INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'07
28 - 31 AUGUST 2007, CITE DES SCIENCES ET DE L'INDUSTRIE, PARIS, FRANCE

EVALUATION OF HOW DRED DESIGN RATIONALE IS INTERPRETED

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ABSTRACT
Documented design rationale is one of the key sources of information about past designs. Ease of comprehension of design rationale might play a crucial role in ensuring that the full potential of documented design rational is realised and the effort and time that go into capturing design rationale pay off. This empirical study explores how structuring textual information about design rationale and supplying it with visual non-textual cues influences reading comprehension. The study compares comprehension of technical documentation presented in different forms by engineering trainees in aerospace industry.

Keywords: empirical evaluation, IBIS, text interpretation and comprehension, aerospace engineering, knowledge management

1 INTRODUCTION
Aerospace engineering design relies heavily on the use of past experience. It is known that engineering designers frequently need to revisit previous design solutions and understand the rationale for their generation. Research into capturing and structuring the rationale for complex decisions dates back to the early seventies and Rittel's proposal of an Issue-Based Information System (IBIS) [1]. A new IBIS-based software tool called DRed (Design Rationale editor) has been developed by researchers at Cambridge Engineering Design Centre (EDC) [2, 3]. DRed allows designers to record their design rationale at the time of its generation and deliberation. The design rationale is displayed on a chart of the application's user interface as a graph of nodes linked with directed arcs. The user creates the nodes by choosing from a predefined set of node types. The key node types are: *issue*, *answer*, and *argument*. The software is already in regular use in design projects in an international aerospace company.

Current understanding of how DRed and other IBIS-based tools help designers to capture, structure and retrieve design rationale is based largely on informal evidence. A project to conduct a rigorous empirical evaluation of how DRed supports designers has been launched. Initial research to determine whether DRed improves the richness of the recorded information suggested that the engineering processes captured and structured in DRed, compared to those presented in Design Definition Reports (DDRs), are richer in the number of recorded design solutions and in the number of pro and con arguments underpinning those solutions [4]. This paper presents further research to explore whether the use of DRed makes the reading and interpretation of recorded information easier for those who would like to reuse it. The research consisted in evaluating reading and interpretation of DRed graphs (structured text) and a text with very few visual textual cues (semi-structured text) by measuring: (1) time taken to answer questions; (2) the completeness of the returned answers; and (3) the correctness of the returned answers. In particular, the specific research questions that this research investigated are: (1) Does the structure of the design information in a technical report affect the time to read, interpret and retrieve information from the report? and (2) Does the structure of the design information in a technical report affect the completeness and correctness of the information retrieved from the report?

2 READING AND INTERPRETING DESIGN RATIONALE

2.1 Design Rationale editor

DRed is a simple software tool that was developed to help designers to capture and structure new design rationale as well as in the reading and interpreting of past design rationale. DRed is intended to be complementary to and used together with analysis software, CAD, office and web applications. It facilitates the creation of a *design folder*, where all electronic information generated during a design project is stored. Information in the folder is structured according to the dependencies inherent in the design rationale.

As a design proceeds, the design folder for the project provides a place where a team of designers can store the emerging product definition, the ideas evaluated and accepted or rejected, clear rationale for these decisions, and all supporting documents. In its implementation, a DRed design folder is simply a directory, either personal or shared, containing at least one DRed chart. On completion of the project, the folder can easily be published on-line using a conventional web server, for future reference within the company.

DRed charts consist of a graph of nodes linked with directed arcs, which represents a traditional designers' notebook or formal design report. A typical design folder will contain a number of DRed charts, each one stored in a single file. Charts are zoomable, scrollable, two-dimensional canvases of unlimited extent scrolling rightwards and downwards. DRed elements (nodes) are created, positioned and linked manually by the user. The user chooses elements from a predefined set of types including *issue, answer, pro* and *con argument*. These are the IBIS element types that allow designers to record and present their rationale [5, 6]. Any element on a chart can be linked without restriction to any other, and any element can easily be converted from one type to another. There is only a single type of link, a unidirectional arrow, which represents a dependency of some sort. The precise meaning of that dependency is inferred from the types of elements at the ends of the arrow. Each element type has a predefined set of statuses, signified by changes in colour and geometry of the background shape or font style of the text. This gives a clear view of the progress of a design and allows the knock-on effects of revoked decisions, or the discovery of new information, to be propagated through the rationale.

