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THE RELATIONSHIPS BETWEEN DATA, INFORMATION AND KNOWLEDGE BASED ON A PRELIMINARY STUDY OF ENGINEERING DESIGNERS.

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ABSTRACT

The aerospace industry, along with other industries, has acknowledged the need to bridge the experience gap between novice and experienced designers [Moore, 1997]. The research aims to identify the support a novice designer requires to gain experience faster. The focus of this paper is to present some initial results of a study of novice and experienced designers.

This initial study highlighted the difficulty in establishing consistent and precise usage for the terms data, information and knowledge. It is concluded that data, information and knowledge are relative concepts that cannot be defined in absolute terms. As relative concepts, these help differentiate experts and novices, and different types of novices. The relationships between data, information and knowledge are examined with the aim of prompting a discussion.

1. INTRODUCTION

A long-term vision to bridge the experience gap between novices and experienced designers is a system that supports the novice designer with appropriate knowledge to provide him or her with 'experience'. In terms of the knowledge used, a design produced with the support of such a system would not be distinguishable to a trained eye as originating from a novice[1] or an experienced designer. The system would contain the appropriate knowledge currently possessed by experienced designers. This knowledge needs to be identified, captured, stored and made available to novice designers. This research is investigating how far this scenario can be realised.

Knowledge and experience influence the success of the design process. Nonaka and Takeuchi attribute the success of Japanese companies to organisational knowledge management [Nonaka, 1995]. Knowledge management has received increasing attention in recent years. Research into the capture, storage and presentation of knowledge has focused upon *how* this knowledge should be captured and presented. A large amount of literature is available on implementation of knowledge-based systems, but less is available on capturing as part of the design process (for a review of design knowledge capture see Jensen, 1998). Tomiyama argues that identifying *what* to capture has been overlooked [Tomiyama, 1997]. This is the focus of this research.

To identify what knowledge to capture, it is important to understand the differences between experienced and novice designers. This paper describes a preliminary descriptive study of experienced and novice designers. In carrying out this research the distinction between the terms data, information and knowledge were found to be unclear, and the existing definitions were not operational. Hence this distinction is discussed later in the paper.

1.1 Experts and Novices

Until recently research into the differences between experts and novices has focused on problems where constraints and context are well defined, and a limited number of rules apply. Examples are chess and domain problems such as mechanics problems. Chase and Simon found the ability to recall configurations of chess increased with the level of expertise (see Chase, 1973 in Ericsson, 1997). The 'experts' were experienced chess players who were also good players. This is due to the experienced players' ability to perceive meaningful

[1] 'Novice' is used to describe a person trained in his or her field, but with little or no practical experience.

patterns and relations between the chess pieces (chunks). Chunks are not innate, but develop through learning [Newell, 1972]. The capacity of short-term memory is limited by the number of chunks. George Miller's paper *Seven, Plus or Minus Two* (1956), is frequently referred to by cognitive psychologists. Miller states short-term memory capacity is limited to holding between 5 and 9 chunks. More experienced chess players can hold a complete chess configuration as one chunk of information. Less experienced chess players hold much smaller amounts of information in each chunk, requiring too many chunks to hold in memory [Newell, 1972]. Similar findings were found in solving domain problems [see Blessing, 1988 for an overview]. Waldron *et al* observed the abilities of experts, semi-experts (graduate designers) and naive designers to reproduce mechanical engineering drawings [Waldron, 1987]. They observed that experts made fewer errors; required fewer references (to the original drawings); and drew longer in between references. The ability to draw for longer before referring to the original drawing was attributed to the more experienced designers holding larger chunks of the drawing in memory. Experts were also found to be more successful at naming parts of the drawing correctly (this is largely dependant on domain knowledge).

The organisation of internal knowledge is thought to be different between experts and novices. De Groot observed experienced chess players to plan several moves ahead, exploring the consequences of these moves and the opponents's likely moves [Groot, 1978 in Ericsson, 1997]. The difference in the ability to find and selectively explore the most promising moves suggests a difference in the internal representation of knowledge [Ericsson, 1997]. In the domains of physics, medicine and design, novices were found to reason backwards, unlike experts who reasoned forwards. This suggests experts access their knowledge systematically [De Jong, 1986, Ericsson, 1997 and Zeitz, 1997]. When solving complex problems, experts alternate between forward and backward reasoning [de Jong, 1986].

