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Journal Item

How to cite:

Cross, Nigel and Clayburn Cross, Anita (1996). Winning by design: the methods of Gordon Murray, racing car designer. Design Studies, 17(1) pp. 91–107.

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Version: Accepted Manuscript

Link(s) to article on publisher's website:

[http://dx.doi.org/doi:10.1016/0142-694X\(95\)00027-O](http://dx.doi.org/doi:10.1016/0142-694X(95)00027-O)

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**Winning by Design:
the methods of Gordon Murray, racing car designer**

Design Studies, vol. 17, pp. 91-107, 1996.

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This is a case study of the working methods of one particularly successful designer in a highly competitive design domain - Formula One racing car design. Gordon Murray was chief designer for the very successful Brabham and McLaren racing car teams in the 1970s and 1980s. His record of success is characterised by innovative breakthroughs, often arising as sudden illuminations, based on considering the task from first principles and from a systemic viewpoint. His working methods are highly personal, and include intensive use of drawings. Personality factors and team management abilities also appear to be relevant. There are some evident similarities with some other successful, innovative designers.

Several studies have appeared recently of creative and innovative designers^{1, 2, 3}. These studies add to earlier, more general studies of creative individuals in science, art and engineering⁴. The motivations for such studies include improving our understanding of the psychology of creative behaviour, identifying features of creative behaviour that might be possible to develop through educational processes, and developing models of the creative design process.

The particular study reported here is of an engineering designer who has established a long and distinguished record as a highly successful and highly innovative designer in a highly competitive environment - Formula One racing car design. Gordon Murray joined the Brabham racing car team as a designer-draughtsman in 1971, and was appointed chief designer in 1973. Brabham cars designed by him were driven by Nelson Piquet to win the World Championship in 1981 and 1983. In 1986, he moved to the McLaren Formula One team as technical director, and again his car design(s), driven by Alain Prost and Ayrton Senna won the World Championship in 1988 and 1989.

Gordon Murray then became technical director of McLaren Cars Limited, an off-shoot of the racing team, and became responsible for the design and development of a completely new, road-going 'super car' - the McLaren F1, which has attracted immense attention as the 'ultimate' motor car. In 1995, GTR versions of the F1 were produced for competition in sports car races: at the 1995 Le Mans 24-hours race, McLaren F1s came first, third, fourth and fifth.

This paper is based on several informal conversations with Gordon Murray, and a more formal, taped interview specifically for this study. Our purpose in preparing this study is to seek insight into the design processes of someone who has a long history of being a successful, highly-innovative designer.

1 Formula One designing

Formula One racing car design is, of course, significantly different from almost every other kind of design domain. Gordon Murray likens it to war. Engineering and technological development in wartime is the closest analogy to Formula One he can think of, with resources - human, financial and technical - being poured into the design and construction of machines that must have, and maintain, vital performance edges over those of the enemy. Throughout the nine-month Formula One season there is a battle to be fought on a different field every two weeks, with a new campaign starting again every year.

There are also, of course, the 'rules of engagement' for this perpetual 'war': the Formula One technical and sporting regulations, which minutely and precisely specify the physical and operational limits within which the teams must compete. Gordon Murray regards the regulations (the constraints) of racing car design, along with its intense pressure and competition, as fundamental to the necessity to innovate. With every team working within the same constraints, only innovation, coupled with constant refinement and improvement, can provide the competitive edge. In other design fields, as he has discovered, the lack of regulations can be slightly bewildering, allowing the designer to wander at whim in a more loosely-bounded solution space.

Innovative design, Gordon suggests, comes down to people and their environment. 'It comes from the environment and the situation you're in; you're governed by these regulations; you're in this sort of a war situation; and you're desperate to try and think of things all the time - alongside all the normal design [improvement] processes which are more laborious . . . I can't tell you how hyper it is, relative to architecture, bridge design, furniture design . . .'