Dependencies between elements that belong to different charts are represented by *tunnelling links*. These appear to tunnel into the chart and reappear in a different chart at the destination element. The tunnel entrance and exit mouths are shown as small circular icons, which are always created as a pair. Such links permit the rationale for larger design projects to be distributed across multiple charts and laid out legibly while facilitating navigation between them.

2.2 Current research to understand reading and interpretation from structured text

Research into how the structure of information influences comprehension is valuable for organisations and individuals that are engaged in education, news publishing, and delivering business information. This research received a powerful boost with the introduction of e-learning, which started with the advent of the World Wide Web and on-line hyper-linked documents. Despite the fact that engineering design documents differ in many aspects from a news article or from school teaching material, in the absence of specific data on engineering documentation it is important to be aware of the lessons learnt in the research of text comprehension in the above-mentioned domains.

Dickson et al. [7], in a review on the relations between the organisation of text and reading comprehension in an educational context, concluded that the effect of the presentation and structure of text on reading comprehension is more global that local, i.e. well-presented and structured text results in better comprehension of the main ideas, while having little or no effect on comprehension of details.

Duke et al. [8] point out that students should experience writing the range of genres educators wish them to be able to comprehend. Students should develop abilities "to write like a reader and to read like a writer". The following effective individual comprehension strategies are believed beneficial for developing readers: prediction (encouraging students to use their existing knowledge to facilitate their understanding of new ideas encountered in the text), think-aloud, text structure, visual representations of the text, summarization, questions/questioning.

These authors also mention the importance of student motivation and note that the level of motivation students bring to the task impacts whether or not and how well they will use comprehension strategies. The authors note that, given the growing use of hypertext, web links and texts that are webs of loosely coupled, but independently generated, texts, increasingly more material will have to be read in a nonlinear style, thus, in future text navigation may be linked with text comprehension.

Melville et al. [9] performed a trial of clinic letters. Structured letters were compared with conventional letters containing problem lists. The authors showed that a structured letter takes no longer to read, is strongly preferred by doctors, and improves comprehension. It may also train the reader to read subsequent unstructured letters more effectively. It is interesting to note that the authors found no correlation between reading time and recall.

Hypertexts allow for non-linear access to information, thus dividing information into smaller chunks and structuring it in the form of hierarchies or networks. McDonald et al. [10] studied the phenomenon of disorientation in hypertext, i.e. a situation when the user is unable to make informed decisions about which paths to follow in order to satisfy their information goals. Disorientation manifests itself in longer times to find the required information and a loss of accuracy. The authors stress that, despite these possible adverse effects during their immediate use, hypertexts are likely to help in tasks that require the use of long-term memory. Brown reported [11] that jumping between small sections of text has no detrimental effect on recall.

Vaughan et al. [12] studied the effect of time on navigation of certain types of web pages and showed that over time users increased their navigational exploration in their reading tasks and improved their navigational efficiency in their information-seeking tasks. The authors suggest that these improvements reflect the development of mental representations of information structure. Repeated exposure helped users develop these representations, which in turn helped improve their use of on-line sources.

Since DRed charts not only organise information in certain way, but also use visual notations (lines, arrows, geometric shapes and images), it is important to be aware of the influence graphical notations might have on comprehension. Whitley in her seminal paper [13] examined empirical evidence for and against the use of visual notations in programming. The cognitive complexity of programming and the fact that software development is a form of engineering makes findings and approaches in the field of visual programming very relevant for engineering design.

3 RESEARCH APPROACH

The evaluation consisted in conducting an experiment to compare how two groups of six engineering trainees read and interpreted a report to find the answer to a predefined question. The experiment consisted of undertaking four key steps as described in Table 1. The experiment was designed in this way in order to create a scenario as similar as possible to a real working situation, in which designers access past design rationale.

Table1. Steps of the experiment

Step	Action	Object
1	Reading	Question
	Interpreting	
2	Reading	Report
	Interpreting	
3	Retrieving	Information
4	Composing	Answer

Prior to the experiment the participants were split into two groups on a random basis. Both groups worked on four Design Definition Reports (DDRs), which were presented to them in the same order. The groups worked alternatively on two types of DDRs. The first type was the standard report generated using an office application (see Section 3.2). The second type was a structured report generated by the researcher reverse-engineering the same design information into DRed. This means that the information that each group received differed only in its representation. Standard DDRs present information within a predefined text template, which has several compulsory sections, whereas DRed-structured DDRs present the same information in the form of a graph, i.e. nodes that are linked with directed arcs. From now on, the two groups of trainees are referred to as group A and group B. Group A started the experiment with a DRed chart, while group B started with the same information presented in a Microsoft Word document. On the second question, group A worked with a Microsoft Word document and group B with DRed charts, and so on.

