Original paper

Research in Engineering Design 14 (2003) 1–11
DOI 10.1007/s00163-002-0023-z

Understanding the differences between how novice and experienced designers approach design tasks

Saeema Ahmed, Ken M. Wallace, Luciënne T.M. Blessing

Abstract Research was undertaken to understand how to provide the most appropriate support for novice designers in engineering design. However, how designers apply their experience and knowledge is not understood and further research in this area is required. This paper describes an observational study to understand how novice and experienced designers approach design tasks.

Keywords Design knowledge, Design experience, Empirical research, Design strategies, Problem solving

1 Introduction

Recent studies suggest that designers rely heavily on their memories and experiences and that research is required to understand how this knowledge and experience are used [8, 21]. In addition, industry has recognised the need to capture 'experience'. In order to capture experience, the nature and use of design experience within industry need to be understood more clearly.

This research aims to understand how novice and experienced designers approach design tasks, in particular within the aerospace industry, and thereby contribute towards developing a cognitive theory of how designers design. This research does not assess the quality of the designs or the designers. The specific aims are to gain an understanding of:

- the nature of design experience within the aerospace industry; and
- how novice and experienced designers approach design tasks.

2 Existing literature

Until recently, research into the differences between novices and experts has focused on problems where constraints and contexts are well defined, and a limited number of rules apply. Examples are chess and domain problems such as those of mechanics. Design is frequently described as an ill-defined problem. Usually many possible solutions exist, and there are no clearly defined rules to obtain these solutions [17, 9]. Cross and Cross [9] describe the limitations in drawing too many conclusions from studies of expertise in disciplines such as psychology, as the problems traditionally dealt with are well defined. The relationship between well-defined problem areas and the ill-defined area of design is poorly understood, and hence the applicability of findings from studies in well-defined areas to design is not clear [12, 34].

The main points to emerge from the literature reviewed relating to novice and experienced designers are that novice designers were found to have a tendency to reason backwards and to use a deductive approach. Experienced designers tended to reason forwards, and when solving more complex problems, to alternate between forward and backward reasoning [11, 12, 34, 31]. Christiaans [7] found that a designer's problem space increased with experience. Short-term memory is limited by the number of 'chunks' rather than the quantity of information it can hold, so the ability to recall increases with experience [6, 12]. Research carried out by Waldron et al. [32] found that experienced designers hold larger amounts of information in a single 'chunk'. Kavalki and Gero [20] carried out a protocol analysis of an expert and a novice designer. They found that the expert's cognitive activity and productivity is approximately three times higher than that of the novice designer. They suggest that this may be because of different 'chunking' of processes by the novice and expert. Kavalki suggests that the experienced designers use strategic knowledge, but does not identify what this strategic knowledge is. Experienced designers were found to have better spatial memory than novices [16]. These findings were also applicable to well-defined problem areas, and a more detailed overview can be found in [1].

Received: 5 July 2001 / Revised: 24 May 2002
Accepted: 31 July 2002 / Published online: 6 December 2002

S. Ahmed (✉), K.M. Wallace
Cambridge Engineering Design Centre,
Department of Engineering,
University of Cambridge,
Trumpington Street,
Cambridge CB2 1PZ, UK
E-mail: sa233@eng.cam.ac.uk
Fax: +44-1223-332662

L.T.M. Blessing
Technische Universität Berlin,
Konstruktionstechnik und Entwicklungsmethodik,
Sekr. H10 Straße des 17. Juni 135,
D-10623 Berlin, Germany

The authors acknowledge the support for this research from the Engineering and Physical Sciences Research Council (EPRSC) and from Rolls-Royce. The authors acknowledge Patrick Langdon for his contribution to the development of the research methodology and Michael Moss (Rolls-Royc.) for his support throughout the project.

The majority of studies of novices and experienced designers were found to focus upon differences in external activities, such as time spent gathering information, rather than problem-solving activities. The literature review highlights that there is a clear need to understand more deeply how designers design and, in particular, to identify differences between how novice and experienced designers approach design tasks.

3
Description of observations

The starting point of this research was that there are differences in how novice designers and how experienced designers approach design tasks. In order to investigate if these differences exist and to understand the differences, a combination of research methods was used because multiple sources of evidence increase the reliability of data [33]. Three studies were conducted: observations and post-observation interviews, discourse analyses, and interviews. This paper describes the research method and findings of the observations (for details see [1]). The research was data driven, and the findings from each study influenced the direction of subsequent studies. This approach, where the analysis is driven by the data and designers are studied from within their environment, i.e. in industry, can be described as an ethnographical approach (or as an ethnomethodology). As ethnography essentially observes from within the natural setting, it is considered to provide deeper insights than protocol studies in a laboratory environment [3, 15, 23]. In this type of study, data is collected without a predetermined data categorisation method or hypothesis. This results in voluminous amounts of data, which are gradually filtered as a data categorisation develops through progressive refocusing.

The use of ethnography was adopted in order to allow a structure for data collection to be developed during the studies. This approach meant that data could be analysed and reflected upon as the research proceeded. The structure for data collection was redefined as necessary in order to avoid excluding any data.

In order to understand the differences between how novice and experienced designers approach design tasks, six experienced and six novice designers were observed. The experienced designers had between 8 and 32 years of experience, and the novice designers between 1 and 2–5 years. The designers were observed individually and were from two different groups within an aerospace company. Two groups were selected to avoid overburdening any one group and also to ensure that the findings were not just applicable to one particular type of design task. As the groups were from the same company, they were both familiar with the culture of the company and were working on the same product, but at different stages of the design process. One of these groups was working on preliminary concepts for a whole aero-engine at the conceptual design stage. The other group worked at the detailed design stage on one subsystem of an aero-engine. Three novices and three experienced designers were observed from each group. The designers were observed in their own environments whilst working on their own design tasks. An interview of 15–20 min followed each observation to provide background information about each design task and each designer's experience.