2 Designing radical innovations

Throughout a racing season there is constant, relentless pressure on the designer to keep making design improvements. But there is a limit to what can be achieved with any car design, before a jump has to be made to basically a new design, an innovation. As Gordon Murray says, 'Given the situation and the pressure at any one time, you do get to the brick wall . . . I mean you're doing all these normal modifications, you know you can't go any quicker, you need to make the step forward.' The constant pressure during the racing season breeds a fervour to succeed that never stops, Gordon says; 'You gotta go quicker, gotta go quicker.' The pressure then to come up with something new becomes intense, and the responsibility is all yours, 'and you get more and more sort of - panicky, almost.'

The situation can only be resolved by a new car design. In many instances, and for most teams, this will be a new version of the previous season's car; perhaps a new chassis, new suspension, or new engine to be accommodated; perhaps a change in regulations to be met. For Gordon Murray it would often mean trying a radical new concept. In the midst of the pressure, the fervour, the panic, he 'used to get breakthroughs, I mean I used to get like suddenly a mental block's lifted.' These breakthroughs would come as a sudden illumination: 'I know it's a cliché, but I did have a lot of good ideas in the bath, I really did.' The illuminations came, again in classical form, after long periods of preoccupation with the problem, and after what Gordon Murray emphasizes as the most important factor in innovative design, of reconsidering the problem situation from first principles; he stresses the need to 'keep looking back at fundamental physical principles.'

Another crucial factor is the motivation to carry-through the bright idea into detailed implementation. Again, intense pressure - even in the brief close-season - ensures that ideas that look certain to be winners will be pushed through to detailed implementation with the same fervour as in the racing season. Other possibly good ideas are discarded on a rapid evaluation of their implications for a car's weight, performance or handling. In racing car design, it is not just a matter of having ideas, but of really implementing ideas that are going to improve performance - of having to 'do it', as Murray says; 'You have the idea, but you have to do it, and that's what cuts the bullshit out.'

2.1 Framing the problem

At the start of the 1981 season, the Formula One governing body, FISA, 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, 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 the g-force effects that were being imposed on the drivers. FISA banned 'sliding' skirts from the start of 1981, but allowed fixed skirts and set a minimum ground clearance of 6cm. For Gordon Murray this sudden change in regulations was a stimulus to innovation.

'The 1981 car, which was a World Championship winning car, came absolutely from the regulation change. You sit there and you read the regulations and think, how we are going to do it? How the hell can we get downforce back? What [the regulations] said was "At all times the car will have a 6cm gap between the bodywork and the ground . . . and there can be no driver-operated device to change that gap." . . . And everybody looked at it, and built cars with 6cm gaps . . . And I looked at it and I thought, if that 6cm gap could be a 1cm gap I could double the downforce on the car; and it's going to go down to a 1cm gap at some point, like [under braking] at the end of the straight. So if I can make a physical thing - something that involves physics again - that drives the car down on its own, and holds the car down on its own without any mechanical aid or button or electrics or anything, it's legal. So in three months we developed a hydro-pneumatic suspension.'

Gordon Murray's thinking on this - and he says it came as a sudden illumination - 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 6cm 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, the 'bits of nature', 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 could, if the car was 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, and then allow the car to return to 6 cm clearance at standstill.

The ingenious solution which Gordon developed incorporated hydro-pneumatic suspension struts at each wheel, connected to hydraulic fluid reservoirs. As the car went faster, the natural 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 corners, 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 6cm ground clearance.

'So I rushed around and looked at the technology of micro-filters, mainly in the medical industry . . . they were using these organic micro-filters which let the fluid through themselves but very, very, very, slowly. And we built the world's tiniest throttle valve with one of these filters in it, and a tiny little pin - we were using drills that you couldn't even see! We went and quickly developed what size hole we needed, so that it took a lap to push the fluid through these little holes - all naturally with the downforce - pushed the fluid into the reservoirs and the car was stuck on the ground, running with its skirts virtually touching the ground. And because it took so long for the fluid to get back through the same valves and filters, it held the car down there, and after the race you have the slowing down lap . . . and the car just slowly came back up. Nothing to do with the driver at all, just physical forces! And we went to the first race in Argentina and just blew everybody into the weeds, just totally; and everybody went bananas!'