The answers obtained by the participants were evaluated based on the time required to retrieve them as well as their completeness and correctness. Table 2 presents definitions for the three metrics used in the analysis.

Table 2. Evaluation metrics

Metric	Definition
Time	Measures how much time a participant required to read and interpret a document in order to retrieve an answer to a pre-defined question. It is referred as 'retrieval time' in the text. It covers steps 2-4 in Table 1
Completeness	Measures how much relevant information a participant returned
Correctness	Measures how much of the information a participant returned was correct

All questions were complex and required answers that could be broken down into several forming *entities*. Therefore, completeness and correctness were measured by counting the number of correct and incorrect entities identified by the participants in each returned answer. The two metrics were defined as follows:

- Completeness (recall): number of correct entities in the answer given by the participant divided by the total number of possible correct entities in the document
- Correctness (precision): number of correct entities in the answer given by the participant divided by the total number of entities given by the participant.

3.1 Participants in the experiment

The twelve participants were engineering graduates undertaking the training programme provided by the collaborating company. Normally, the duration of the training varies between eighteen and twenty-two months. At the time when the experiment was conducted, the trainees were tackling the *Engineering Project*, one of the modules of the training programme with a duration of fifteen weeks. The first three weeks of the project focus on Product Lifecycle Management (PLM), engineering skills and project management, whereas the remaining twelve weeks are dedicated to the *Design and Make Project*. The participants were trained to use DRed during the first of the three initial weeks and participated in the experiment during the third week. It is important to emphasise that in the time between the training and the experiment the trainees did not have a chance to use the software.

3.2 Experimental set up

The experiment was conducted in one of the computer rooms at the Learning and Development Centre of the collaborating company. Prior to the start of the experiment, the researcher delivered a 20-minute presentation to the participants to explain the motivation of the research and to instruct them how to carry out the activity. After the presentation, each participant was provided with a PC (Windows) with a good quality large colour screen and a set of instructions. The participants were asked to work at their own pace. They were also informed that the time allocated for the activity was 90 minutes and that they could complete it in shorter time. The experiment was conducted from 4pm to 6pm, i.e. at the end of the working day. It is noteworthy that this time slot was chosen by the company contact.

3.3 The technical reports used in the experiment

DDRs are technical reports produced at the end of design tasks by the designers from the collaborating company. These reports capture the rationales behind the development of specific design solutions. The template for DDRs is predefined and designers write them using Microsoft Word. DDRs are generally structured into three main sections as follows: (1) specification requirement; (2) alternative solutions; and (3) final solution description. The reports also include a number of further sections, such as statement of compliance, risk and reliability, etc. It is important to state that the reports start with a summary of the solution and include graphs and images. The average length of a DDR is eight A4 pages. DDRs vary significantly depending on the nature of the design solution and the individual styles of their authors. Four DDRs were used in the experiment and the participants had to answer one question per report. These reports were selected in order to identify examples of design rationales that had been thoroughly documented. The design tasks undertaken by the designers who produced the DDRs were variant designs, which means that the work involved incremental innovation to extend existing product solutions. The topics addressed in the four DDRs are presented in Table 3.

Table 3. Topics of the Design Definition Reports

Report No	Topic
Report 1	Redesign of the spinner fairing assembly
Report 2	Redesign of the service pipe insulation system
Report 3	Redesign of the cruciform seal strip in the compressor
Report 4	Redesign of the cross-key outer segment in the combustor outer casing

3.4 Reverse engineering technical reports into DRed

Reverse engineering a DDR into DRed is a time consuming and difficult task. It generally requires developing an in-depth understanding of the design solution and identifying the issues considered during the design process and the solutions proposed, together with their dependencies. Figure 1 presents an example of a fragment of a DDR reverse engineered into DRed. All reports were reverse engineered into DRed by the same researcher, who was not an experienced DRed user.

