing viewpoint emerged, which seemed to arise from considering the client's needs as well as those of the user (which had dominated Dan's thinking so far). The client for the design task was a manufacturer who wanted to sell the carrying device in conjunction with their already-existing backpack. The device therefore needed to have unique selling points that differentiated it from other, similar products. During the development of his design concept, Dan kept in mind that he needed the product to have a 'proprietary feature', as emerged in some of his comments, discussed below.

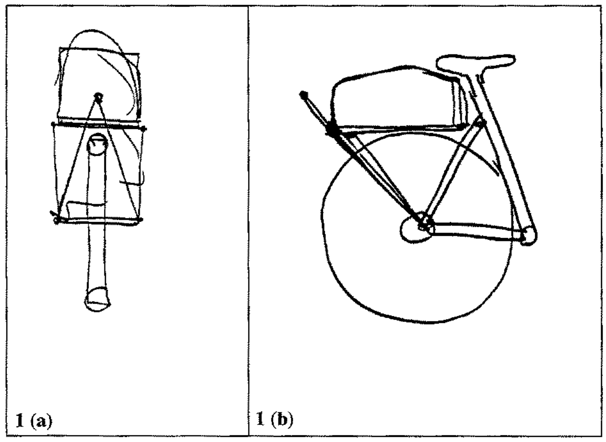

Fig. 1. Dan's sketches of rear and side views of the bicycle and carrying device, in which he first sketched the 'obvious' arrangement, which leads to a parallelogram structure, and then overdrew a suggestion for extended rods running up to a point and thereby forming a triangular structure.

3.4. Designing from First Principles

The third aspect of Gordon Murray's approach as an outstanding designer that we identified was his concern with designing 'from first principles'. Dan also showed this aspect, as he developed his concept design for the carrying device. A 'first principle' that Dan identified and followed was that a triangulated structure is inherently rigid. This led him to avoid designing a rectangular, parallelogram form of structure, which was the form that rather naturally seemed to arise from considering the basic shape of the carrier and the location of its supporting structure on the bicycle. Whilst drawing Fig. 1(a), Dan commented:

> (01.07)
> one of the problems with a bicycle carrier where the frame is mounted out here and it goes to that, is that you end up with a parallelogram; bad thing, bad thing!

He expanded on this comment, identifying his concern with stability as a key requirement:

> (01.08)
> if I were to make a frame that looked like this, that would be a very poor design because basically what I've got is, I've got a parallelogram which has very little lateral stability

He then introduced the 'first principle' of triangularity, whilst drawing the triangular form onto Fig. 1(a):

> (01.09)
> it would be nice if I could , for instance, run these rods up here to some point and therefore create a triangle, this would give me great stiffness – good idea!

The 'first principle' of triangularity subsequently guided Dan's generation of the basic form and the detailed design features of his carrier. As he drew his design in more detail, (Fig. 2), he commented:

> (01.16)
> we're going to have this as a triangular structure here to provide the lateral stability

And as he developed his design in detail (Fig. 2), he constantly referred to structural principles, seeking to avoid 'bad' configurations and to generate 'good' ones, making comments such as:

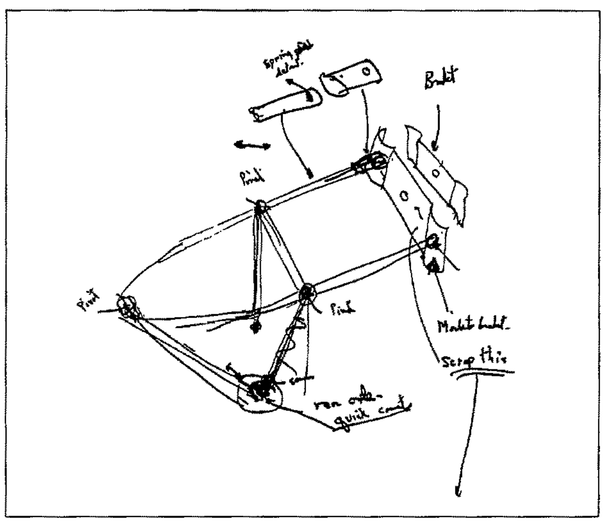

Fig. 2. Dan's detailed development of his design.

(01.42)
my detail here is going to have to be something like this because my forces along this tube are this way . . good, this is good; and then this detail is going to be, er, let's see . . alright that's bad . . that's bad . . that's bad, so I'm going to need something like that

In the meanwhile, as we noted above, Dan also used the client's requirement of a unique selling proposition to help guide and to reinforce his decision to seek a design based on triangular structures:

(01.10)
that is going to be our proprietary feature, a triangular, rigid structure with no bends in it; these rods are then going to be in tension and compression, no bending
(01.41)
I want to make sure that this rod here comes to a point, not stop right there . . that's to a point; that's going to be my feature

In these comments, Dan demonstrated that he regarded the pronounced triangular form at the rear of the product as something to be maintained as a feature that would help give the product an attractive, unique selling point.

3.5. Summary of Dan's Design Approach

Dan's design for the carrying device is an integrated design in which user requirements are addressed through the problem frame of stability, leading to the use of triangularity as the guiding first principle, which also addresses the client's goal of having a proprietary, unique selling feature to the product, as summarised in Fig. 3.