Other teams protested that the Brabham cars must have been fitted with a driver-operated device. It was obvious that the cars were lower during racing than they were in the pits, but of course the scrutineers could find no illegal device. Under pressure from the other teams, the authorities pointed out that the Brabham cars were clearly lower than 6cm when out on the circuit, which contravened the regulations, but Gordon countered that, at various points so was every other car. To stop the protests, he suggested to the authorities that every car should have its underbody painted, and at the end of the race every car which showed that at some point the underbody had rubbed the ground should be disqualified; and of course the other teams would not accept this.

For some time the other teams experimented haphazardly with varieties of hydro-pneumatic suspension systems, to Gordon's amusement, but, very frustratingly for him, just a few races later in the season, FISA reversed its stance and allowed driver-operated switches for controlling suspension height.

The hydro-pneumatic suspension system was an example of an innovation initiated by a change in regulations which forced Gordon Murray's thinking onto how to retain the ground-effect advantage. It is an example of radical innovation, through thinking from 'first principles' about the effects of natural forces, and having the motivation to follow through a basic idea into finely-

detailed implementation.

2.2 Systemic design

As another example of radical innovation, Gordon Murray refers to the Brabham team's introduction of planned pit stops during a race, in the 1982 season. This was not so much a radical innovation in the car design per se, but reflects more 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. For Gordon Murray, the innovation of introducing planned pit stops was part of an overall strategy arising from taking his thinking back to a basic issue - how to make the car lighter. As part of that strategy, he pursued the idea of running the car with only half the normal, full-race fuel load, and including a pit stop for re-fuelling. But that was only the starting-point for a thorough investigation of the implications of such an idea, and of working-through the detailed implementation.

Nowadays, Formula One pit stops have been refined down to an incredibly quick norm of about six or seven seconds actual stopped time, in which time all four wheels are changed and up to 130 litres of fuel taken on. The total racing time lost is perhaps some 20 seconds. In 1982, Gordon Murray calculated that if the total racing time lost by a pit stop was less than twenty-six seconds, there could be sufficient advantage gained elsewhere to make it worthwhile.

There were many factors that came into calculating the advantage. Obviously, the lighter the car is, the faster it is - not only in straight-line top speed but also in accelerating and decelerating. Half-size fuel tanks also have an advantage over full-size ones in that the weight distribution is lower, the roll-couple on corners is lower, and is more constant throughout the race. Tyre wear, and the complicated choices of harder or softer tyre compound, also becomes a critical factor, because a lighter car can run on softer compounds which improve cornering speeds. Even the psychology of racing came into it, because a car with obvious advantages in the early part of a race could lead other competing drivers into pushing their cars harder, causing them more tyre wear, or into taking more risks. For all of the objective, measurable factors, fine calculations were made, leading to the conclusion that a pit stop had to lose less than twenty-six seconds racing time to be worthwhile.

At that time, a quick pit stop for tyre changes took about 15 seconds of actual stopped time. Gordon Murray calculated that he had to get this down to about ten seconds and to reduce as much as possible the slowing-down and warming-up times. An extraordinary development programme had to be undertaken in an incredibly short time.

‘From having the first idea to having a pit-stop car running and doing a test was three or four weeks - and that's all the time that you have. So you would take each individual thing and tackle it. Say, OK, how can we get thirty-five gallons into the car in ten seconds? The only way you're ever going to do it is using pressure, and then you have a crash programme to develop a system.... That's what is great about race car design, because even though you've had the big idea - the “light bulb” thing, which is fun - the real fun is actually taking these individual things, that nobody's ever done before, and in no time at all try and think of a way of designing them. And not only think of a way of doing them, but drawing the bits, having them made and testing them.’

