

Researching Expertise Development in Complex Computer Applications

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RESEARCHING EXPERTISE DEVELOPMENT IN COMPLEX COMPUTER APPLICATIONS

INTRODUCTION

This chapter describes research in the three-dimensional computer aided design (3D-CAD) context outlining the factors that need consideration when choosing appropriate knowledge elicitation techniques and research methodologies for the types of learner/computer interactions that occur. The teaching of Technology Education progressively involves greater use of computer technology. Computers are now commonly used to enable students to control devices such as lathes, mills and robots, to acquire data for input into the process of improving the solutions to problems, to design new products through the use of 3D-CAD, to design and test electronic, hydraulic and pneumatic circuits, to store and present information, to access information via the internet, and as a means by which learning material is presented, tested and recorded through computer based instruction. However, despite the plethora of new software with which both technology students and teachers interact on a daily basis little research has been undertaken that seeks to understand, in any systematic way, the nature of the cognitive interaction involved, or the manner in which students can progress from using the software at a relatively simple or superficial level to efficient or expert software use. In order to undertake this research new knowledge elicitation techniques need to be employed that will help to gather the detailed data that enables generation of an understanding of the cognitive processes and human-software interactions involved.

The research outlined in this chapter formed a part of a larger study designed to devise and test methods that may improve the use of expert strategies by novice users of 3D-CAD. This task involved identifying expert 3D-CAD users and then identifying the cognitive strategies used by those experts. The research therefore needed to be grounded in the cognitive psychology literature on both expertise and knowledge elicitation. Expertise, in order that the data collected reflected expert use of the software and was therefore valid, and knowledge elicitation so that the data collected was sufficiently rich and reliable for effective analysis of the cognitive skills involved. This approach is supported by Taylor (in Evans, 1991 pp. 170-171) who maintains that the first stages of any research into the novice-expert shift should entail;

Identification of the cognitive skill performance that is the ultimate objective of instruction;

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Analysis of expert performance of this skill in terms of the content, structure and organisation of the underlying declarative knowledge base;
Design of instrumentation to measure salient aspects of this declarative knowledge base and associated actual cognitive skill performance. (Taylor, in Evans, 1991, pp. 170-171).

The first stage of this process involves the identification of individuals for inclusion in the research in order to ensure valid data is collected. In the case of the type of research being discussed in this chapter, research into the expert use of computer software, it becomes even more critical as the knowledge being sought relies on the initial subject(s) being not just users but expert users.

Expertise

Matlin (2005), Mieg (2001) Sternberg (1990) and Sternberg and Grigorenko (2003) argue that experts, unlike novices or advanced novices, possess high levels of domain knowledge, well developed cognitive structures in the form of schemas, the ability to recognize large numbers of domain specific patterns, a propensity to represent problems at a deeper more structured level and prominent use of executive control or metacognition during problem solving. It is hypothesised that expertise in 3D-CAD exhibits similar characteristics and it is therefore critical that experts be identified, as other users may not possess the cognitive structures that characterize expertise in the 3D-CAD domain.

There are potential difficulties associated with the identification of computer software expertise, and 3D-CAD expertise in particular. Mieg (2001) supported by Charness and Schultetus (1999) define expertise as “consistently superior performance on a specified set of representative tasks for the domain that can be administered to any subject” (Mieg, 2001, p.76). The criteria suggested for expert selection include distributions on tests (Charness & Schultetus, 1999), peer nomination (Mieg, 2001), or experience (Charness & Schultetus, 1999). For 3D-CAD, as with many other areas of complex computer software use, these methods present difficulties due to the absence of tests across the various software applications and the lack of data available for peer nomination through related professional associations. Charness and Schultetus (1999) also point out that experience does not always equate with expertise, a position supported in the CAD research of Bhavnini and John (1997) who found that experienced CAD users often persisted in the use of sub-optimal strategies. Hoffman, Shadbolt, Burton and Klein (1995) and Schraagen, Chipman and Shalin (1999) observe that there is a scarcity of true experts, but make the observation that “articulate experts with recent experience in both performing and teaching the skill are particularly useful” (Schraagen, Chipman & Shalin, 1999, p.6).