The observations were adapted to include a verbalisation (thinking aloud) process, as observations alone only provide a limited insight into how experienced or novice designers design. The observations were audio-recorded. The regulations of the company meant video recording was not possible. Activities that could not be captured by audio recording, such as instances of a designer referring to drawings, were noted.

The designers were observed for periods of between 90 to 120 min, but this did not restrict the total amount of time they could spend on their particular tasks. It simply defined the duration of the observations. Hence, an observed *task* is not necessarily a completed design task, but an observation of a designer working on a design task for a specific period. The observations covered both conceptual and detailed design tasks. The designers were not presented with a special design task, but were observed working on their own design projects (refer to Table 1 for a description of the tasks observed). The implications of this were:

- The design tasks observed were real tasks, i.e. their complexity was suitable for each subject's experience, and the tasks did not stand alone but were part of larger projects. Since the designers participating in the study were not experienced in the same area, using the same design task would have resulted in some of the experienced designers being 'novices' when carrying out a design task outside of their areas of expertise.
- Comparison between designers was more difficult than would be the case if they had all been working on the same design task. Carrying out multiple observations to demonstrate the validity of the data aided in overcoming the difficulties in comparison between tasks [29]. In addition, the comparisons were more valuable and the conclusions easier to relate to industry, as they matched ongoing activities [27].
- The observations hardly impinged on the designers' time, as they continued with their own work. Therefore, the amount of time involved for participants could be kept to a reasonable level.

Table 1 summarises the tasks observed, together with the amount of experience of each designer, the time already spent working on the project, the expected project time, and the stage of the task within the design process. The letter N in the first column denotes a novice designer and the letter E an experienced designer. The tasks were observed at various stages in different projects, for example, the novice designer 1N in Table 1 was observed working on the design of a gearbox, which was reported to have encountered problems. The designer had already spent eight weeks working on the project and anticipated a further week was needed to complete it. All the design tasks observed at the conceptual design stage represent one of the two groups observed and those at the detailed design stage represent the other group.

Table 1. Description of design tasks observed: each row represents one observation and shows the experience of the designer (novice designer, N; experienced designer, E); the stage of the design process; position of the project at point of observation; and a task description

	Years of experience	Stage of design process	Project time in weeks		Task description
			Time already spent on project	Total expected time on project	
1N	1	Detail design	8	9	Redesigning gearbox reported to have encountered problems
2E	19	Detail design	56	64	Designing a shaft
3E	8	Detail design	52	54	Designing O-ring and squeeze film
4E	9	Detail design	0.25	0.5	Specifying tolerances and specification on piston ring
5N	1.5	Detail design	2	4	Checking tooling to investigate sensitivity of carbon seals to breakage on assembly
6N	2.5	Detail design	2	4	Redesigning cage for intermediate pressure bearing as original no longer suitable for project
7N	2.5	Conceptual design	8	16	Designing of intercase adjusting mount to reduce weight and cost
8E	18.5	Conceptual design	1	1.5	Checking feasibility of a compressor blade design to engine specification
9N	0.75	Conceptual design	1	1	Checking feasibility of a compressor blade design to engine specification
10E	9	Conceptual design	2	4	Understanding if possible to remove the supporting structure of a nozzle guide vane to reduce costs
11N	0.25	Conceptual design	2	4	Generating a new design for engine; fixing cycles, deciding number of stages for compressor
12E	32	Conceptual design	8	12	Designing nose cone of supersonic engine

3.1 Participants

Designers with little experience within the company were classed as *novices* and those with many years of experience as *experienced designers*. It was not assumed that an experienced designer was necessarily a good designer: no attempt was made to assess the *quality* of any design work. Experience is thought to contribute to being a *good* designer, but once a particular level of experience has been reached other factors become more important [28]. The period necessary to become experienced, defined as having attained an international level in fields such as chess, arts, sports, and sciences, is thought to be 10 years [26, 19, 5, 13]. By selecting novices with less than 2–5 years experience and experienced designers with over 8 years experience, it was assumed that the novice designers had not reached the level of experience required to be *good* designers. Therefore, the participants in this research were selected based upon the number of years of relevant industrial experience and were not assessed on their design skills.

3.2 Limitations of the observations

As the observations captured about 2 hours of design activity, they could only provide a short, but detailed, insight into the activities of the designers. However, as 12 observations were carried out, a total of 20 hours of data was analysed. The duration of an observation was restricted by the busy schedules of the designers and their willingness to participate in the study. Considerable flexibility was required in arranging the observations to fit in with each designer's schedule. The observations could have been carried out for longer periods; however, observations are time consuming. For each hour of observation, around 25 hours of additional time were required for planning, transcription, and analysis.

Various research issues were considered when planning the observations. The influence of thinking aloud on the behaviour of a participant is a debated subject. Ericsson and Simon [13] consider the effects to be negligible. They found no reliable evidence that structural changes occurred to cognitive processing if subjects were simply asked to verbalise their thoughts. However, they did find changes when subjects were asked to *explain* their cognitive processes. Stauffer et al. [29] argue that thinking aloud can interfere with a participant's thought processes; however, thinking aloud was essential in order to gain some insight into the designers' thought processes. If they are asked to reflect on their decisions, thinking aloud may prompt designers to consider their design in a greater detail than they otherwise would. They may consider more carefully why they are making a particular decision. The designers were therefore not asked to reflect on their thoughts, but simply to verbalise them.

The effect of being observed may have altered the behaviour of the designers. Participants may try and be *good* subjects by trying to produce the data that they think is desired [24, 22]. To reduce the effect of subject bias, it was made clear that the design task and the designer would not be evaluated. Also, all the participants were in the same situation, so any measure was relative. It is, however, possible that novices and experienced designers may have reacted differently to being observed.