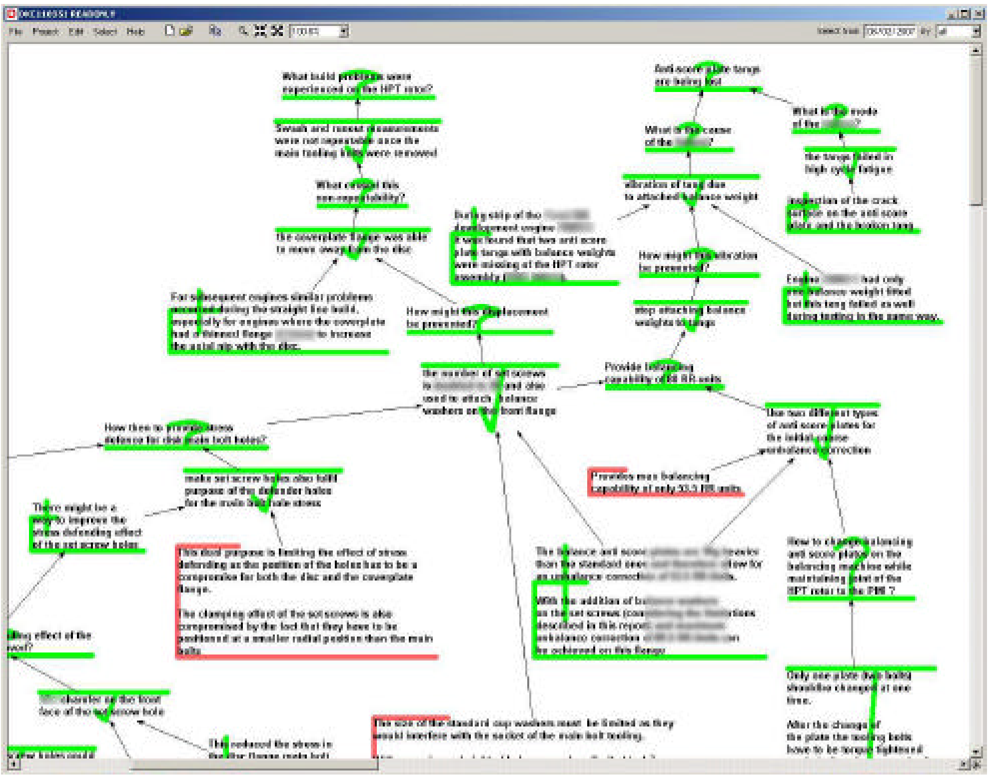

Figure 1. Fragment of a DDR reversed engineered into DRed (confidential information is blurred on purpose)

3.5 The questions used for the experiment

The four questions and their associated answers are presented in Table 4. The questions were presented to the participants in the order in which they are listed in the Table. The first question is answered by retrieving a set of *issues* associated with the design of the spinner fairing assembly. It is noteworthy that these issues are associated both with the specification of the requirements and the development of the final solution. The second question required that the participants identify the *methods* used by the actual designer of the pipe insulation system to solve the problem of carbon formation. The third question required identifying the *problems* that the designer of the sealing strips faced in attempting to tack weld the sealing strips. Finally, the fourth question required identifying the *reasons* to use a certain solution for the outer cross-key segment rather than an alternative one.

Table 4. Four questions and associated answers

No	Question	Answer	Number of entities
1	What issues were addressed in the design of the fairing? (the reader should find the requirements and other issues addressed)	Cost reduction, weight reduction, vibration avoidance, failure prevention, erosion avoidance, flutter reduction, impact resistance, balancing, tooling, assembling, interface, mounting, manufacturing	13
2	How was the issue of carbon formation addressed?	Jacketed insulation with sliding joints, extending insulation, straightening the pipes, finishing pipes surfaces	4
3	What problems arose in the attempt to tack weld the sealing strips to the vane packs?	Inspections of the vane, sealing strip assembly and weld penetration	3
4	Why was the 3-piece outer cross-key segment selected and not the 2-piece?	Spot welds are not strong enough to hold the 2-pieces of the assembly together, the plate metal used in the 2-piece assembly is expensive	2

The four questions differ in the type and amount of information required to answer them. The answers are constructed by analysing information from different parts in the associated document and identifying a set of *entities*. It is interesting that the larger the number of entities included in an answer, the wider the search undertaken to answer the question should be.

In the questions used for this experiment, the entities are in the form of *issues*, *methods*, *problems* and *reasons*, respectively. The researcher defined the entities before undertaking the experiment. In Table 4, the answers to the questions show a decreasing number of entities, with question 1 having a considerably higher number of entities than question 2, 3 and 4.