The criteria that may be effective in the identification of experts therefore are: superior performance on tests, peer nomination, experience and recent teaching

experience (Charness & Schultetus, 1999; Mieg, 2001). However, test performance has been found to be impractical in the 3D-CAD domain. On this basis, and taking cognizance of the expertise literature, criteria for the identification of potential research subjects for this 3D-CAD research were developed as follows:

- They have a number of years experience in the domain.
- They currently use 3D-CAD on a regular basis.
- Others regard them as possessing domain expertise.
- They have experience in teaching/training others.

Subject Selection

Using the criteria established above the selection of subjects was undertaken. Two different methods were used in this process. Firstly, subject identification was undertaken via an advertisement in a specialized CAD magazine with nation-wide distribution. The magazine editor was supportive of the research and provided free space for the research description and a call for volunteer participants who would meet the selection criteria. Four subjects were identified through this process, however, data collected from three of these subjects proved unusable as they were unable to complete the modelling process, indicating that they were not as expert as hoped. A second identification process utilised individual CAD vendors known to the researcher. These were contacted in an effort to identify further subjects who would meet the selection criteria. Three additional subjects were identified through this process. The four subjects for the study were therefore considered to meet the selection criteria for expertise in CAD. In addition, these subjects used a range of 3D-CAD programs thus providing data that would be independent of specific software. The processes of eliciting expert 3DSM-CAD knowledge from these subjects in order to undertake detailed analysis of the nature of 3DSM-CAD expertise are discussed below.

Knowledge Elicitation

The processes and validity of data collection, or knowledge elicitation, are critical in the type of research under discussion. Cooke (2000), for example, points out that:

unlike performance-critical applications such as expert systems, applications like training that go beyond knowledge use to the transfer of knowledge, require more attention to the validity of elicited knowledge (Cooke, 2000, p. 481).

Cooke (2000) provides an overview of knowledge elicitation methods outlining four alternative methods; verbal reports, observations, interviews, and process tracing, noting that each method has inherent advantages and shortcomings. Each of these processes is discussed in the following section.

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Verbal reports

Verbal reports involve the subject documenting their cognitive processes either orally or in written form. Ericsson and Simon (1993) propose verbal reports as a suitable method “to study superior performance on specific tasks under controlled conditions and to assess the cognitive processes, knowledge and acquired mechanisms that mediate the superior performance of experts” (p. XXXVIII). Verbal reports may take a number of forms: concurrent oral reporting during the process of performance, often referred to as think-aloud protocols; retrospective reports in the form of either recorded verbal or written reports following performance; or a structured or unstructured interview whereby the researcher seeks to gain insight into cognitive processes via specific questioning of performance (Cooke, 2000). Each of these types of verbal reports is now discussed.

Think-aloud protocols

In the think-aloud process the subject undertakes a specific task (in the case of this research the production of a 3D-CAD model) while at the same time talking out aloud saying everything that they would otherwise say to themselves. Think-aloud verbal protocols thus enable the researcher to gain information from the expert while they are in the process of performing the task. While this may be advantageous, there is some concern (Cooke, 2000, Gordon, 1992; Hoffman, Shadbolt, Burton & Klein, 1995) that the process of verbalising may affect task performance and that the information gathered may not provide the necessary insight as many of the expert's cognitive processes may be automated. It is suggested (Cooke, 2000) that concurrent verbalizing can only report current consciousness and not explanations or interpretations. To attempt to do anything else may interfere or in fact change the thought processes of the individual. Thus automated processes or information regarding perception or retrieval may not be collected accurately in this manner but would need to be inferred from the information collected. Rowe (1985) points out “the analysis of ‘thinking aloud’ protocols does not provide a complete description of the problem solving process. It is, however, a method which permits the externalization of certain covert processes, and thereby provides the investigator with an initial tool” (p. 106).