The presence of an experimenter (in this case, the researcher) may also effect the behaviour of the designers [25]. The experimenter may bias the experiment by verbal communications or gestures, e.g. nodding when an expected response is observed. At the start of each observation, there was no expectation of any particular response, hence experimenter bias was considered to be minimal. As the earlier observations were analysed, care was taken with further observations to ensure that any expected responses were not communicated to the participants.

The use of an audio recorder may also have affected the experiment, as the participants may have altered their behaviour if they were aware that they were being recorded. Permission was asked from each participant to use the audio recorder. The audio recorder was placed on the table in an attempt to be as discrete as possible. Nobody refused to be audio-recorded and no problems arose from this approach.

3.3
Analysis method

The observations were transcribed from the audio recordings. As no categorisation of data was determined prior to the observations, the transcripts were analysed, a few lines at a time, to summarise the designers activities. Categories were created to summarise all these activities. For example, if the designer was concerned about the high stress of a component, this would be summarised as considering the issue of stress and the category *consider issues* was generated.

Additional categories were required in the analysis of later transcripts to accommodate all the data. The final transcripts required no further categories, resulting in a comprehensive set. The earlier transcripts were reanalysed using the final coding scheme. This approach of generating the coding scheme from the data, instead of using a predetermined scheme, ensured that as much of the data as possible was categorised. The coding scheme describing the designers' activities was grouped under the following types (Table 2):

- *thought*, the designers expressed their thoughts, e.g. 'express difficulty';
- *action*, the designers carried out an action, e.g. a task to gain understanding was categorised as 'gain understanding';
- *pattern*, the designers carried out a pattern of behaviour, e.g. 'use trial and error';
- *design strategy*, the designers carried out an action that was a strategy to aid the progress of the design, e.g. 'aware of reason';
- *general activity*, the designers carried out an action that did not directly help the progress of the design, e.g. 'ask advice'.

Suwa et al. [30] describe two main approaches to segmenting a transcript: (1) to segment based on verbalisation events such as pauses, intonations as well as syntactic markers for complete phrases and sentences; or (2) to divide the protocols based on the subject's intention, e.g. Goldschmidt [18] describes a segment as an act of reasoning that presents a coherent proposition pertaining to an entity that is being designed. A change in the subject's intention or the contents of their thoughts or their actions flags the start of a new segment. The approach used for this research was the latter, so a single segment consisted of between 10 and 15 sentences. The ends of the segments were chosen to keep the amount of data manageable and to indicate when a designer reached the end of a sequence of activities, i.e. the next activity represented a change in the designer's line of thought. An example of a sequence was all the activities a designer carried out to accommodate a longer

Table 2. Categories identified through observations

Category	Behaviour adopted mostly by:	Type
Use trial and error	Novice	Pattern
Lack confidence in own decision	Novice	Thought
Gain understanding	Novice	Action
Visualise in 3-D	Novice	Thought
Express difficulty	Novice	Thought
Consider issues	Experienced	Design strategy
Aware of reason	Experienced	Design strategy
Refer to past designs	Experienced	Design strategy
Question is it worth pursuing	Experienced	Design strategy
Question data	Experienced	Design strategy
Keep options open	Experienced	Design strategy
Aware of trade-offs	Experienced	Design strategy
Aware of limitations	Experienced	Design strategy
Use intuition	Experienced	Design strategy
Give advice	Experienced	General
Ask advice	Both	General
Express need for advice	Novice	General
Find different problem	Experienced	General
Collect drawings/documents	Novice	General
Resolve computer issues	Both	General
Execute sub-task to proceed	Both	General
Ask for reason	Experienced novices	Design strategy

squeeze-film in a bearing. Another sequence was the activities undertaken by the same designer to attempt a completely different approach to accommodate the longer squeeze-film. Each segment of the transcript was categorised and could contain more than one category. For example, a designer may have referred to a past design to understand how a particular component behaved in the past. This would be categorised as both 'refer to past designs' and 'aware of reason' (Table 2).

3.4 Coding scheme reliability

One person carried out all of the categorisation of the data. This was because only the researcher who was present during the observations actually *observed* the designers, since the company did not allow video recording. However, the coding scheme was tested for reliability using Cohen's Kappa coefficient of reliability (described in [4]). The Kappa coefficient subtracts the percentage agreement that can be expected from chance from the actual percentage agreement. One complete transcript was categorised by three people: the researcher and two coders who were considered 'naïve'. These two coders were provided with a transcript that had been segmented. This was necessary, since an agreement was defined as the coders agreeing that the activity occurred or (agreeing that it did not occur) in the same segment. Prior to categorising the transcript, both the coders were provided with a description of each category. The transcripts of each of the coders were compared to that of the researchers. The Kappa coefficients calculated were 0.89 and 0.97, which are indicative of high intercoder reliability. The Kappa coefficient does not reveal details of the disagreements, for example, if all the disagreements belong to the same category. However, by inspecting the method used to calculate the Kappa, it was clear that the disagreements of the coder who had a Kappa coefficient of 0.89 mainly belonged to one particular category, 'consider issues'. When this was discussed with the coder, it was evident that the definition of this category was not clear to the coder. The definition was adapted to clarify the category for further use.

4 Findings

In total, 22 categories representing the activities of the designers were identified from the observations. The categories are grouped together and presented as follows: overall patterns (Sect. 4.1), behaviour of novice designers (Sect. 4.2), behaviour of experienced designers (Sect. 4.3), and general designer behaviour (Sect. 4.4). Table 2 lists all the categories together with the type of designer who adopted this behaviour and the type of activity (as described in Sect. 3.3). For example, the row *use trial and error* was predominantly adopted by novice designers and is categorised as a pattern.