It is assumed that problem solving takes place by searching through one's 'problems space'. The problem space is used to achieve the goal state of the problem and consists of 'representations, the information processes and all knowledge available' [Goldschmidt, 1997]. Problem space is thought to increase with expertise [Christiaans, 1992].

Cross *et al* suggest expert designers employ the following strategies in design:

- a systematic view of the design situation
- the framing of a problem in a challenging way
- the use of first principles in generation of design concepts.

Cross *et al's* findings were based upon two designers, both considered expert, observed using different methods. A comparison of expert designers with novice designers was not made, so it is difficult to determine if the strategies employed by novice designers would have shown any difference.

Cross *et al* 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, e.g. chess playing; and suggest referring to disciplines such as computer programming which deals with ill-defined problems. Design problems are described as ill-defined. One of the reasons for this is that many possible solutions exist [Goldschmidt, 1997, Cross, 1997]. In addition, not all of the characteristics of the situation can be found in the problem statement [Blessing, 1988]. The study described in this paper found some of the differences between novices and experts in relatively well-defined problem areas were also applicable in the ill-defined area of design. This confirms the suggestions made by Blessing [Blessing 1988].

2. OBSERVATIONAL STUDY

The aim of the research is to help novice designers gain experience faster. To achieve this, the differences between experienced and novice designers need to be better understood. The focus of the preliminary study was to observe the differences between novice and experienced designers in the aerospace industry.

2.1 Approach

Four experienced and four novice designers were observed carrying out design tasks. The experienced designers had between 8 and 32 years of experience and the novice designers between 8 and 30 months. They were from two different groups within the aerospace company.

The observations were 90 - 120 minutes in duration. An example of the tasks observed was the design of a second-stage high-pressure compressor blade. A 15 - 20 minute interview followed each observation. The interview provided background information about the design task and the designer's experience.

The observations took place within the designers' environments. The designers were observed individually and were asked to think aloud. Ericsson and Simon found no reliable evidence that structural changes occured to the cognitive processing if subjects were asked to simply verbalise their thoughts (they found changes when subjects were asked to explain their cognitive processes) [Ericsson, 1993 in Ericsson, 1997]. The researcher did not ask the designers the reason for doing something, as this may have influenced the process. They were only prompted to speak during periods of silence.

The observations provided a real-time account of the design tasks. The designers were not presented with a special design task, but observed while working on their own design work. The implications of this are:

- The design tasks observed were real tasks i.e. their complexity was suitable for each subject's experience and the tasks do not stand-alone but are part of a larger project.

This makes comparison more valuable as the task is not artificial and the conclusions are easier to relate to industry as they match ongoing activities [Smith, 1998].

- Comparison between designers is more difficult than would be the case if they were all working on the same design task. However, the use of a single design task for all subjects might have resulted in a task that was too easy for an experienced designer; outside the designers' area of expertise; or too difficult for a novice designer.
- The observations take less of the designers' time, as they continue with their own work.

2.2 Data Collection

All the observations and interviews were audio recorded and transcribed, resulting in 51 pages of transcripts. No categorisation of data was determined prior to the observations. The transcripts were analysed, a few lines at a time, to summarise the designers *thoughts* and *actions*. Categories were created to summarise all these thoughts and actions. A few 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, which was then used to reanalyse the earlier transcripts. Twenty-one categories of thoughts and actions were generated from the analysis of the observations.

3. PRELIMINARY ANALYSIS AND RESULTS

Table 1 shows nine selected categories, highlighting differences between the four novice and four experienced designers observed. The following symbols are used to indicate within each category: ■ the highest number of occurrences observed; ◪ medium number of occurrences observed; and □ no occurrences observed. Each of the categories is discussed briefly. Categories related to the design process are discussed in sections 3.1 and 3.2 and those related to supporting activities in section 3.3.

3.1 Typical Novice Behaviour

The novice designers used a particular pattern of trial and error, resulting in several iterations (refer to Figure 1). The designers would generate a decision and then immediately implement this decision. The results of the implementation were evaluated and, if satisfactory, the designers would move to the next decision. If rejected, the process was repeated. This process of trial and error was observed many times with novice designers and only once with experienced designers. Smith and Leong found a similar difference in their observations of students (novices) and professional engineers [Smith, 1998].