Ericsson and Simon (1993) outline three levels of verbalisation. Type 1 involves “vocalization of covert articulatory and oral encodings” (p.79); Type 2 “involves description, or rather explication of thought content” (p.79); and Type 3 “requires the subject to explain his thought processes or thoughts” (Ericsson & Simon, 1993, p. 79). These authors provide an analysis of the efficacy of verbal reports as data claiming that verbalizing of Type 1 and Type 2 thoughts is found to have little effect on task solving performance. Where some effects may be evident, they pertain to speed and accuracy, neither of which are considerations in this research. However, Type 3 verbalization, due to the fact that the reasoning processes are

articulated, has been found to affect the problem solving process. Ericsson and Simon (1993) therefore claim that it is imperative that very specific instructions are given to participants in order to ensure that only Type 1 and Type 2 verbalizing is undertaken by the subject. The suggested wording of instructions includes;

I will ask you to talk aloud as you work on the problems. What I mean by talk aloud is that I want you to say out loud everything that you say to yourself silently. Just act as if you are alone in the room speaking to yourself (Ericsson & Simon, 1993, p. 376).

The nature of the instructions given to participants is therefore important in order to ensure that the problem solving process remains valid. The issue of overall validity of data gathered via verbal protocols is discussed below.

Validity of verbal protocols

Ericsson and Crutcher (1991) point out, in relation to the validity of data collected through think-aloud protocols, that it is:

difficult to seriously argue that the verbal reports are not a valid model for generating the correct answers to the problems. Such a critical claim must assume that the subject used one model to generate the verbal report and a different model to generate the problems solution, when, in fact, the model used to generate the report is sufficient to generate the problem solution as well (Ericsson & Crutcher, 1991, p. 67).

Based upon their extensive review of the literature on verbal protocols as data, Ericsson and Simon (1993) propose six assumptions upon which verbal protocols are based. These are:

The verbalized cognitions can be described as states that correspond to the contents of STM (short term memory) (p. 221)

The information vocalized is a verbal encoding of the information in short-term memory (p. 221)

The verbalization processes are initiated as thought is heeded (p. 222)

The verbalization is a direct encoding of the heeded thought and reflects its structure (p. 222)

Units of articulation will correspond to integrated cognitive structures (p. 225)

Pauses and hesitations will be good predictors of shifts in processing of cognitive structures (Ericsson and Simon, 1993, p. 225).

Ericsson and Simon (1993) conclude “the information that is heeded during performance of a task, is the information that is reportable; and the information that is reported is information that is heeded” (p. 167) thus supporting the validity of the collected data. Ericsson and Simon (1993, pp. 171-172) provide a number of means by which the validity of the data may be confirmed when undertaking analysis of the data. The relevant questions are:

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1. Were the processes in the verbal protocol necessary for the solution of the problem – if so the data is reflecting the cognitive processes involved and not being generated as an independent process? The data could therefore be considered a valid representation of the cognitive processes involved.
2. Are the verbalizations relevant to the task?
3. Are the verbalizations relating to the preceding ones?
4. Are the verbalizations consistent with information previously mentioned – if so they are accessing the same memory?
5. Are the verbalizations consistent with perceptual information – not using cues such as eye movement as in prior research but recoding screen capture of image and mouse movement?

If these conditions are met, Ericsson and Simon (1993) argue that validity of the verbal protocol data is established.

Retrospective reports

A retrospective report is one where “the subject focuses on the task until its completion and then recalls, as accurately as possible, the sequence of thoughts that occurred while doing the task” (Ericsson & Crutcher, 1991, p. XVI). In relation to the process of knowledge elicitation of expert 3D-CAD processes there are a number of potential problems with collecting retrospective reports. Ericsson and Simon (1993) point out that for tasks longer than 0.5-10 seconds’ duration the sequence of thought will lack completeness and accuracy. As the completion of a 3D-CAD model is often a quite long process, well in excess of the duration suggested by Ericsson and Simon (1993), this presents a potential problem for the validity of the collected data. Cooke (2000) and Rowe (1985) also highlight a number of potential difficulties with retrospective reports that may also affect the validity of data collection in the current research. These are: there may be a difference between the described method and the actual method; the process of recording the description orally may be unfamiliar or rushed resulting in essential information being omitted; and the process of recording the description in written form may be extremely time consuming, imposing a further impost on the experts that they may be unwilling to undertake or may again rush, resulting in incomplete data. Retrospective reports were thus considered problematic as a valid knowledge elicitation method for 3D-CAD.