4.1 Overall patterns

One of the main findings was the overall design patterns adopted by the designers, i.e. the process of generating and

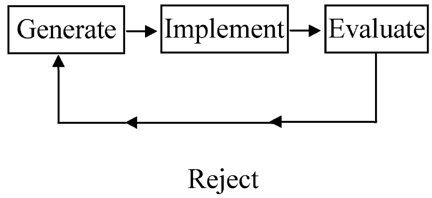

Fig. 1. Novice designer pattern

implementing decisions. The novice designers used a particular pattern, referred to as *trial and error*, which resulted in several iterations [2]. They tended to generate a decision and then immediately implement that decision (Fig. 1). The results of the implementation were evaluated and, if satisfactory, the designers moved to the next decision. If rejected, the process was repeated. A decision can be described as the designer's judgement reached after considering how to approach a particular design problem. The carrying out of a decision is described as implementation and may involve computational analysis, requiring several hours of work, e.g. stress analysis. The assessment of a decision or a modification to the design, i.e. implementation, is described as an evaluation.

During the observations, both a novice designer and an experienced designer were observed working on the same design task (designers 9N and 8E in Table 1). Both of these designers were checking the feasibility of a compressor blade design against the engine specification. In the case of the novice designer, he *generated* a decision on how to modify a compressor blade to reduce the stress in the blade and then proceeded immediately to *implement* the modification. Having modified the blade on the computer screen, he then went on to *evaluate* the implementation. If the outcome of the evaluation was unsatisfactory, the process was repeated.

This *particular* pattern of trial and error was observed 23 times with novice designers and only 3 times with experienced designers over a 20-hours period. Smith and Leong [27] found a similar pattern in their observations of students (novices) and professional engineers. The use of a trial and error process can be likened to reasoning backwards. Backward reasoning has been observed in novices in the domains of physics, medicine, and design [7, 11, 12, 34].

Experienced designers were observed to evaluate their decisions *prior* to implementing them, and thus avoided the longer cyclic process of trial and error adopted by novices (Fig. 2). If this preliminary evaluate stage indi-

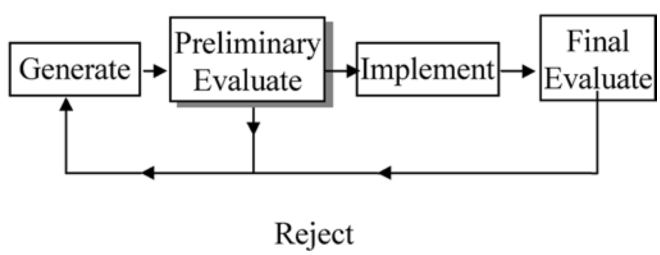

Fig. 2. Experienced designer pattern

cated that the implementation of the decision was not likely to be feasible or beneficial, it was rejected there and then. The specific activities carried out at this stage are described in Sect. 4.3. The process of generating a decision and evaluating it was repeated until the designer was satisfied with the result. Only then would the decision be implemented and the result finally evaluated.

In the compressor blade example, the experienced designer carefully evaluated the decision about a proposed modification *prior* to implementing that modification to the blade. For example, during the preliminary evaluate stage the designer carefully questioned whether it was worthwhile to implement a modification (categorised as *question is it worth pursuing*).

The preliminary evaluate stage described in Fig. 2 refers to an internal process. The experienced designer has a larger experience base across which to search than does a novice designer. However, the differences observed between novice and experienced designers are not simply whether their knowledge bases are external or internal but also the strategies that are employed when accessing these knowledge bases. For example, the novice designer obviously has less knowledge of past projects than an experienced designer, however, the novice does have access to external knowledge of past projects. Therefore, the novice designer could follow the same strategy as an experienced designer but use a different knowledge source. These differences are discussed in the following sections.

4.2
Behaviour of novice designers

Novice designers carried out several activities that were classified as a *thought* or an *action* rather than a design strategy Table 3. The novice designers expressed that they were often uncertain about a decision they had made (categorised as *lack confidence in own decision*). This may explain the need to implement a decision prior to evaluation, and hence the use of the novice's trial and error pattern. Novice designers were observed undertaking tasks to gain a better understanding of the problem (categorised as *gain understanding*). Examples of such tasks include novice designers spending time to understand how the design functioned or how it was assembled. Four of the six novice designers observed expressed difficulty in visualising the design while working on the computer. They expressed the need to visualise in three dimensions (3-D) or to be able to see a physical model in order to understand better the component or assembly (categorised as *visualise in 3-D*). The designers found it difficult to visualise the components from two-dimensional (2-D) drawings.

Unsurprisingly, the novice designers expressed difficulty in the task they were undertaking, as they had not done it before (categorised as *express difficulty*). Novice designers, in contrast to experienced designers, were found to be much more likely to treat numerical data obtained from a variety of sources, including computer models, as accurate values. The novice designers were not observed to question data. They tended to consider issues sequentially, and were not observed to differentiate between important and less important issues.

Since novice designer were observed to follow a pattern of 'trial and error', this describes their overall approach to design tasks. There is no category describing how designers carried out the implement stage, therefore it appears as if novice designers are not doing very much in comparison to experienced designers (see Sect. 4.3). This is not the case. They were observed to generate, implement (e.g. by making modifications to designs using computer software), and evaluate, which has been included in *trial and error*. However, when generating, implementing, and evaluating they were not observed to use the design strategies that were adopted by experienced designers.