3.6 Application to capture the actions of the trial participants

The initial task consisted in identifying a list of requirements, which was as follows:

- to record the answers to questions
- to record time per question
- to ensure that the participants perform the tasks in a consistent and controlled manner
- to reproduce as closely as possible an order of user actions during information retrieval for work-related purposes (raise a question; find a report; retrieve information; compose an answer)
- to use a method for data collection that permits a trial with many people participating at the same time
- to install no new software and not use client-server applications
- to use software that requires the minimum learning curve for the participants.

After this initial phase, a solution was sought that would address as many requirements as possible. Microsoft Excel was selected because of its convenient event-driven programming model, its flexible and resizable grid that allows the entry and display of text of variable length, an easy access to system libraries (for capturing time), a possibility of further numerical data processing within the same application, and the fact that engineers often use MS Excel in their work and are familiar with its features. The Microsoft Excel workbook was programmed in such a way that the user first sees and evaluates the question and only afterwards the document; thus, the natural sequence of events in the information retrieval process is preserved.

The graphical user interface is presented as a vertical stack of four identical blocks, one block per question. Only one block is active, that is responds to user actions, at a time. Each block consists of a horizontal sequence of five Microsoft Excel cells, see Figure 2. When the user moves to a new question, all cells of the block but the first one are empty. The first cell contains a hyperlink. Pressing this hyperlink displays a question in the 2nd cell and a link to a document in the third cell. Once the user has evaluated the question, the link in the third cell should be clicked, which results in a relevant document being displayed on the user's desktop. The user types the answer in the 4th cell, and then presses the link in the 5th cell to indicate that the question in this block has been answered. At this point the cursor moves to the beginning of the next row where the link to the next question is displayed; the links in the previous row are disabled and the documents that were open for examination are closed automatically. Now the user can take a break if required. Time of clicking each link is recorded in hidden columns in the same sheet. Some protection is built into the workbook in order to make sure that time is not reset with repeated link clicking.

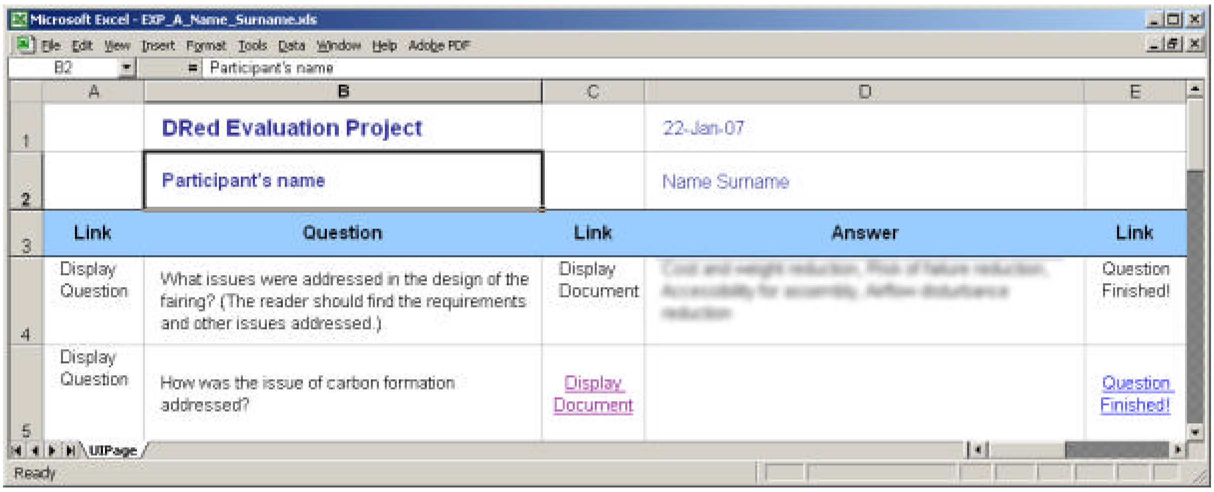

Figure 2. An application for evaluating reading comprehension (confidential information is blurred on purpose)

4 RETRIEVING INFORMATION FROM TEXTUAL AND DRED-STRUCTURED REPORTS

The answers returned by the participants were analysed using the three evaluation metrics, i.e. time, completeness and correctness. However, the results reported in this section focus only on time and completeness. The results for correctness are not reported because further research is required to fully interpret them. These two metrics were analysed and computed by two independent researchers in order to exclude possible bias in the data analysis.