Interviews

The use of interviews as a method of knowledge elicitation is, according to Cooke (2000) a “direct way to find out what someone knows” (p. 487). Cooke (2000), Gordon (1992) and Hoffman, Shadbolt, Burton and Klein (1995) outline two methods by which interviews may be undertaken, unstructured interviews and structured interviews. Gordon (1992) argues that these methods, in the main, elicit declarative and not procedural knowledge, a position supported in part by Cooke (2000) who explains that considerable skill and training may be necessary in order

for interviewers to use unstructured interviews or the highly specific interview methods necessary in order to gain insight into an expert's procedural or strategic knowledge.

Hoffman et al. (1995) describe an unstructured interview as “an open dialogue in which the interviewer asks open-ended questions about an expert’s knowledge and reasoning” (p. 134). This technique, according to Cooke (2000) and Hoffman et al. (1995), may enable the researcher to elicit a wide variety of data regarding declarative, procedural and metacognitive knowledge through the inclusion of open-ended (what, why, how) questions. However, the disadvantages of the unstructured technique include the need for interviewer training, the possibility of the interview getting ‘off the track’, the possibility that the expert may assume that the interviewer has a knowledge of the domain and the exhaustive nature of the data collected that will need transcription and analysis (Hoffman et al., 1995).

Structured interviews, on the other hand, are designed and planned in advance in order to provide a greater focus on domain specific information. They rely on the interviewer having knowledge of the domain but, according to Hoffman et al. (1995), have the advantages that the interview time is reduced and specific declarative and procedural domain knowledge may be elicited. Cooke (2000) and Hoffman et al. (1995) describe a number of forms of structured interview. In a scenario simulation interview, the expert is presented with a problem and the interviewer walks the expert through the problem solving process. The use of questions such as “Why would you do that?”, “How would you do that?”, “What alternative strategies could you use? will, according to Hoffman et al. (1995), help to elicit domain procedures and reasoning rules. An alternative structured interview strategy is to use event recall whereby the expert is asked to explain a particular past event or events. These events may be either typical or particularly salient or difficult cases. Hoffman et al. (1995) argue “probed recall of past tough or salient cases can be very effective in revealing experts’ knowledge, especially their tacit knowledge and reasoning strategies” (p. 136).

Cooke (2000) posits a number of advantages for the use of verbal descriptive reports for knowledge elicitation. In relation to the elicitation of expert 3D-CAD knowledge the interview method has two advantages. It saves time on the part of experienced users and therefore potentially gains more cooperation, and it provides the opportunity to request experienced users to use an alternative strategy from their initial preference. Analysis of these data enables the researcher to discover whether the strategy chosen initially is linked to the functions available within the software package being used or is independent of them.

However the use of interviews may have a number of disadvantages. Firstly, there may be a difference between the described method and the actual method of software use that could affect the validity of the study. Secondly, the method of operation described may not actually work within the software environment

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therefore also affecting the validity of the study. These validity issues may only be reduced if the interviewer has well developed domain knowledge of all the specific software being used. Finally, the description provided may concentrate too much on the surface processes without providing sufficient insight into the automatic processes employed. Schraagen, Chipman and Shalin (1999) support this notion in that experts may often not have “direct conscious access to their relevant knowledge and skills” (p. 8).

A number of alternative knowledge elicitation methods utilising verbal reports has been described and their merits and shortcomings in relation to expert 3DSM-CAD knowledge discussed. These methods include; think-aloud protocols, written and verbal retrospective reports, and, structured and unstructured interviews. Cooke (2000) and Ericsson and Simon (1993) argue that, provided specific conditions are met, each of these techniques is capable of providing valid data. For this research it is decided to use think-aloud protocols. Think-aloud protocols enable the capture of data during the process of completing a 3D-CAD task avoiding the potential problems associated with retrospective reports.

An additional method, process tracing, may also be applicable in the 3DSM-CAD environment. This process is discussed in the following section.

Process tracing

Schraagen, Chipman and Shalin (1999) describe the 'process tracing' method as an observational method of data elicitation. Further Cooke (2000) defines process tracing as “the collection of sequential behavioural events and the analysis of the resulting event protocols so that inferences can be made about the underlying cognitive processes” (p. 490). The strength of process tracing, according to Cooke (2000), is that the data are collected, providing the researcher is unobtrusive, in a natural setting, thus enabling the actual expert behaviour to be viewed. Data collection may be undertaken via direct observation and recording by the researcher or more commonly through an alternative method such as video recording. This data collection method may have the advantages, in the case of 3D-CAD expertise, that:

- the actual process of software use is recorded thereby providing a more authentic understanding of the procedures employed,
- the relationship between the software strategy being employed and the particular stage of the process would also be available to the researcher.