Within three weeks, they had thought of, designed, made and tested a pressure-fed re-fuelling system which eventually delivered 100 litres into the car within three seconds. To improve pit-stop procedures, Gordon 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 would include 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. One 'big killer' remained: '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 seventy degrees centigrade ... 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 the 'pit-stop car' illustrates how a radical innovation was driven by the competitive urge to find a significant advantage within the constraints of the regulations; how the basic, 'light bulb' idea had to be evaluated on precise calculations; how a total systems approach was adopted; and how implementation had to be carried through to fine levels of detail. The new pit-stop approach was first tried by the Brabham team during the 1982 season, on the Brabham BT50 car. For the 1983 season, Gordon Murray designed his new 'half-tank' car, the BT51, only to be faced with an unexpected change of regulations affecting the car's 'skirts' (which helped produce the 'ground effect'), so that another crash programme had to be initiated to design the BT52. With this car, and with the help of pit stops, Nelson Piquet won the Formula One World Championship again in 1983.

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, '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 if you want to make a step forward, if you're looking for ways of making it much better and much lighter, than you have to go right back to load path analysis. It is like designing things for the first time, rather than the n th time.

As one example of his approach to designing from first principles, Gordon refers 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.' 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 driver needs, and the McLaren F1 is supposed to be a driver's car.

So Gordon decided to apply racing design principles, 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 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 the steering column itself as an aluminium tube of just 1mm wall thickness; 'it's only taking torque and it weighs nothing.' The steering rack is cast integrally with the bulkhead, so that there can be no relative movement. The support bush is right behind the steering wheel rather than down at the dashboard, and the system is now lighter but stronger than a conventional solution, and also has the right racing feel. (Figure 1.) The re-design process 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.

2.4 Learning from failures

Not all of Gordon Murray's racing car design innovations have been successes; he has had a share of failures, too. One of his largest failures was the 'surface cooling' car, the Brabham BT46 of 1978. This radical concept was meant to be several 'steps forward' at once; reduction in weight, improvement in driver safety, and what was meant to be a long-term technical advantage over the opposition. His imaginative idea of 'surface cooling' was to do away with normal radiators for cooling the engine, and instead to pass the water and oil through surface heat exchangers built integrally into the monocoque structure: the 'skin' of the car was both structure and radiator. Other refinements included improved monocoque form, elaborate electronic engine and lap-time instrumentation systems for the driver, carbon fibre brake discs, and an on-board air jacking system for quicker tyre changes.

There were innumerable detailed implementation problems with the surface cooling features, and trials soon showed that surface cooling was not going to work. Gordon Murray says, 'I knew why it didn't work, but before the first race we just literally ran out of time.' So a revamped version of the BT45 was quickly rushed out. It had been a very expensive failure.

Another innovative design that failed was the last one Gordon Murray designed for Brabham, for the 1986 season. This car was designed to be as low as possible, with the driver virtually lying flat. It involved also putting the engine into a lying-over position from the vertical, and this was the feature that proved not to work. 'We just could not get the lay-down engine to scavenge the oil properly, and we kept losing a lot of horsepower.' Later, at McLaren for the 1988 season he was able to develop the same concept more successfully. 'I did a lay-down McLaren, exactly what we did at Brabham but with a Honda engine that worked, and we won fifteen out of sixteen races. So you do have things that don't work; but in that case it wasn't the idea that didn't work, I just ran out of time and money, and I took on much too much in a very short period to get it to work properly.'

3 Design process and working methods

In explaining his approach to innovative design, Gordon Murray stresses the need constantly to work from 'first principles.' In Formula One racing, he was often surprised to find that other teams were not taking such a basic approach, and that they would frequently merely copy the successful innovations of someone else. Working from first principles, and working in a highly organized way seem to come naturally to him, but his personal design process is much less structured than the results might suggest. Although he can tightly organize his team and run a complex racing organisation, his personal ways of designing are relatively unstructured, based on

annotated, thumb-nail sketches. 'I don't sit down and say, OK, now I've had the idea, let's see, this is a solution, these are the different ways to go, if I do this, and do that; I do lots of scribbles just to save it, before I forget.'