4.1 Retrieval time and answer completeness

Figure 3 presents the results of the time required for the two groups to answer the four questions. Irrespective of the structure of the design information contained in the reports, the data indicate a pronounced downward trend in the average time taken to answer a question when moving from question 1 to 4. This trend can be explained by a number of factors: (1) the types of questions used in the experiment; (2) the order in which the questions were presented to the participants; and (3) the experience acquired by the participants while executing the experiment.

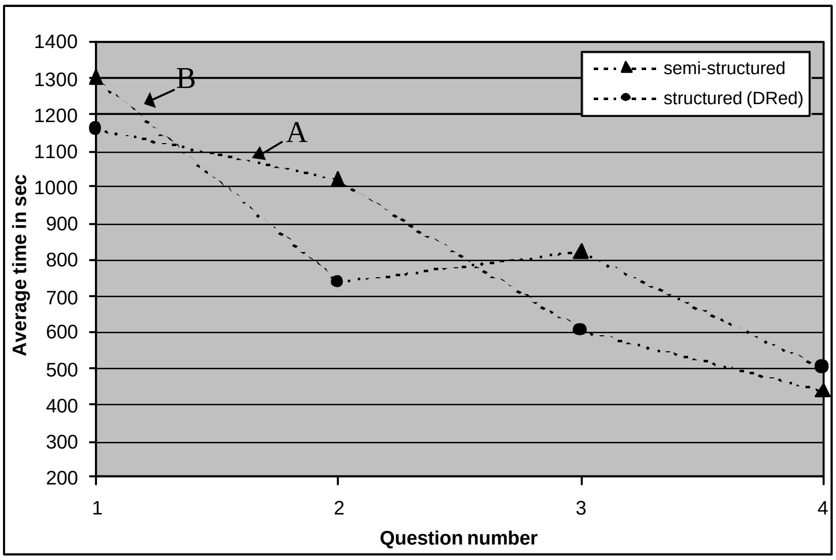

Figure 3. Average time to answer the four questions. The dotted lines show the progression of each group through the questions

In the first three questions, the times of the participants, who interpreted structured information, were always shorter than those of the participants who dealt with semi-structured information. In the final question this trend was reversed, but, taking into account large values of standard deviation for all average data, the difference is insignificant. The experience acquired by the participants while progressing in the task, possibly, accounts for this; section 4.2 lists more reasons in support of this explanation. Overall, these results suggest that structuring design rationale and breaking it down across interlinked charts slightly improves the speed of task execution.

However, a reduction in the time to answer questions can be considered an important result only if it is accompanied by a better retrieval performance. In order to investigate this key point, the answers to the four questions were analysed in detail. The analysis showed that a clear difference emerged in the performance of the two groups only when they tackled question 1, which required the identification of the highest number of entities. The answers to the remaining three questions did not allow the drawing of any definite conclusion as far as the performance of the two groups was concerned.

Figure 4 presents the results of the analysis undertaken to investigate the completeness of the answers to question 1. The fact that one of the twelve trainees did not participate in the experiment, as it was originally planned, created an asymmetry in the two groups. Figure 4 shows how groups A and B were composed of 5 and 6 participants respectively.

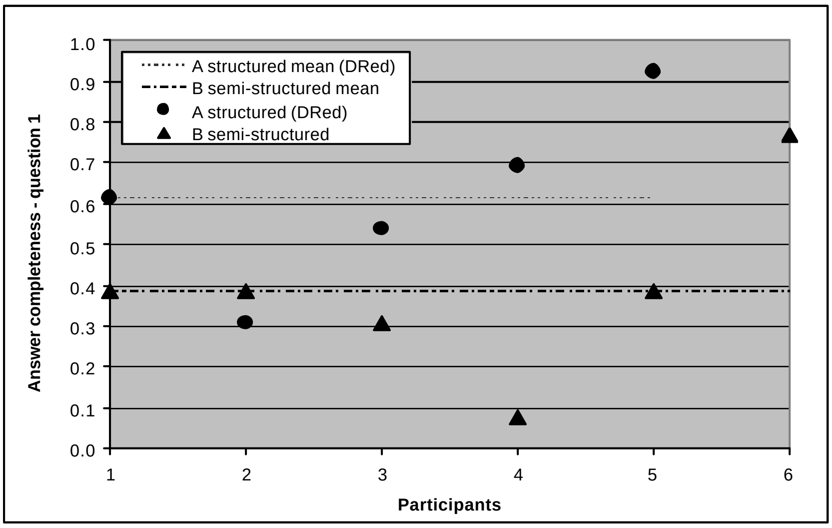

Figure 4. Answer completeness for question 1

The data indicate that the participants examining structured information performed considerably better than those examining semi-structured information, i.e. retrieving from structured information led to more complete answers. In particular, the mean completeness of the answers given by group A was 40% greater than that given by group B. This result suggests that structuring design rationale allows improving retrieval performance when the question requires identifying many entities and undertaking a wide search across the available information space.