It may have the disadvantages that:

- subjects may not have the available technology necessary for the recording process,
- the time and inconvenience involved in establishing the recording process may mitigate against subjects volunteering to be involved in the study,
- subjects may feel constrained due to the recording process,

- the process can be costly,
- rich data associated with lengthy data collection sessions mean that data analysis may be unwieldy, time consuming and interpretation difficult (Cooke 2000; Schumacher & Czerwinski, in Hoffman, Ed. 1992).

In order that process tracing may be employed as a knowledge elicitation method for this study the disadvantages outlined above would need to be addressed. In addition the recommendation of Schraagen, Chipman and Shalin (1999) to include the “collection of verbal think-aloud protocols while the SMEs [subject matter experts] perform a representative set of task problems” (pp. 8-9) needs consideration. Adopting both methods would combine the benefits of the think-aloud process outlined above with process tracing. This combination would provide a very rich data source and facilitate the linking of verbal and visual data thus enabling each data source to validate the other. The validity of the verbal protocols would be able to be appraised in accordance with the criteria established by Ericsson and Simon (1993), noted earlier: applicability to the solution of the task, relevancy to the task and consistency with perceptual information.

In their summary of data collection methods Schraagen, Chipman and Shalin (1999) point out that in the choice of a suitable knowledge elicitation technique it is important that the process needs to be “easy and natural for the subjects” (p. 469). In choosing a process tracing method this would require a recording method that took into account the needs of the subjects and the potential logistic difficulties presented to the researcher by having subjects in widely disparate locations. For this and economic reasons video recording was rejected. Following the recommendation of Cooke (1999, p. 501) that “unlike traditional knowledge elicitation and task analytic methods, methods that focus on computer-recorded events can amass data in the background, posing little threat of interference to task performance” a number of computer software options was identified that allowed for the process of recording to be achieved. These included the Lotus product “ScreenCam”, Microsoft “Camcorder” and the TechSmith product “Camtasia” that are commonly used for the production of computer-based instruction or product promotion material. In each case the software enables the capture of all computer operations as they occur in real time on the screen and records them in a video format. They all have the additional feature of being able to record sound at the same time in the form of voice-over.

These products were evaluated therefore as having the potential for process tracing. For each, the software could be readily installed on the subject’s computer, and a microphone supplied, so that the subject could record think-aloud protocols as they undertake the production of a 3D-CAD model. Once the recording process is commenced the software recedes into the background and remains unobtrusive while the 3D-CAD task is undertaken. All computer actions and think-aloud protocols are recorded without further subject intervention. Once the 3D-CAD

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task is complete the subsequent video is then saved to a CD-ROM and returned to the researcher for analysis.

Tests of each of the software packages were undertaken to ascertain their effectiveness. While each was capable of performing the necessary function “Camtasia” was chosen as the preferred option for a number of reasons. Firstly, it was the only package useable over a range of computer operating systems. This was an important factor, as subjects working in industry, in particular, often run their CAD software on alternative systems, such as Windows NT, in order to obtain network stability. Secondly, it was also available in a time restricted trial version via the Web, thus overcoming the potential problems associated with software licensing. The trial version could be downloaded to CD and supplied to subjects with instructions for installation. Thirdly, the resultant video file was in a form readable on almost any computer thus enabling ease of analysis. Process tracing using “Camtasia” software, with the addition of think-aloud protocols, was therefore considered an appropriate combination of knowledge elicitation methods for this study.