The data showed that the novice designers lacked confidence in their own decisions. This may explain the need to implement a decision before evaluating to determine if this decision is suitable. They were also observed undertaking tasks to gain a better understanding of the problem.

Table 1. Occurrences of Thoughts and Actions (number of occurrences observed: ■ highest, ◪ medium, □ none).

Categories	Novice Designers				Experienced Designers			
	1	2	3	4	1	2	3	4
Use of Trial and Error	◪	■	◪	◪	□	◪	□	□
Lack Confidence in own Decision	◪	■	◪	◪	□	□	□	□
Consider Issues	□	□	◪	□	■	◪	■	◪
Aware of Reason	□	□	□	□	■	◪	■	◪
Refer to Past Projects	□	□	◪	□	■	◪	◪	◪
Question is it worth Pursuing	□	□	□	□	■	■	◪	□
Have Low Confidence in Data Provided	□	□	□	□	□	■	■	□
Keep Options Open	□	□	□	□	□	■	■	□
Aware of Trade-offs	□	□	◪	□	□	◪	■	■

Novice designer 3 (refer to Table 1) was the most experienced of the novice designers with two and a half years experience. He was occasionally observed considering issues, referring to past projects and being aware of trade-offs. This typical behaviour of experienced designers.

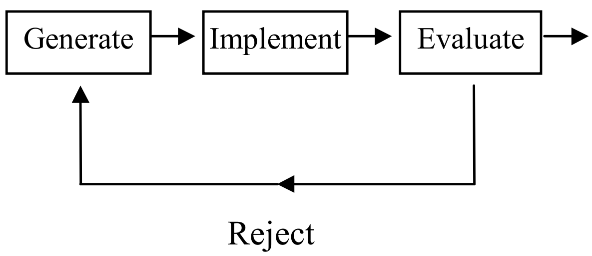

Figure 1. Novice Designers' Pattern

3.2 Typical Experienced Designer Behaviour

Experienced designers were observed to adopt a different pattern. They generated decisions and then evaluated the consequences before their implementation. If this first evaluation indicated that the implementation of the decision was not feasible, it would be rejected there and then. The process of generating a decision and evaluating it was repeated until the designer was satisfied (Figure 2). Only then would the decision be implemented and then re-evaluated.

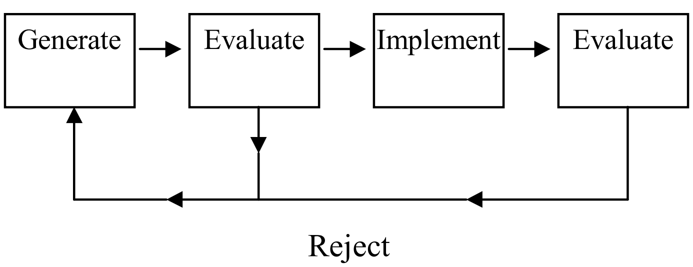

Figure 2. Experienced Designers' Pattern

The preliminary evaluation prior to implementation of the decision enabled experienced designers to avoid the longer process of trial and error. Experienced designers also carried out a number of activities that the novice designers did not. These are described below (see Table 1).

- Consider issues: Experienced designers considered the effects of implementing a decision on manufacturing, assembly, maintenance, etc. They would reject a decision, e.g. a choice of material, if the current manufacturer could not supply that material.
- Aware of reason: Experienced designers were aware of the reasons behind a particular component or a specific manufacturing process that was used in a particular design. They assessed the reasons and their applicability to the situation at hand. If the component or process was not necessary and leaving it out would help solve the problem at hand, the component or process would be removed or modified. This illustrates how the boundaries of the problem solution space could be expanded. The designers' problem space is thought to increase with experience. A specific example was the use of a cold expansion process, which caused difficulty in manufacturing. The designer was aware of the stress conditions that required this additional manufacturing process, and was confident that these conditions would not occur. He therefore decided that this process was no longer required. The experienced designers' understanding of the product they were dealing with (the engine) was also evident, as they were very aware of how a component affected the overall engine and its performance.
- Refer to past projects: Designers often referred to past projects when deciding to modify or remove a process or component, as described above. They would also refer to past projects to ensure consistency. A specific example was ensuring notes on drawings were consistent between projects.
- Question is it worth pursuing: This question was asked in relation to the implementation of a decision and also in relation to the design task. For example, the experienced designers would question whether reducing the weight of a component is worth pursuing, if only a small reduction was feasible.
- Have low confidence in data provided: Experienced designers questioned data provided to them. For example, how models were loaded was questioned before accepting the results of stress analysis.
- Keep options open: The experienced designers would reject an option, if it unnecessarily limited later options in the design task. However, they kept rejected options in the back of their minds in case they needed them later.
- Aware of trade-offs: Experienced designers were aware that many decisions are based upon compromises. For example, when trying to reduce weight, the cost of implementing such a solution would be considered. Their awareness of issues and how they related led to trade-offs.