This finding prompted the investigation of the dependency between answer completeness and retrieval time. Figure 5 presents the dependency of the completeness of the answer on the amount of time required by each participant to obtain an answer.

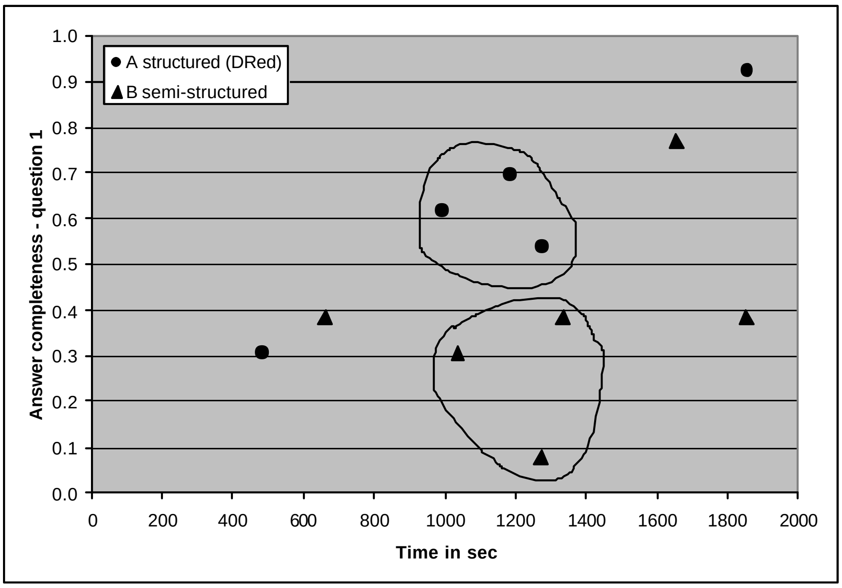

Figure 5. Answer completeness over retrieval time for question 1

The data clearly show that in the medium time (see circled data points) participants who used structured information gave more complete answers than those who examined semi-structured information. This result suggests that structured design rationale helps to improve cognitive performance for medium length searches. In addition, the data show that the best answers were the result of a thorough text examination, which resulted in longer times.

4.2 Effects of experience on retrieval performance

After analysing the average times to read and interpret information, the view emerged that experience plays a role in retrieval performance. It is interesting to note that the participants who started the experiment by examining structured information improved their performance with each consecutive question (see again Figure 3). In particular, on the fourth question, while examining semi-structured information, they completed the task in slighter shorter time than the participants who examined structured information. The participants who started with semi-structured information also improved their speed considerably, but in their case the differences in the speed of interpretation of structured and semi-structured information persisted for the duration of the experiment.

Further occurrence of this phenomenon was found when analysing the average completeness of the answers provided by group A and group B, see Figure 6. When the data in this Figure were plotted, the answers of one of the trainees in group A during question 3 and one trainee in each group during question 4 were disregarded. Their contributions at the end of the experiment were completely negative; possibly because of tiredness. This can probably be attributed to the time of the day when the experiment was conducted.

The data clearly indicate that on average the performance of the participants who started the experiment using structured information was always higher that those who started with semi-structured information. In particular, the percentage difference in the performances of the two groups decreased moderately from question 1 to question 2, decreased significantly from question 2 to question 3 and increased from question 3 to question 4. These results suggest that the individuals who started the task reading and interpreting structured design rationale developed better comprehension strategies for the analysis of DDRs. This phenomenon is in agreement with Melville's finding that interpreting structured information may also train the reader to subsequent interpretation of semi-structured information [9]. Melville attributed the enhancement in strategic reading to improved semantic processing.