Methodology

The knowledge elicitation method of process tracing with concurrent think-aloud verbal protocols was used while subjects completed a set modelling task (this task is described below). It is argued that this method is appropriate for collecting declarative command knowledge and specific procedural command knowledge. It also enables the identification, through both direct and inferential techniques, of strategic knowledge but not the reasoning processes underlying the procedural knowledge. The design of the task used in the study needed to meet a number of criteria. The task was sufficiently complex to challenge the expert while, at the same time, the modelling process would not be taking too long to complete. In this manner the expert would be engaged in, but would not feel compelled to devote excessive amounts of time to the process. The task incorporated a number of parts, both main and peripheral, so that parsing needed to occur and decisions regarding the category of part (main, peripheral) and the order of part generation could be made. The individual parts were capable of being modelled using a number of different algorithms so that choices of strategy would be made and opportunities existed for efficiencies of production to occur through a strategic approach. The designed model is illustrated in Figure 1 below.

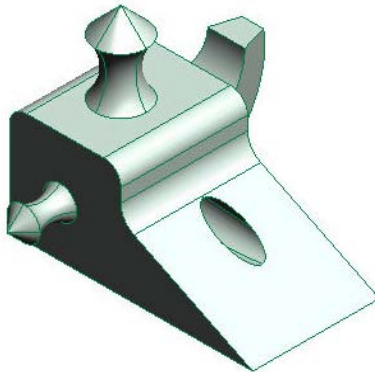


Figure 1. CAD Task

Data collection for the subjects was undertaken in their individual workplaces without the presence of the researcher. This procedure was chosen due to the disparate locations of the subjects and in order to overcome the possibility that the presence of a researcher may have inhibited the verbalisation of the subject. Subjects were provided with a package of materials including: instructions for the installation of the Camtasia software, drawings of the object to be modelled, CD ROM containing the software and onto which the data was to be saved and returned for analysis, a headset microphone for use when undertaking the process tracing and think-aloud protocols and a stamped addressed envelope for the return of the CD ROM.

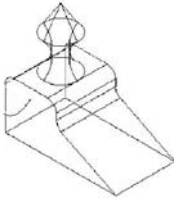
During the construction of the model, data capture using video capture, with associated verbal protocols, was undertaken. Consistent with the findings of Ericsson and Simon (1993) specific instructions were given to the subjects to avoid the possibility that they would try to explain their reasoning. Subjects were instructed to “talk aloud constantly from the time you see the problem until you have generated the solution. I don’t want you to plan what you say or try to explain what you are doing” (Ericsson & Simon, 1993, p. 376). Further, subjects were instructed to trial the use of the video capture software with their CAD system prior to actual data capture so that they would gain experience in the process of verbalising their thoughts while they undertook a CAD task. Subjects were also instructed to undertake the process of data collection alone. These procedures were incorporated into the instructions so that subjects became more comfortable with both the data capture and concurrent verbalisation processes. Analysis of the expert data gathered through this knowledge elicitation technique was designed to provide insight into the cognitive processes undertaken by CAD experts involved in the process of constructing 3D-CAD models. The process of data segmentation prior to analysis is described in the following section.

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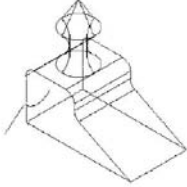
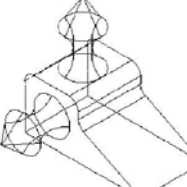
Data segmentation

Verbal protocols were fully transcribed and individual images representing the sequential development of the computer model were captured from the video. These data were placed into a table with the image placed in the cell adjacent to the verbal protocols. In this manner the verbal protocols relating to the particular image were identified. Data segmentation for the purposes of analysis of the data from the study was thus undertaken on the basis of changes in the perceptual or screen image. When a noteworthy change in the screen image was generated by the subject a new row was inserted into the table and the particular image inserted into cell three of the row. It is important to note that the images in the table are representative only of a dynamic on-screen process. The full verbal protocol was inserted in cell two of the row. Individual thoughts are represented as sentences, or clauses; pauses are represented as a series of periods. The analysis of the CAD and cognitive processes is included in cell 6 of the row and the coding for CAD and cognitive operations are inserted into cells four and five respectively. (An example of the data segmentation and coding for Subject 2 is illustrated below in Table 1). The individual coding is described in the following section.