4.3
Behaviour of experienced designers

Experienced designers tended to carry out a number of activities that novice designers did not. These activities were mainly carried out during the preliminary evaluate

Table 3. Comparison of designer behaviour for eight selected categories (frequency of occurrence calculated for each category, i.e. across each row). High number of occurrences observed: *filled-in square*; medium number of occurrences observed: *half-filled-in square*; minimal or no occurrences observed: *blank square*

Category	Novice Designers						Experienced Designers					
Designer	N1	N2	N3	N4	N5	N6	E1	E2	E3	E4	E5	E6
Company experience (years)	0.3	0.75	1	1.5	2.5	1.5	8	9	18.5	11	19	32
Non- company experience (years)						1.5				8		
Consider issues	□	□	□	□	◪	◪	■	□	□	■	■	◪
Aware of reason	□	□	□	□	□	◪	■	□	◪	■	■	◪
Refer to past designs	◪	□	□	□	◪	□	◪	■	◪	■	◪	◪
Question is it worth pursuing	□	□	□	□	□	□	■	□	■	■	◪	□
Question data	□	□	□	□	□	□	■	■	■	□	■	□
Keep options open	□	□	□	□	□	□	■	□	■	□	■	□
Aware of trade-offs	□	□	□	□	◪	◪	◪	□	□	□	■	■
Aware of limitations	□	□	◪	□	□	□	◪	◪	□	◪	■	□

stage (Fig. 2). Table 3 shows the eight categories that were typical of experienced designer behaviour and compares these with those typical of novice designers. These activities can be described as *design strategies*. The designers are ordered in Table 3 by their length of experience, starting with the shortest, i.e. N1 and E1 are the least experienced, and N6 and E6 the most experienced in their respective categories. Each of the columns represents a designer, and each row represents an activity. The following symbols are used in Table 3: high number of occurrences observed, filled-in square; medium number of occurrences observed, half-filled-in square; minimal or no occurrences observed, blank square.

A high, medium or minimal occurrence is classified by the frequency of occurrence *within* each category, i.e. across each row. For example, if the highest occurrence of a category, e.g. *refer to past designs*, was 14 times during an observation, then between 8 and 14 occurrences was described as a high occurrence; a medium occurrence may be between 2 and 7; and a minimal occurrence may be 1 occurrence or no occurrence. Although individual differences can be seen in the behaviour of the 12 designers, there is a clear difference in the patterns shown between the novices and the experienced designers.

Typical activities of experienced designers can be described as the following eight design strategies:

Consider issues experienced designers were more aware of relevant issues and decided which were the most important. As the designers were asked to think-aloud, their statements were sequential; however, they were observed to consider several issues at once. For example, one experienced designer stated, 'if the eccentricity on a particular component is reduced, what else would be effected other than ease of manufacture?' The designer was trying to identify all the issues that needed to be considered.

The experienced designers used the context of the current design task to decide when issues were not relevant. For example, the issue of a particular stress in a turbine blade may not be so important, as the designer may be aware that an earlier turbine blade of a similar design was able to cope with the loading conditions.

Aware of reason experienced designers tended to be aware of the reasons behind the use of, for example, a particular component or manufacturing process in a particular design. The particular reasons why a component or process was used may be due to how the engine functioned, the capability of a particular supplier, or the manufacturing process. For this knowledge of previous projects was required. Their understanding of how the engine functions and of manufacturing processes was evident, as the experienced designers assessed the reasons for using a particular component or manufacturing process and its applicability to the current problem. They often referred back to past projects to compare how a similar component behaved. If removing or modifying the component or process helped solve the design problem, this was done. A specific example was the use of a particular cold expansion process, which had caused difficulty in manufacturing. The experienced designer was aware of the stress conditions that required this additional manufacturing process, and, after referring back to a past design project to see how a similar design had behaved, he was confident that these conditions would not occur. He therefore decided that this process was not required for the current design problem.

Refer to past designs experienced designers often referred to past designs from the following sources: memory, drawings, reports, and colleagues. They tended only to refer to projects that were known to them. Past designs were referred to for the following reasons:

- to understand why a particular component or manufacturing process had been used;
- to find designs similar to the current design problem;
- to find designs that were similar with regard to environmental or functional conditions, and to understand how the components had behaved in these conditions, e.g. a paint coating at high temperature;
- to find projects where similar problems had arisen and how they were resolved;
- to use as a starting point for new designs and to ensure consistency between designs;
- to obtain numerical data for the current problem, e.g. to estimate a weight, a designer used the ratio of the weight and the volume of a past design.

Question is it worth pursuing experienced designers frequently asked themselves how much they could expect to achieve if they continued a particular approach, that is, if they implemented a decision. They used this information to decide if a task was worth pursuing. For example, if an experienced designer could only reduce the weight of a design by two or three percent, he would question whether that particular approach was worth pursuing.

Question data experienced designers regularly questioned the data they obtained, including values given for tolerances, standards, stress models, etc. They questioned the accuracy of the data, for example, how components were modelled or tested. They asked themselves how much accuracy was required for a particular design task and also questioned the applicability of standards to the current design conditions. During one observation, a designer was presented with a compressor blade subject to high stress. He questioned if the blade had been correctly modelled, and if this was the reason for the predicted stress being so high.

Keep options open the experienced designers often rejected an option if it limited later options in the design process. For example, if using a particular seal limited how the design could be assembled, this option was be rejected. However, they kept rejected options in the backs of their minds in case they needed them later. They were much more aware of what had to be considered further down the design process and delayed making a decision between options as long as possible. They planned ahead for likely changes, e.g. they designed to allow a margin for any change in the requirements, say, the amount of thrust required. The process of keeping options open can be likened to an experienced chess player's ability to plan several moves ahead as observed by De Groot [10] in Ericsson and Smith [14].

Aware of trade-offs experienced designers were clearly aware of the relationships between issues. When considering an issue they knew the effect this issue had on other issues and were aware that many decisions were based on compromises. Once aware of the trade-off, they questioned whether it was worthwhile continuing to pursue the task or to implement a decision. For example, when trying to reduce the weight of a component, the cost of implementing such a solution would be considered.