Gordon's design process is based on starting with a quick sketch of a whole idea, which is then developed through many different refinements. 'I do a quick sketch of the whole idea, and then if there's one bit that looks good, instead of rubbing other bits out, I'd put that bit to one side; I'd do it again and expand on the good bit, and drop out the bad bit, and keep doing it, doing it; and end up with all these sketches, and eventually you end up throwing ninety percent of these away.' He also talks to himself - or rather, writes notes to himself on the sketches; notes such as 'rubbish', 'too heavy' or 'move it this way 30mm.' Eventually he gets to the stage of more formal, orthographic drawings, but still drawing annotated plans, elevations and sections all together, 'Until at the end of the day the guys at Brabham used to call them "Wonder Plots", because they used to say "It's a wonder anybody could see what was on them"!'.

Although Gordon Murray carried immense personal responsibility for the design work of his racing cars, inevitably it involved a lot of teamwork. Clearly he has been successful in inspiring others to work with him. He likes to involve team members in the design problems, and for that reason prefers to recruit all-rounders to his team; 'I never have engineers that aren't designers.' He also likes to work collectively, standing around a drawing board discussing problems and trying ideas.

For this kind of teamwork, and especially for conceptual design work, he finds computer aided design systems too restrictive. For the McLaren F1 super-car, he installed a five-metre long drawing board in the design office, so that the car could be drawn full size. 'The problem with CAD for this sort of stuff is that you can never have a full-size drawing, unless you do a print, and by the time you do a print it's out of date in the concept stage.' He also does not like the one-person emphasis of CAD screens; 'You can only ever talk to one person at once - you stand behind and look over somebody's shoulder, which is not very good for a boss-designer relationship anyway, to have somebody standing behind you is never a good thing. To look over somebody's shoulder at a tiny little screen, it's just wrong, it's totally wrong.' On the other hand, he fully acknowledges that tasks like a complex suspension plot to determine the wheel envelope are ideal for CAD.

As for managing a team, he regards it as treading a fine line between dictator and diplomat. He knows exactly what he wants to achieve, but he likes being able to have people around 'to bounce ideas off.' He prefers being able to hand-pick a team, and to give his people enough freedom and responsibility to feel that they are really making a worthwhile contribution to the team.

4 Comparisons with other studies

A number of similar studies of highly creative or innovative designers has been published in recent years, and several points of similarity emerge. Lawson¹ interviewed ten highly successful, creative architects. One thing that emerges strongly from his studies that resonates with this study of Gordon Murray is the architects' use of drawing as a design aid. Lawson observed that, 'Frequently, drawings are overlaid and mixed together. Two-dimensional plans or sections can be seen with sketches and more diagrammatic marks all on the same piece of

paper in what appears a confusing jumble.’ These sound like Gordon’s ‘wonder plots’. The architects also use their drawings as a means of thinking ‘aloud’, or ‘talking to themselves’, as Gordon put it. For example, Lawson reports the architect Richard MacCormac as saying, ‘I use drawing as a process of criticism and discovery’; and the engineer-architect Santiago Calatrava as saying, ‘To start with you see the thing in your mind and it doesn’t exist on paper and then you start making simple sketches and organizing things and then you start doing layer after layer.... it is very much a dialogue.’

The common elements in these similar descriptions are the use of drawing not only as a means of externalising cognitive images but also of actively ‘thinking by drawing’, and of responding, layer after layer and view after view, to the design as it emerges in the drawings. These observations also confirm Schön’s⁷ observation of designing as a ‘reflective conversation’ between the designer and the emerging design. It is the reliance on drawing, and the preference for the immediacy of the interaction and feedback that manual drawing gives, that makes the architects, like Gordon Murray, unenthusiastic about CAD as a conceptual design tool.

Lawson also draws attention to similarities in the working methods of the architects he studied, which we can see also have similarities with Gordon Murray, such as the need to maintain periods of intense activity, but interspersed with periods - usually away from the normal work environment - of more reflective contemplation. Lawson’s architects also are characterised by a dedicated sense of purpose, which they share with small, highly-motivated teams of co-workers. There is also a sense of focussing on, or framing a problem so precisely that it can be approached from ‘first principles’; as Santiago Calatrava is reported: ‘It is the answer to a particular problem that makes the work of the engineer... you need a very precise problem...’