3.3 Asking and Giving Advice

During the observations the designers gave, asked for and expressed the need for advice (refer to Table 2). They

Categories	Novice Designers				Experienced Designers			
	1	2	3	4	1	2	3	4
Express need for advice	■	◪	□	□	□	□	□	□
Ask for advice	□	□	◪	◪	□	◪	■	□
Give Advice	□	□	◪	□	■	◪	◪	□

Table 2 Asking and giving advice

spoke to colleagues, by phone or face to face as the need arose. The experienced designers were not hesitant in requesting information. When asked for advice experienced designers often referred to a different knowledge source. Baird and Marsh also observed the expert as a pointer to other knowledge sources [Marsh, 1997, Baird, 1999].

The novice designers expressed the need to talk to an expert, noting this down. This maybe due to a preference to ask the expert several questions at once, as opposed to approaching the expert often. Novice designer number 3 (in Tables 1 and 2) was more confident in asking questions. He was the most experienced of the novice designers. He kept a contact book with names of experienced designers and how they could be of use to him. He felt that he was more confident in approaching colleagues for advice than when he first started in design. He attributed this to having more knowledge and, hence, being more likely to understand the experienced designers. During his interaction with colleagues, he was observed asking for the reason for a particular component and process. He was obviously aware that he needed to know this.

3.5 Discussion

The results are tentative and further observations and interviews are being undertaken to understand the differences between experienced and novice designers in more detail. Many of the findings are in agreement with literature on well-defined complex problem areas, e.g. the process of keeping options open can be likened to an experienced chess player's ability to plan several moves ahead.

In order to develop support for novice designers, it is important to determine how each of the differences can be reconciled. A direct transfer of 'what experienced designers know and do' is unlikely to be successful, as the ability to apply this knowledge and approach depends on the existing knowledge and approach of the user (novice). After reference to the literature and considerable discussion, relative definitions of data, information and knowledge that take into account the user are proposed. These definitions provide insight into the differences between experienced and novice designers. The definitions are operational in that they can help to define the required support. Furthermore, a clear understanding of these terms is necessary to interpret the results of other researchers.

4. KNOWLEDGE, INFORMATION AND DATA

This section discusses the relationship between data, information and knowledge to help shed light on the differences between experts and novices.

4.1 Existing Definitions

Existing definitions of data, information and knowledge become inconsistent when examined in relation to one another.

Data are often described as *information* in numerical form [Benyon, 1990 in Court, 1995] or as one or more symbols which represent something [Court, 1995]. Information is described as *data* within a context [Court, 1995]. Nonaka and Takeuchi describe information as the flow of messages [Nonaka, 1995]. Confusion arises because definitions of data and information often refer to each other.

In general, definitions of information distinguish information from data through a context, implying that this context is present within information and not within data

The definition of knowledge is of interest to many research areas, such as philosophy, Artificial Intelligence, etc. Nonaka and Takeuchi expand upon the traditional definition of knowledge as 'justified true belief'. They emphasise the 'justified belief' viewing knowledge as dynamic (for a review of knowledge as discussed in western philosophy, refer to Nonaka, 1995). Knowledge is related to human actions and is created from a flow of messages [Nonaka, 1995].