Table 1. Example data segmentation and coding - Subject 2.

| | Verbal protocol | CAD Image | Code 1 | | Analysis |
|--|---|---|--------|-----------|---|
| | | | CAD | Cognitive | |
| | <p>and let's trim it off. Now we need to trim off and select these as a smart line and it is continuous now.</p> <p>We need to delete the last little bit if we can no!! no!! no!! UNDO!!</p> |  | | MS CM | <p>Mental subtraction is used to ascertain which sections of the line/circle need to be removed to get the correct profile.</p> <p>Following the deletion process the result is checked for accuracy.</p> |

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| | | | | |
|---|---|-----------|------------------------|---|
| <p>That I said drop ... I didn't say drop a line string!</p> <p>Delete that last little bit.</p> <p>Okay we've done that now let's revolve that.</p> <p>Oh bugger!!! I didn't join them up while I had the chance.</p> <p>Take that point and that one finished.</p> |  | <p>RS</p> | <p>CM MS E</p> | <p>Following checking the operation is undone and reconstructed correctly. Imaging of correct mental subtraction enables this process to be corrected.</p> <p>Rotation sweep enables the completed shape to be imaged prior to competing construction.</p> <p>Subject evaluates the process used.</p> |
| <p>Let's revolve this little sucker yep axis of revolution</p> <p>yep yep yep yep done.</p> |  | <p>RS</p> | <p>CM</p> | <p>Subject uses rotation sweep in order to generate the desired solid from the produced profile, the direction and extent (number of 90° sectors) of the operation is imaged and constructed.</p> <p>Resultant construction is then checked.</p> |

For explanations of codes, see below.

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Coding the protocols for CAD and cognitive processes

Data collected needs to be coded so that the number the cognitive process used by the experts may be quantified, inferences may drawn about and nature the processes undertaken and comparisons made between the experts. Coding of the data for this project was undertaken through an analysis of both the verbal protocol and the video images and a summary table for each subject was generated identifying a number of different categories of CAD processes and cognitive processes. These categories are identified on the basis of previous research in both cognitive science and the particular domain under investigation are described in the following section.

CAD process categories.

A number of separate CAD processes are used in 3DSM-CAD modelling and were therefore able to be identified within the data from experts engaged in the study. These CAD processes were identified through the algorithmic processes chosen by the subjects and through the on-screen image manipulations evident in the video.

- Multiple View [MV] - creating multiple views
- Rotation Object [RO] – rotating the CAD model to a new orientation.
- Rotation Sweep [RS] – creating a solid object by rotation of a cross-sectional shape around a central axis.
- Rotation on Path [RP] – creating a solid object when a cross-sectional shape is rotated or swept along a path or axis to produce, for example, tubular shaped objects.
- Rotation of Individual Surface [RIS]
- Construction Extrude [CE] – extruding an object
- Object Resizing [OS] – changing the size of an object.
- Construction Lofting [CL] – using a number of planar shapes to generate a solid object. This process is sometimes referred to as blending.
- Mirror Imaging [MI]
- Geometry Identification [GID] –identifying the geometry necessary to produce a give solid.
- Geometry Construction [GC] – constructing specific geometry.

Cognitive process categories.

In this study it was hypothesised that the strategic knowledge of 3DSM-CAD experts is characterised by the use of a range of mental imagery and metacognitive processes and these divisions were used as a basis for analysis. The following cognitive processes involving mental imagery were identified in the data:

- Mental Deconstruction (including parsing) [MD]
- Core Part Selection [CP]
- Mental Construction [MC]

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- Mental Subtraction [MS]
- Spatial Positioning [SP].

The following metacognitive processes were identified in the data:

- Planning [PL] – planning or goal setting (Anderson, 1993)
- Strategy Selection [SS] (which CAD strategy or algorithm to use) (Bhavnani 2000; Bhavnani & John, 1996)
- Predicting Consequences [PC] (Gaughran, 2000; Rodriguez, Ridge, Dickinson & Whitwam, 1998)
- Checking / Monitoring [CM]
- Evaluation [E] (Veenman & Verheij, 2003; Resnick, 1976; Sternberg, 1990).

Analysis

The data for Subject 2 on the study is used below as an example. Subject 2 successfully completed most aspects of the modelling task in a time of 32 minutes 59 seconds. The ‘horn’ shape was unable to be modelled by this subject due to a combination of an inability to find an alternative algorithm in the software and unwillingness to spend the time necessary to calculate the size change for the transition that would have enabled the construction of the part using the algorithm with which the subject was familiar. Table 2 presents a summary of the CAD processes, cognitive processes involving mental imagery and metacognitive processes used by Subject 2.