Roy² studied two innovative industrial designers, one of whom, James Dyson, reported that (unlike Gordon Murray) he almost never solved problems by getting ‘brainwaves in the bath’, but more often when doing some practical work, ‘welding or hammering something in the workshop’. However, this practical work may in itself be a way of letting the mind relax. Two of James Dyson’s most well-known design innovations, the ‘Ballbarrow’ wheelbarrow and the ‘Cyclone’ vacuum cleaner, both came from practical experience and from drawing on technology transfer from other fields (rather like Gordon Murray’s example of transfer of filter technology from medicine). The ‘Ballbarrow’ drew from his experience with balloon tyres on amphibious vehicles, and the ‘Cyclone’ drew from his installation of an industrial cyclone to remove fine powder from the air of the factory where the ‘Ballbarrow’ was being produced. For both of the designers studied by Roy, James Dyson and Mark Sanders, technology transfer appears to have been instrumental in their innovative thinking, together with personal motivation and deep immersion in the problem area.

A study of highly innovative engineers by Maccoby⁵ was based on interviews with eight such people, nominated by their peers. One of the observations Maccoby makes especially is the ‘systems approach’ adopted by these innovative engineers: ‘The innovator has a systems mind, one that sees things in terms of how they relate to each other in producing a result, a new gestalt that to some degree changes the world.’ Again, this sounds similar to the approach adopted by Gordon Murray. Maccoby continues with an example which might also be describing Gordon’s approach: ‘For example, one can think about a car in terms of all its parts working together to make it go... In contrast, most engineers do not think in systems terms. They are concerned about designing a good piece-part, like a clutch.’ This sounds like Gordon describing how his

approach is different from conventional, piece-focussed, engineering design.

Maccoby also identifies the life-long commitment of the innovators he studied, extending back to examples of interests stemming from their childhood or youth; the fact that innovators are not put off by failure, but expect to learn from failure; and that they have 'the courage to innovate'. He also points to several examples amongst these innovators of their experience of solutions arising from sudden illumination of problems that they had been worrying about. For example, like Gordon Murray's bathtime insights, the engineer-inventor Jacob Rabinow reported that 'flashes of inspiration come to him while shaving, driving, or partaking in other activities. Solutions are usually sudden.' Not all the innovators reported examples of sudden illumination, and for some, solutions only come from continuous hard work, but it is clear that sudden illumination (of a prepared mind) is a frequent element in creative thinking.

Another study of an innovative designer, by Candy and Edmonds³, is particularly relevant because it is also based upon the design of race-winning competition vehicles. Candy and Edmonds studied the design process of the racing-bicycle designer, Mike Burrows. His innovative, carbon fibre, 'monocoque' design of 1985 was at first banned by the cycle racing authorities, but later became the basis of the LotusSport Olympic pursuit bicycle on which Chris Boardman won the 4,000 metres individual pursuit in world record time at the 1992 Olympic games. Interestingly, there are many features of Mike Burrows' design approach that are very similar to that of Gordon Murray.

Like Gordon Murray, Mike Burrows is an enthusiast for his sport, and has participated as a racing cyclist. They both therefore have a very high personal motivation that drives their work, and both are steeped in the knowledge and expertise of their domains. They both constantly keep abreast of progress and current developments in their own and related fields, simply out of personal commitment, and this can often lead to insights and the transfer of technology from one field to another. The use of analogical thinking, a systems view, and total immersion in the problem are also identified as features of Mike Burrows' approach by Candy and Edmonds. A significant difference in working methods, however, is Mike Burrows' limited use of sketching as a design medium; he prefers to move quickly to immediate physical realisations of ideas in models and mockups. Nevertheless, his successful approach to the 'monocoque' cycle design reflects Gordon Murray's approach of concentrating on a major objective and designing from 'first principles'. In Mike Burrows' case it was a concentration on pursuing the dominant principle of minimising aerodynamic drag, and being prepared to completely re-conceptualise the conventional bicycle frame.