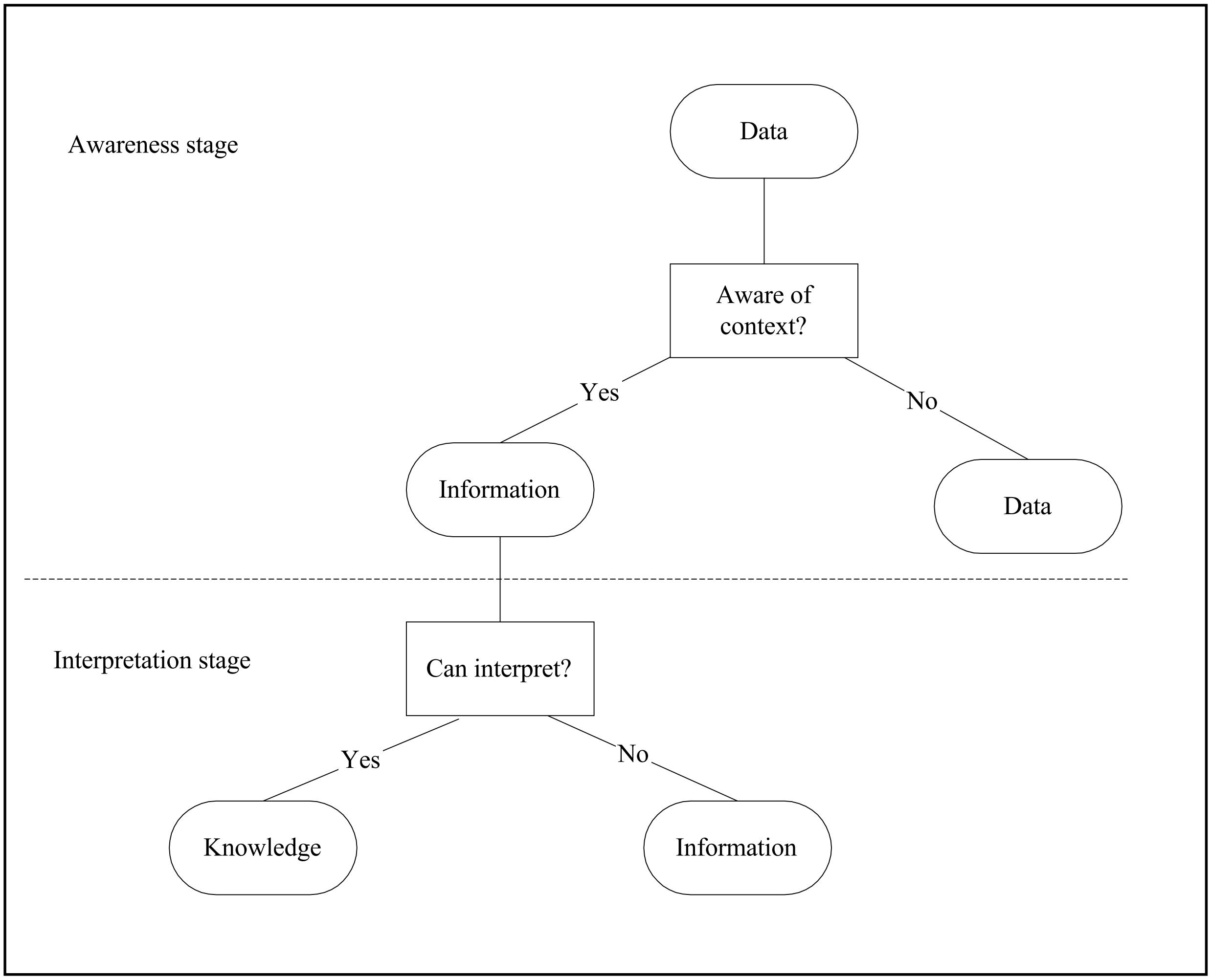

Figure 3. Data, Information and Knowledge Relative to the Potential User.

Knowledge can be held in a person's memory (internal), i.e. personal storage. Terms such as knowledge-based systems, etc., imply knowledge can also be stored externally. Wigg suggests knowledge can indeed be possessed outside of the human mind and also suggests *agents* are capable of beliefs and judgements [Wigg, 1999]. He describes knowledge as 'truths and beliefs, perspectives and concepts, judgements and expectations, methodologies and know-how and is possessed by humans or other agents'.

Some authors do not see the distinction between information and knowledge as an important one, e.g. Hubka and Eder [Hubka, 1996].

In general, the definitions given tend to be absolute definitions. These definitions are not useful for our purposes because they do not take into account what happens when a source and a user are involved.

4.2 Data, Information and Knowledge

Defining data, information and knowledge in absolute terms implies data is always data, information is always information, and knowledge is always knowledge. Defining in relative terms implies that, for example, information can be data for some users and knowledge for others.