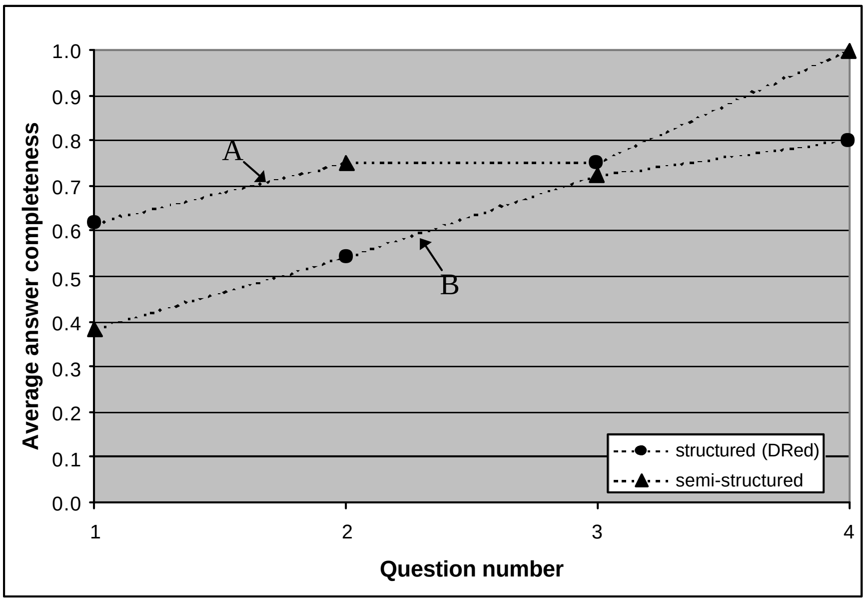

Figure 6. Average answer completeness

4.3 Limitations and applicability

This research was carried out on a small data set. This means that the findings presented in this paper are preliminary and have to be confirmed by further research.

The fact that the researcher who reverse-engineered the reports was neither an experienced DRed user nor an experienced engineering designer, may have had adverse effect on the quality of the information presentation. The bias that may have been introduced to the experiment by this would be unfavourable to DRed.

The fact that the participants were proficient users of the text editor, but had little experience of using DRed, had a number of repercussions. Some participants were observed using the search facility integrated in the text editor, whereas they appeared not to be familiar with the search facility provided in DRed. The copy and paste facilities of the text editor were used extensively by the participants; while most of them did not know how to use these facilities in DRed. These issues created an asymmetry in the way they searched for information and composed their replies. The cognitive load might have been unnecessarily high in DRed's case.

Regardless of the format of the report, in order to relieve load on their long-term memories, up to three different strategies were used by the participants: (1) text was copied and pasted from a source of information directly to its final destination in a Microsoft Excel spreadsheet; (2) a simple text editor (Notepad) was used as a temporary storage area for the text; (3) paper was used to write down some notes. A number of participants were observed using some of these strategies, while some of the participants, probably, did not employ these strategies at all. Whether the use of these strategies is consistent with an experiment on comprehension is open to a debate. Clearly, some sacrifices are inevitable when negotiating a trade-off between the purity of the experiment and the authenticity of the experience for the users.

In addition, the researchers also observed that the participants using DRed sometimes experienced difficulties in the navigation from one chart to the next. All the above-mentioned observations have to be taken into account when planning future reading comprehension experiments.

5 CONCLUSIONS

The complexity of current aerospace projects means that designers require support when retrieving and interpreting past design rationales. An IBIS-based software tool to support designers in this task is already in regular use in a major power systems company. The use of the software has also been integrated into the engineering training provided by the company for its yearly intake of engineering graduates. This has provided resources to evaluate how trainees use the tool. In particular, the focus has been on exploring how trainees interpret structured design information to retrieve answers to pre-defined questions. An approach was devised to evaluate the reading and interpretation of structured reports against those generated using the standard company practice. Preliminary results show that the use of the tool improves the speed with which recorded information is retrieved and results in more complete answers to questions requiring wider, more global searches. The research also indicates that reading and interpreting structured information helps to develop comprehension strategies and methods to retrieve information that individuals tend to use for semi-structured text.

6 FURTHER WORK

Further work could be undertaken determine:

- for which *types* of questions structured texts give better results
- the effects of experience on retrieval performance
- the trade-off between reading and interpretation time and retrieval performance for different types of information presentation
- the situation when designers are tackling more that one question at the same time.

ACKNOWLEDGEMENTS

The authors acknowledge the support of EPSRC and Rolls-Royce through the UTP for Design, and would like to thank Jim Wickerson, Michael Moss and all the trainees who evaluated DRed for providing valuable ideas and feedback.

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