It is also interesting and relevant that Buijs⁶ used the example of another racing car designer - Jim Hall, the American Indy-car designer - to illustrate his suggestion that creative innovation occurs in 'jumps' from one level to another in the spiral of learning. Buijs likens the jump to a change in paradigm, based on a new conceptualisation of 'the problem'. The new concept arises from a single-minded vision of how to achieve or maintain a competitive advantage. The examples of Jim Hall's innovative designs are very close to our examples of Gordon Murray's innovations: for instance, his introduction of aerofoil wings, and especially his introduction of undercar fans to 'suck' the car onto the track surface, which - as Buijs points out - was also something tried again later on Brabham cars, designed by Gordon Murray.

5 Conclusions

There appear to be sufficient striking similarities between this study of the racing car designer Gordon Murray and other studies of innovators and creative designers for us to be able to draw some conclusions about common features of a successful approach to innovative design.

In particular, there are some potentially useful observations to be made about the methods and approaches adopted by successful, innovative designers, and which might perhaps to some extent be transferrable to others. Firstly, there is the approach to defining or framing the problem to be solved. The goal is set at a high level, with clear objectives, and in direct terms which might even seem to be simplistic. It is this simple clarity which might make other people conclude that the goal is simply impossible. There is a holistic, systems view of the problem encapsulated in the goal. A clear concept of how to reach this goal is devised - sometimes by means of a sudden insight which comes when relaxing after deep immersion in the problem - and the solution details then cascade from the concept. Intense work is needed to develop, evaluate and refine the solution details - creativity is still '1% inspiration and 99% perspiration'. The clear, generative concept is not simply 'found' in the problem as given, but created by the designer; it is not a matter of pattern recognition, but of pattern creation.

This approach seems to require, or is synergistic with, a particular style of working. Some aspects of this style arise from the innovative designer's personality characteristics - for instance, their personal motivation means that they are steeped in their chosen domain, and they are prepared when necessary to work obsessively at their chosen problem and solution. The working style is based on periods of intense activity, coupled with other periods of more relaxed, reflective contemplation. This working style may not be a reflection of a particular personality trait, but a necessary aspect of creative work, which requires alternating intense effort with relaxation. The innovative designer also likes, perhaps needs, to work with a small team of committed co-workers who share the same passions and dedication.

The working methods of the innovative designer are, for the most part, not systematic; there is little or no evidence of the use of systematic methods of creative thinking, for example. The innovative designer seems to be too involved with the urgent necessity of problem solving to want, or to need, to stand back and consider their working methods. Their design approach is strategic, not tactical. An important feature of their strategy is parallel working - keeping design activity going at many levels simultaneously. The best cognitive aid for supporting and maintaining parallel design thinking is drawing. Drawing with the conventional tools of paper and pencil gives the flexibility to shift levels of detail instantaneously; allows partial, different views at different levels of detail to be developed side by side, or above and below and overlapping; keeps records of previous views, ideas and notes that can be accessed relatively quickly and inserted into the current frame of reference; permits and encourages the simultaneous, non-hierarchical participation of co-workers, using a common representation. The drawing of partial solutions or representations also aids the designer's thinking processes, and provides some 'talk-back'. As well as drawing, innovative designers frequently like to undertake practical work related to the design solution, such as building models or mock-ups, or participating in construction.

We hope that these conclusions might offer guidance for those involved in the management of design activity or the development of methods or tools to support design activity, for those involved in design education, and for designers themselves.

Acknowledgement

We are, of course, indebted to Gordon Murray for the time and attention he gave to explaining his working methods to us.

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FIGURES

Figure 1 The McLaren F1

Figure 2 The Brabham BT49C, driven by Nelson Piquet to the World Championship in 1981

Figure 3. Gordon Murray (white shirted, centre left) supervises a pit-stop for Nelson Piquet to change tyres and take on fuel during the 1983 British Grand prix

Figure 4 Gordon Murray's explanatory sketch of the design thinking behind the steering column of the McLaren F1, comparing conventional steering column design (top) with that of the F1 (bottom)

Figure 5 Front, rear and side views of the McLaren F1, the side view part transparent to show details such as the steering column