It is concluded that data, information and knowledge are relative concepts and that these cannot be defined in absolute terms. The distinction between these terms depends upon the potential user of the data, information and knowledge. Examples of data as symbols and signals are used to illustrate and test this argument. Furthermore in engineering design, it is the use of knowledge that distinguishes experienced and novice designers. A third example taken from the observations is used to illustrate this.

From the definitions in the literature, the following characteristics related to data, information and knowledge were identified: meaning, context, and application. These are used to help understand the distinction between the terms.

Two stages are proposed to differentiate between data, information and knowledge: an awareness stage; and an interpretation stage (see Figure 3). During the awareness stage, an observer becomes aware of the data. If the observer is also aware of the context of the data, the data has meaning to the observer and hence is information. 'Context' is used to describe what is in the situation that can be used to resolve the intended

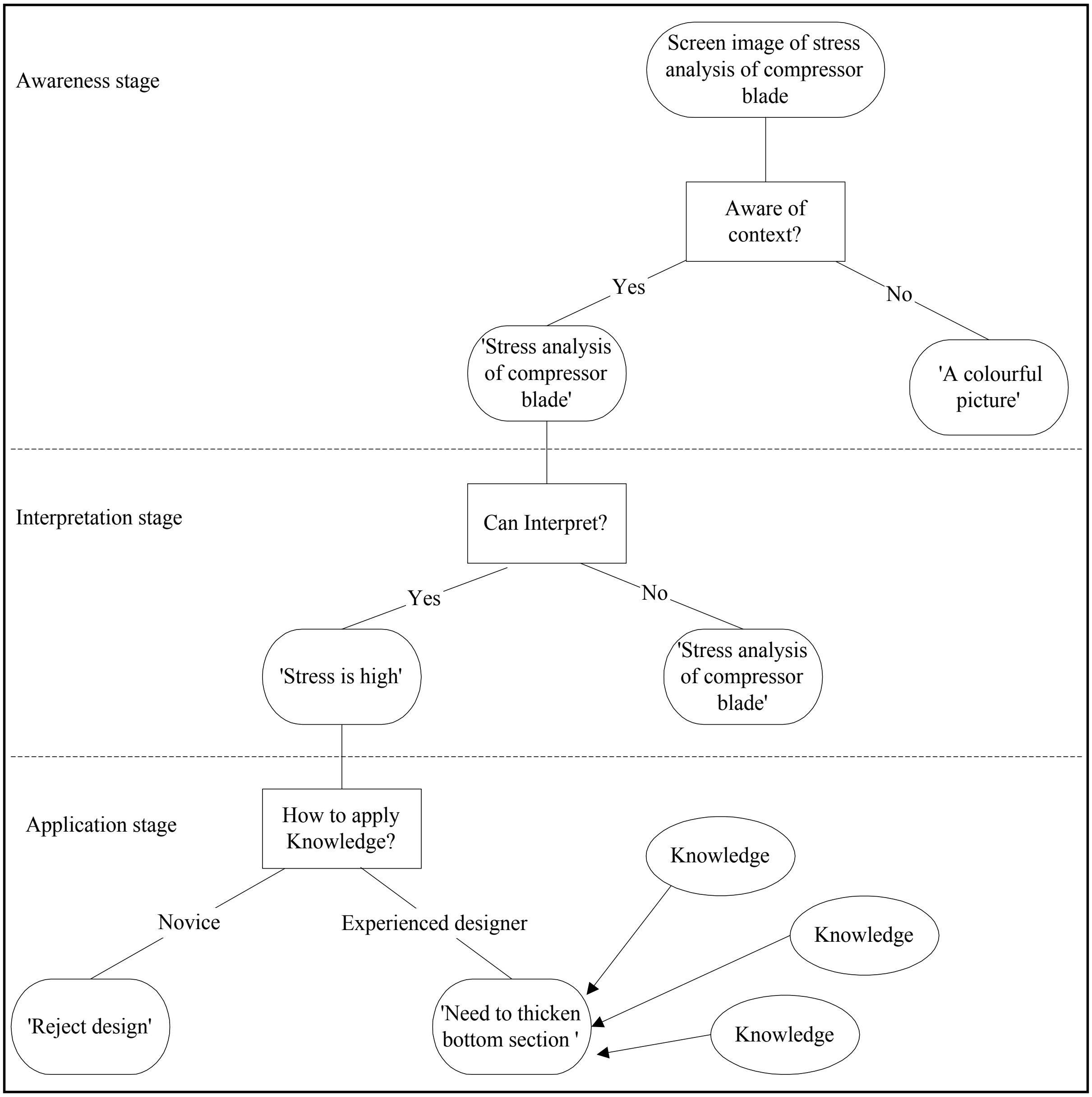

Figure 4. Stress Analysis of a Compressor Blade

meaning. If the observer is unaware of the context, the data has no meaning and hence remains as data (see Figure 3.).

The second stage involves interpretation. If the observer is able to interpret the information, the information can become knowledge. An observer is able to interpret if the observer can understand the language and the concepts, e.g. able to read a technical drawing, able to understand Japanese, etc. If the observer can not interpret the information, it remains as information, but has the potential to become knowledge if the observer learns how to interpret it.

4.3 Examples

As the first example of data as symbols, consider the case of a maintenance manual for a gas turbine engine written in Japanese (refer to Figure 3.). During the awareness stage, the observer is aware of the existence of the data, in this case a bound volume. If this volume is picked up by a technician who is unaware that this is a gas turbine engine manual (unaware of context) and does not recognise Japanese, the symbols on the page remain data as they have no meaning.