Aware of limitations experienced designers were evidently aware of the limitations of the current design task. The following reasons were identified to limit a task:

- the expected achievement of the current task versus later design tasks, e.g. the limitations of carrying out a 2-D stress analysis if the component was to be modelled using a 3-D stress analysis later;
- incompleteness of information, e.g. if further changes were required, or if components required testing.

The limitations of the design task allowed the designers to select a level of accuracy of data appropriate for that task and to allocate the right amount of time to spend on the task.

Use intuition three experienced designers were observed to make intuitive decisions (categorised as *use intuition*). The number of total occurrences was low. Hence, this finding is not conclusive and has been separated from the main findings. A decision was defined as intuitive if the designers, during the thinking aloud process, explicitly described the decision as intuitive based upon their previous experience. For example, during one observation, an experienced designer modified the design of a nose cone of a supersonic engine. He stated that he had modified the design based upon what had worked before and that it looked right. This category has been distinguished from *refer to past designs*. *Use of intuition* is based on past experience; however, as the designers are not aware of exactly what past experience they are referring to, this has been described as intuitive (based on previous knowledge). An experienced designer will obviously have more past experience to refer to than a novice designer. *Refer to past designs* is when the referral to past design knowledge is exact, and therefore a novice designer could also have followed this approach by referring to an external database of past projects.

4.4 General designer behaviour

During the observations the designers carried out activities, described as *general designer behaviour*, that were not directly associated with achieving the goals of the design task. Some of these activities were adopted by the novices, some by experienced designers, and some by both.

The observations took place in the designers' own environment, which in the company concerned were large open-plan offices. The designers were therefore subjected to interruptions from phone calls, or face-to-face contact with colleagues. The novice designers often expressed the need to talk to experts (categorised as *express need for advice*); however, they did not immediately ask for advice, instead preferring to note down questions. This may be due to a preference to ask experienced designers several questions at once, as opposed to approaching them often. On the other hand, it may be a consequence of being observed. During the post-observation interviews, the novice designers were asked why they preferred to save questions to ask experienced designers rather than asking them immediately. One of the novice designers thought it was due to the knowledge possessed by novice designers and their level of confidence. These observations are in line with Marsh's [21] study of designers in the aerospace industry, which showed that designers needed to have confidence in their queries.

Both novice and experienced designers were observed to *ask for advice*. However, only experienced designers were observed to *give advice*. The experienced designers were not hesitant in requesting information and would get up to ask colleagues questions as and when necessary, or use the phone. When asked for advice, experienced designers often referred to a different knowledge source. Frequently, that knowledge source was another person. Baird et al., Court et al., and Marsh also observed the expert as a *pointer* to other knowledge sources [3, 8, 21]. Experienced designers were, not suprisingly, far more likely to give advice than novice designers.

During the observations, two of the experienced designers discovered additional problems to that of the original design task (categorised as *find different problem*). For example, an experienced designer who was specifying the tolerances on a piston ring realised that the material that had been specified by a novice designer could not be obtained from suppliers.

Novice designers were found to collect drawings and documents more frequently than experienced designers (categorised as *collect drawings/documents*). Both novice and experienced designers were found to spend time resolving computer-related issues (categorised as *resolve computer issues*) and carrying out activities that were necessary to proceed with the task (categorised as *execute sub-task to proceed*). There was no conclusive evidence as to whether *resolve computer issues* affected the novice designers any more than it affected the experienced designers, however the data suggests that novice designers spent more time resolving computer-related issues. The novice and experienced designers both executed subtasks, for example, changing between imperial and metric units, or scaling drawings.

4.5 Moving from one activity to another

Once the activities undertaken by designers were identified, the transcripts were analysed to discover if there was a pattern to how designers moved between these activities. The analysis showed that experienced designers did adopt a pattern of moves whilst designing. The following were identified:

- activities that were likely to *follow* one another;
- pairs of activities that were carried out *close together*, but did not necessarily follow one another (Table 4);

Table 4. Pairs of activities carried out close together. High number of occurrences observed: *filled-in square*; medium number of occurrences observed: *half-filled-in square*; minimal or no occurrences observed: *blank square*

Pairs of activities carried out together	Number of designers observed carrying out activities together												Number of occurrences in 10 hours of observation	
	Novice designers						Experienced designers						Novices designers	Experienced designers
	1	2	3	4	5	6	1	2	3	4	5	6		
Consider issues + aware of reason	□	□	□	□	□	□	■	■	◪	◪	□	□	0	46
Consider issues + refer to past designs	□	□	□	□	□	□	■	◪	◪	◪	□	□	0	29
Aware of reason + refer to past designs	□	□	□	□	□	□	■	◪	◪	◪	◪	□	0	25
Aware of reason + question is it worth pursuing	□	□	□	□	□	□	◪	◪	◪	□	□	□	0	11
Question is it worth pursuing + refer to past designs	□	□	□	□	□	□	◪	◪	◪	◪	□	□	0	10
Refer to past designs + use intuition	□	□	□	□	□	□	◪	◪	□	□	□	□	0	3
Refer to past designs + find a different problem	□	□	□	□	□	□	◪	□	□	□	□	□	0	8
Lack confidence in own decision + Use trial & error	■	◪	□	□	□	□	□	□	□	□	□	□	5	0

- *combinations* of activities that were likely to occur together (Table 5).

First, the activities that were likely to *follow* one another were identified. The six most common moves between activities that were likely to follow one another were all combinations of three activities: *refer to past designs, consider issues*, and *aware of reason*. The experienced designers were observed to follow these six moves 74 times during the 10 hours of observation. The two most experienced novices were also observed to follow three of these moves four times in total. This finding suggest that their behaviour was beginning to move towards that of experienced designers and is discussed in more detail in Sect. 4.6.