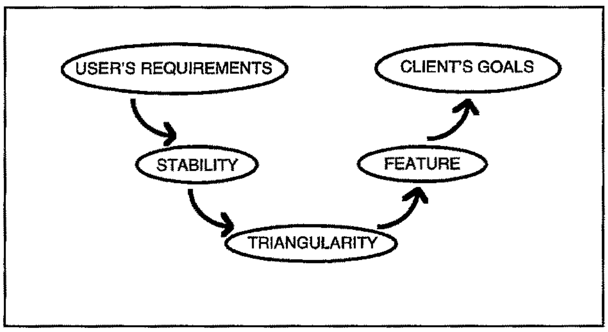

Fig. 3. Dan's approach summarised as hierarchical levels of systemic design, problem framing and designing from first principles.

4. Expertise in Design

It appears that there are similar aspects to the approaches to design taken by both Gordon and Dan. Both take a systemic approach to the overall design task; both frame the design problem in a way that challenges them to innovate; and both use first principles to guide their conceptual and detail designing. It is perhaps surprising that we see commonalities between these two designers, considering the great disparity between the design projects in which they were engaged – between Formula One racing cars and a simple bicycle luggage rack! It is also worth noting that these similarities emerge from two quite different kinds of study – informal interviews with Gordon and a formal protocol analysis of Dan. There would also appear to be some similarities with the results from the extensive retrospective study of the expert racing-bicycle designer, Mike Burrows, by Candy and Edmonds [8]; for instance, they also referred to the relevance of such aspects as 'systems thinking' and the importance of 'problem formulation'.

However, there remain methodological problems of verifying the accuracy or relevance of the analyses that we and others have so far been able to make of the skills of outstanding designers. The difficulties of studying the performance of such people in formal ways may always limit the validity of the analyses, but more studies of expert and outstanding designers might at least lead to an informed consensus about the nature of their skills and how they practise them.

Although our observations fit with the recommendations of some design theorists and methodologists, it seems that practising, expert designers find it unnecessary to resort to the prescriptive methods offered in textbooks such as Pahl and Beitz [5] and Cross [9]. It is perhaps in the nature of expert performance that formalized, step-by-step procedures, which may be necesary in education and training, become subsumed into a more seamless, personalized way of working. However, there remain considerable difficulties about explaining and learning how to 'frame' problems in creative ways, and how to identify the appropriate 'first principles' in any particular case.

Expertise has been studied in other fields (see, for example, Chi et al., [10] and Ericsson and Smith [11]), but what we can learn from these other studies is often limited, because of the particular, distinctive characteristics of design activity. 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.

However, some studies of expertise in fields such as creative writing and computer programming [12,13], where problems are more ill-defined, do suggest some parallels with our observations of expert designers. These studies suggest that some of the 'standard' results from studies of expertise do not match with results from studies of expertise in creative domains. For example, creative experts will define the given task so that it is problematic, i.e. deliberately treat it as ill-defined, which is contrary to the assumption that experts will generally solve a problem in the 'easiest' way, or certainly with more ease than novices. In some ways, therefore, creative experts treat problems as 'harder' problems than novices do. We have seen that both Gordon and Dan are not content to adopt an 'easy' view of the design problem that they are given; both of them choose to take harder, more innovative routes to finding a solution concept. Creative experts are also reported as solving similar tasks from first principles each time, rather than recalling previous solutions. Again, we see similarities with our observations of expertise in design: both Gordon and Dan have an approach in which experience of previous solutions is 'at the back of the mind, not at the front', as Gordon expressed it, and both refer, either directly or indirectly, to 'first principles' as the stimuli for creative design.

It is important to recognize the distinctions between strategies employed by creative experts and those employed by experts working in well-defined problem domains and in routine problem solving. Any general theories of expertise, and any applications in education and practice drawn from more general studies of expertise, need to recognize these distinctions between expertise in creative and in routine problem solving.

5. Conclusions

We have been able to explore the strategies employed by two highly-expert designers, and have found some parallels in their ways of working. To create innovative designs, they adopt a systemic view of the design situation, frame their view of the problem in a challenging way, and then use 'first principles' of engineering to guide the generation of the design concept and its detailed development. Our observations also tend to fit with other findings about the cognitive strategies employed by experts working in creative domains where problems are ill-defined.

It is important that we learn more about expertise in design. Too many studies have been based on novices or, at best, average-ability designers. Studying novice and average designers may well limit our understanding of design, holding back progress in design methodology and leading to weak or even inappropriate models of design activity. Studying expert designers might enable us to identify the seeds of 'best practice', and then to transfer these insights more widely across the professions. This should also be useful in education, for guiding the development of better-than-average designers. If, as we suggest, it seems that some common aspects of expertise are indeed shared by outstanding and expert designers, then we may hope that these successful strategies and approaches might also be coached and developed in less expert and novice designers.

Note

This is a revised version of a paper on 'Expert Designers' delivered at the University of Darmstadt Symposium on Designers, Darmstadt, Germany, December 1997 [14].

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