The same data becomes information in the mind of this user. If she is aware that she is looking at a maintenance manual written in Japanese (aware of context). For the manual to provide knowledge, the manual needs to be translated.

If the observer of the data is aware of the context and how to interpret the information, knowledge can be gained. In this example, the manual is information for someone who is aware of the context and knowledge of carrying out maintenance on a gas turbine can be gained.

Hence, information is dependent on an awareness of the context of the data. Knowledge is what is learnt after interpreting this information (although interpreting information is not the only source of knowledge).

A second example of data is a signal from an electrocardiogram (ECG) tracing the heart's beat. The signal is data to someone who is unaware that this is an ECG. If the signal is observed by the patient, who is aware that this signal is from the heart, the data becomes information. The signal is potential knowledge to a patient who is also a medical student and able to interpret the ECG. When the medical student interprets the ECG, he or she has gained knowledge of the heart's condition.

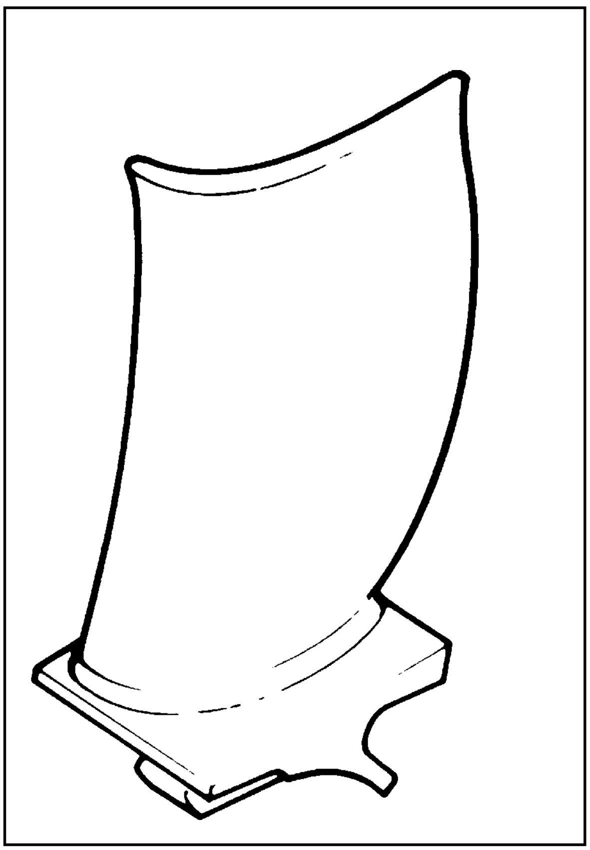

Figure 5. An example of a Compressor Blade

Research using 'empty novices', will find differences in these two stages (awareness and interpretation). However, in this research we are dealing with novices who have training but little experience in the investigated domains. In this case, the novice and experienced designers are both aware of the context of the data, and are able to interpret it. They can both obtain a piece of knowledge (a knowledge fragment) from data, e.g. the area of high stress on the blade from the output of an analysis programme. The difference between these novices and experienced designers becomes apparent during the use of the piece of knowledge gained. For this reason a third stage is added, i.e. the application stage (see Figure 3 and 4).