Second, the pairs of activities that were carried out *close together* were identified from the transcripts. These activities did not necessarily follow one another, as they may have belonged to the same segment and hence are independent of the direction of the move. In total eight pairs were found, and only one of these (*lack confidence in own decision* plus *use trial and error*) was adopted by novice designers. Table 4 shows these pairs of activities together with the number of times they were observed and the number of designers observed to carry out these pairs of activities. For example, the first row indicates the pair of activities *consider issues* plus *aware of reason* was carried out by four experienced designers, with a high occurrence for two of the designers and a medium occurrence for the other two designers. In total, this pair of activities was carried out 46 times by the experienced designers and was not carried out at all by the novice designers. These findings suggest that experienced designers frequently carry out certain activities close together, particularly combinations of the following activities: *consider issues*, *aware of reason*, and *refer to past designs*.

Finally, combinations of activities that were likely to occur together before the designers changed their approach to a particular problem were identified. Experienced designers were found to combine activities in a variety of sequences. The novice designers were not observed to combine activities in any regular manner and only tended to carry out two activities at most before trying a different approach to solve a problem. A sequence consisted of carrying out a series of related activities. A new sequence tended to indicate a new line of thought for a designer.

An example of a sequence is all the activities a designer carried out to accommodate a longer squeeze-film in a bearing. Another sequence was the activities undertaken by the same designer to attempt a completely different approach to accommodate the longer squeeze-film. A total of 18 combinations of activities were found, combining between 3 and 5 activities together in a sequence. These are illustrated in Table 5, in which each row represents a different combination of activities together with the designer(s) who used that combination. For example, in the third row combination C combines the five activities: *consider issues*, *refer to past designs*, *question is it worth pursuing*, *keep options open*, and *aware of trade-offs*, and the experienced designer E5 used this combination. Out of the total of 22 categories, 15 form part of the 18 combinations of activities.

Each of the 18 combinations A to R in Table 5 was observed only once during the observations, with the exception of combination E, which was used by two designers, E4 (observed once) and E5 (observed twice). Combination E combines the categories *consider issues*,

Table 5. Combinations of activities

Combinations of activities	Use trial & error	Consider issues	Aware of reason	Refer to past designs	Question is it worth pursuing	Question data	Keep options open	Aware of trade-offs	Aware of limitations	Use intuition	Execute sub-task to proceed	Find different problem	Ask advice	Give advice	Express need for advice	Designers
Combination A	■			■						■						E1
Combination B	■									■			■			E2
Combination C		■		■	■		■	■								E5
Combination D		■	■					■								E5
Combination E		■	■	■												E4 E5
Combination F		■	■						■							E5
Combination G		■	■										■			E5
Combination H		■	■									■	■	■		E5
Combination I		■	■									■				E5
Combination J		■	■	■	■											E4
Combination K		■	■		■											E1
Combination L		■	■												■	E4
Combination M		■				■							■			E5
Combination N		■							■					■		E1
Combination O				■		■					■					E3
Combination P				■		■			■							E2
Combination Q				■								■		■		E4
Combination R			■	■	■				■							E4

aware of reason, and *refer to past designs*. These categories were the most common categories to follow one another. Designers E4 and E5 carried out combinations of activities five and eight times, respectively, whilst designer E6, the most experienced designer with 32 years of experience, was never observed to carry out more than two activities together and therefore does not appear in Table 5. The designers working on detail design (E4, E5, and E1) used combinations of activities more often than those working on conceptual design.

The use of a combination of activities suggests that experienced designers adopt a multiactivity approach to solving design problems. The combination of activities used varied from designer to designer; however, there are some common elements. The activities *consider issues* and *aware of reason* appeared together in 9 of the 18 combinations (columns D–L). *Ask advice* appears in four of the combinations and is always together with *consider issues* (columns B, G, H, and M), suggesting that the designers always asked advice about a particular issue. The activity *aware of trade-offs* always appeared with *consider issues*. All the observed trade-offs were between different issues, which is a possible explanation for such a combination.

Combination A brings together *use trial and error*, *use intuition*, and *refer to past designs*. As noted earlier, experienced designers were observed to use a trial and error process three times during the 10 h of observation. The experienced designers considered their use of trial and error to be based on their intuitive feel and mentioned their past experience as the basis on which to judge if their intuitive decisions were correct. Combination B also combines *use trial and error* with *use intuition*. As these are the only combinations involving trial and error, this suggests that experienced designers use trial and error in a different way than novice designers. The novice designers used a particular pattern of trial and error; however, they did not describe their decisions as intuitive and they were not observed to refer to past designs.

5
Conclusions

The literature reviewed showed that there is a need to understand more deeply how designers design. In order to contribute to this understanding, observations were carried out that focused on investigating the differences between how novice and experienced designers approach design tasks. Observations were found to be time consuming, though the data collected was rich. Each hour of observation required approximately 25 further hours in data collection, transcription, and analysis.

The findings show clear differences between how novice and experienced designers approach design tasks. The novice designers tended to use a particular pattern of *trial and error*. The use of trial and error is a familiar pattern in literature, however, this research has contributed to understanding the approach adopted by experienced designers instead. Experienced designers used particular *design strategies*, whereas novice designers did not. Novice designers were unaware of these design strategies. This suggests that when developing support methods for novice designers, consideration should be given to informing them of such strategies in addition to providing them with knowledge and information.

Experienced designers tended to combine between three and five activities before changing their approach to a particular problem. In total, 18 such combinations were identified. The experienced designers were also found to have developed individual approaches to a design task. Individual approaches seem to be dependent on the type of design task (conceptual versus detail design) and also on age and experience. However, further research is required to verify these observations.

The observations identified that two novice designers, N5 and N6, carried out some of the activities characteristic of experienced designers. It is interesting that these two were the most experienced of the novices: N5 with 2–5 years and N6 with 3 years experience. They were also observed, at times, moving from one category to another as identified in experienced designer behaviour. The behaviour of these designers suggested they were moving towards experienced designers behaviour, but this only involved the most common activities *consider issues*, *aware of reason*, *refer to past designs*, and to a lesser extent, *aware of trade-offs*.