Table 2 Subject Two – CAD and Cognitive Process Totals

| CAD Processes | | | Cognitive processes involving mental imagery | | |
|---------------|--------------------------------|-----|--|---------------------------------|-----|
| Code | | No. | Code | | No. |
| MV | Multiple View | | MD | Mental Deconstruction - Parsing | 9 |
| RO | Rotation of Object | 9 | CP | Core Part Selection | 1 |
| RS | Rotation Sweep (Revolve) | 5 | MC | Mental Construction | 9 |
| RP | Rotation on Path | | MS | Mental Subtraction | 11 |
| RIS | Rotation of Individual Surface | | SP | Spatial Positioning | 14 |
| CE | Construction Extrude | 3 | | Metacognitive Processes | |
| OS | Object Resizing | 1 | Code | | No. |
| CL | Construction Lofting | 1 | PL | Planning | 2 |
| MI | Mirror Imaging | 1 | SS | Strategy Selection | 1 |

| | | | | | |
|-----|-------------------------|--|----|-------------------------|----|
| GID | Geometry Identification | | PC | Predicting Consequences | |
| GC | Geometry Construction | | E | Evaluation | 4 |
| | | | CM | Checking/Monitoring | 24 |

Analysis shows that Subject 2 engaged in a range of CAD processes during the construction of the model. These processes include those aspects of both declarative command knowledge and specific procedural command knowledge needed to undertake the specific task. In addition the two expected categories of cognitive processes were evident. Subject 2 engaged in a range of mental imagery supported processes specifically related to the controlled selection and execution of appropriate CAD algorithms. These processes include high instances of spatial positioning, mental subtraction, mental construction and mental deconstruction. These mental imagery processes were undertaken in order to visualise methods by which the model or the geometry could be constructed and to visualise the relationships between various parts of the model.

Accordingly, subject 2 utilised frequent checking and monitoring strategies, a number of which were associated with the CAD process of object rotation. This technique was used to enhance the process of checking and monitoring progress through re-orientation of the partially completed model in order to view it from a specific viewpoint. Subject 2 engaged in a number of evaluative processes thereby identifying when alternative modelling strategies would have been more efficient.

Discussion

The knowledge elicitation methodology of process tracing with concurrent verbal protocols using video capture software was found to be particularly effective in the acquisition of fine grained data. These data were able to identify both the declarative knowledge and specific procedural command knowledge of 3D-CAD experts. In addition this methodology enabled the identification, both directly and through inference, of the use of a range of metacognitive processes used by 3D-CAD experts. These included the automatic parsing of objects into algorithmically salient parts and a range of visualisation techniques used to identify the process by which the object might be modelled (e.g. mental construction and mental subtraction) and checked for accuracy (e.g. mental rotation). The findings also demonstrate that the 3D-CAD experts, in a similar fashion to experts in other domains, made frequent use of a range of the metacognitive processes of planning, strategy selection, predicting, checking and monitoring. The remaining key issue identified through the study was the expert 3D-CAD strategy of selecting modelling approaches that used algorithmic commands such as fillet or round for model generation, in preference to geometry, in order to maintain model integrity and make the model easier to modify at a later time in the design process.

The methodology developed for this study will have application in research involving complex computer applications other than 3D-CAD. In order to gain additional data regarding the cognitive processes undertaken by subjects, it is possible that the technique could be modified and used to overcome the disadvantages of collecting think-aloud protocols which may interfere with the cognitive processing of the individual when undertaking complex tasks. For example this technique could involve video-capture of the initial modelling process and initial analysis by the researcher. Video-capture could again be used while the initial video-capture file is replayed to the subject in a process of stimulated recall while recording verbal protocols of explanations for the strategies that were used. The initial video could be paused to enable detailed explanations and individual aspects highlighted through mouse movements. The result would be a video of a video that included the verbal protocols of the stimulated recall. Final analysis by the researcher could then follow with the original video and the stimulated recall data in the one file. Further discussion regarding the efficacy of stimulated recall as a research methodology is found in Chapter #.

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