The third example comes from the observations and illustrates this difference. A novice and an experienced designer were designing a blade for the second-stage of a high-pressure compressor blade (see Figure 5.). A finite element analysis of the compressor blade resulted in a screen image of the blade in different colours. The stress analysis was used to decide how to proceed with the design.

An observer not trained in engineering is unaware of the context, and therefore doesn't understand that this picture shows a compressor blade and the stresses in this blade. For this observer, it is a 'colourful picture' (see Figure 4.). An engineering student who observes the data, would be aware of the context of the data, i.e. that this picture shows the stresses in a blade. The picture is information to the student. If the student is unable to interpret the results, he or she is unable to gain knowledge from it. Provision of a legend indicating how the colours relate to stress values and the knowledge of what is high stress may help the student to interpret the results. Then he or she can gain knowledge about the blade, i.e. 'stress is high'.

Both the novice and the experienced designer concluded that the stress was high at certain places in the blade. Not until they applied this knowledge did the difference become clear. During the application stage, the novice designer decided to reject the design as the stress was too high. The experienced designer used this knowledge fragment in a different way, and could have used this knowledge fragment in many different ways. Examples taken from the observations specific to the compressor blade example, illustrate how the knowledge fragment could be used (based on Table 1.):

- Consider issues: Adding a radius will reduce stress but the tool design will need to be changed.
- Aware of reason: The stress is high due to this sharp corner, it can be replaced with a radius.
- Refer to past projects: The compressor blade in the last engine had a similar level of stress, therefore this high stress is acceptable.
- Have low confidence in data: The stress looks too high, the way that the model has been loaded needs to be checked.
- Question is it worth pursuing: The stress is due to this sharp corner, we have to keep this feature, hence, this design is not worth pursuing.
- Keep options open: Adding a radius will reduce stress but will limit the choice of manufacturing processes.

- Aware of trade-offs: Thickening the bottom section of the blade will reduce the stress but will increase the weight. Therefore, we only want to reduce the stress a little.

The above example illustrates how the 'use' of the knowledge fragment 'the stress is high' depends on other existing knowledge which the designer has. This can be knowledge of facts, procedures and methods, strategies, and problem situations. This is one of the differences between novice and experienced designers (see Blessing, 1988). Giving novice designers knowledge fragments will not make them experts: the other knowledge which an experienced designer possesses is also required. A support system has to take this into account.

4.4 SUMMARY

To summarise, the observation of novice and experienced designers in a company environment revealed differences in the way they tackled design problems. Knowledge gained was used differently depending on other knowledge they possessed. This study highlighted the role of the user in determining what is data, information and knowledge. Data, information and knowledge are relative concepts that cannot be defined in absolute terms, as they are dependent on the user. The distinction between data and information is dependent on the users' awareness of the context. The distinction between information and knowledge is dependent on the users' ability to interpret the information. The actual usage of a knowledge fragment is dependent on other knowledge the user possesses. The availability of existing relevant knowledge characterises experience.

4.5 DISCUSSION

The number of observations of experienced and novice designers are currently too few. Planning observations has been difficult due to long project time-scales within the aerospace industry and gaps between projects. Initial analysis indicates that experienced designers evaluate decisions prior to their implementation. Further observations are required to identify what knowledge they use in this process, i.e. what knowledge needs to be captured to support novice designers and enable them to evaluate before implementation.

The paper focused on gaining knowledge from external sources. Other methods of gaining knowledge, e.g. from reasoning, have not been discussed.

The distinction between the terms data, information and knowledge that has been introduced was found useful to describe the differences between experienced and novice designers and is expected to help identify the type of support needed for novices to gain 'experience' faster. The presentation of the definitions in this paper is aimed at encouraging a discussion to support further development and refinement.

5. CONCLUSIONS

This paper has discussed data, information and knowledge focusing upon the distinction between them and the relationship between them, based on observations in an industrial environment. The paper highlights the vital role of the user in distinguishing data from information and knowledge, and consequently their usefulness. This helps to define the type of support needed to reduce the differences between experienced and novice designers.

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