Many of the findings from the observations are in agreement with the literature on well-defined complex problem areas, e.g. keeping options open can be likened to an experienced chess player's ability to plan several moves ahead. The research has contributed towards understanding more deeply how designers design and the differences in how novice and experienced designers approach design tasks. These results have been used to develop a method of support for novice designers and are currently being used to help develop an intranet to capture and structure engineering design experience.

References

1. Ahmed S (2001) Understanding the use and reuse of experience in engineering design. PhD thesis, Cambridge University, UK
2. Ahmed S, Blessing LTM, Wallace KM (1999) The relationship between data, information and knowledge based on an observation of engineering designers. In: Design theory and methodology. ASME, Las Vegas, Nevada
3. Baird F, Moore CJ, Jagodzinski AP et al. (2000) An ethnographic study of engineering design teams at rolls-royce aerospace. Des Stud 21:333–355
4. Bakemann R, Gottam JM (1997) Observing interaction: an introduction to sequential analysis. Cambridge University, Cambridge, UK
5. Bloom BS (1985) Developing talent in young people. Ballantine, New York
6. Chase WG, Simon HA (1973) The mind's eye in chess. In: Chase WG (ed) Visual information processing. Academic, New York, pp 215–281
7. Christiaans HHCM (1992) Creativity in design: the role of domain knowledge in designing. Lemma, Utrecht
8. Court A, Cully S, McMahon C (1996) Information access diagrams: a technique for analyzing the usage of design information. J Eng Des 7:1:55–75
9. Cross N, Cross AC (1997) Expert designers. In: Designers – the key to successful product development. Springer, Darmstadt, pp 1–16
10. De Groot AD (1978) Thought and choice and chess. Mouton, The Hague
11. de Jong AJM (1986), Kennis en het oplossen van vakinhoudelijke problemen (Knowledge and solving domain problems). PhD thesis, Technical University of Eindhoven
12. Ericsson KA, Charness N (1997) Cognitive and development factors in expert performance. In: Feltovich PJ, Ford KM, Hoffman RR (eds) Expertise in context. AAAI, Menlo Park, Calif, pp 3–41
13. Ericsson KA, Simon HA (1993) Protocol analysis: verbal reports as data. MIT, Cambridge, Mass
14. Ericsson KA, Smith J (1991) Empirical study of expertise: prospects and limits. In: Ericsson KA, Smith J (eds) Towards a general theory of expertise. Cambridge University, Cambridge, UK, pp 1–38
15. ESRC (1998) Ethnography in support of aesthetic production. The Cognitive Engineering Website, http://www.cogeng.mcg.gla.ac.uk/part_13a.html
16. Gobert JD (1999) Expertise in the comprehension of architectural plans (knowledge acquisition and inference-making). In: Gero JS, Tversky B (eds) Visual and spatial reasoning in design. Key Centre of Design Computing and Cognition, University of Sydney, Australia, pp 184–205
17. Goldschmidt G (1997) Capturing indeterminism: representation in the design problem space. Des Stud 4:441–455
18. Goldschmidt G (1991) The dialectics of sketching. Creativity Res J 4:2:123–143
19. Hayes JR (1981) The complete problem solver. Franklin Institute, Philadelphia
20. Kavakli M, Gero JS (2001) Strategic knowledge differences between an expert and a novice. In: Gero JS, Hori K (eds) Strategic knowledge and concept formation III. Key Centre of Design Computing and Cognition, University of Sydney, Australia, pp 55–68
21. Marsh JR (1997) The capture and utilisation of experience in engineering design. PhD thesis, Cambridge University, UK
22. Orne MT (1969) Demand characteristics and the concept of quasi-controls. In: Rosenthal R, Rosnow R (eds) Artifact in behavioral research. Academic, New York, pp 143–179
23. Rose T (1997) Ethnography. Report CS 6751, Georgia Institute of Technology, College of Computing
24. Rosenthal R (1966) Experimenter effects in behavioral research. Appleton Century Crofts, New York, pp 464
25. Rosenthal R (1963) The effects of early data returns on data subsequently obtained by outcome-biased experimenter. Sociometry 26:487–493
26. Simon HA, Chase WG (1973) Skill in chess. Am Scient 61: 394–403
27. Smith RP, Leong A (1998) An observational study of design team process: a comparison of student and professional engineers. J Mech Des 120:636–642
28. Sonnentag S (1998) Expertise in professional software design: a process study. J Appl Psychol 83:702–715
29. Stauffer L, Diteman M, Hyde R (1991) Eliciting and analysing subjective data about engineering design. Eng Des 2:4:351–366
30. Suwa M, Purcell T, Gero J (1998) Macroscopic analysis of design processes based on a scheme for a coding designer's cognitive actions. Des Stud 19:4:455–483
31. Waldron MB, Waldron KJ (1996) The influence of the designer's expertise on the design process. In: Waldron MB, Waldron KJ (eds) Mechanical design: theory and methodology. Springer, Berlin Heidelberg New York, pp 5–20
32. Waldron MB, Jelinek W, Owen D, Waldron KJ (1987) A study of visual recall differences between experts and naive designers. In: Eder WE (ed) Proceedings of the 1987 International Conference on Engineering Design, (ICED87), Boston, 17–20 August, pp 86–93
33. Yin RK, Campbell DT (1994) Case study research. SAGE, London, pp 165
34. Zeitz CM (1997) Some concrete advantages of abstraction: how experts' representations facilitate reasoning. In: Feltovich PJ, Ford KM, Hoffman RR (eds) Expertise in context. AAAI, Menlo Park, Calif, pp 43–65