

3D-CAD: MODERN TECHNOLOGY – OUTDATED PEDAGOGY?

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3D-CAD has now become an integral part of Technology Education in Schools. It will be argued in this paper that the current pedagogy associated with the teaching of 3D-CAD (Three-dimensional Computer Aided Design) is outdated and inappropriate for the purposes for which 3D-CAD is now employed in Technology Education. That is, 3D-CAD is now viewed as a tool to be utilised in the development of design solutions rather than merely in the process of constructing working drawings for the creation of design solutions. This means that CAD models need to be produced in a manner that enables future design changes and iterations to occur without affecting the integrity of the model. This paper will discuss a reconceptualisation of the knowledge association with 3D-CAD and the subsequent effect this may have on the teaching strategies employed in the teaching of 3D-CAD in schools. Further it will propose pedagogical strategies, based on successful research, that have been found to improve the ability of novice learners to produce 3D-CAD models that remain robust following design changes.

Introduction

It may be hard to believe but 3D-CAD has now been taught in secondary schools for more than twenty years. My personal experience dates back to around 1984 with the introduction of the British architectural package 'Scribe' into schools in Canberra, Australia. Despite a brief, and totally unsatisfying, foray into 2D-CAD in the late 1980's I have been teaching 3DCAD to students, undergraduate Design and Technology teachers and teachers ever since. In late 2001 I began coordinating ProDesktop training throughout Australia on behalf of the Industrial Technology and Design Teacher's Association and I am now involved in ProEngineer training for schools. Throughout my career I have now taught with multiple releases of at least seven different CAD platforms. I mention these facts in order to provide a context for an admission that for the majority of this time I taught 3D-CAD in the manner I was taught. That is, teaching how to use 3D-CAD through a process of learning algorithms – this is how to extrude, this is how to revolve etc. However, in consequence of current research into CAD teaching and learning and the changing role of CAD in Technology Education it is time to question the effectiveness of this pedagogy.

Recent changes in the availability and affordability of 3D-CAD software has meant that new features are now available that potentially change the manner in which it may be used in Technology Education. First it creates a solid model rather than a folded-up series of surfaces and is therefore able to be used for a range of additional processes such as the calculation of engineering data and for direct interface with equipment capable of production of the part itself. The introduction of affordable computer controlled machinery targeted at the education sector now enables secondary schools to engage in direct production from 3D-CAD

models. Secondly, and more importantly, the parametric nature of the software enables design changes to be made to the model at any time, regardless of the order of initial generation, with consequent changes to the model being calculated and automatically updated by the software. Thus both the dimensions and shape of an object may be changed at a later time without effecting processes such as the rounding of corners or the position of holes that were modeled when the initial design concept was established. This parametric capability increases the opportunity to incorporate design changes readily without the time consuming need to generate complete new models and is therefore more applicable to the design and problem solving pedagogy associated with the teaching of technology in schools.

The change in the availability and capability of 3D-CAD software for schools now means that CAD has moved from being a drafting tool to a design tool for use by students in the production of initial design ideas and in the subsequent refinement of those ideas. However, has the pedagogy changed to take into account the changes in software and the nature of its use in Technology Education? In order to gauge the appropriateness of the pedagogy it is first necessary to understand the nature of the 3D-CAD knowledge that is to be taught. This necessarily involves an understanding of expertise and 3D-CAD expertise in particular.

3D-CAD Expertise.

Research with experts in chess, electronics, figure skating, dance, music, bridge and computer programming, to name a few, highlights a number of characteristics of expertise. Experts have:

1. High levels of domain knowledge (Matlin, 2005; Sternberg (1996)
2. Superior speed of task performance (Chi, Glaser & Farr, 1988)
3. Superiority of both short and long-term memory in their domain of expertise (Sternberg, 1996)
4. The ability to do “automatically” things that non-experts find difficult or impossible (Sternberg & French, in Hoffman, 1992; Sternberg & Grigorenko, 2003)
5. The ability to recognize large and meaningful patterns in the domain of their expertise such as chess (Chase & Simon, 1973; Cooke, Atlas, Lane & Berger, 1993; de Groot, 1965), electronics (Egan & Schwartz, 1979), music (Sloboda, 1976), bridge (Charness, 1979; Engle & Bukstel, 1978) and computer programming (McKeithen, Reitman, Rueter, & Hirtle, 1981)
6. The ability to utilize the executive control processes of planning, monitoring and revising while undertaking much of the other information processing automatically and in parallel with these processes (Gott, 1989; Klahr & Kotovsky, 1989; Matlin, 2005; Newell & Simon, 1972; Sternberg, 1999; Sternberg & Grigorenko, 2003; Stevenson, 1984).

The first four of these characteristic are common to almost all the literature on expertise and would therefore be also expected of a 3D-CAD expert. It may also be expected that, in a similar manner to chess experts who recognise patterns of pieces on a board, 3D-CAD experts would recognise shapes that could be modelled through the use of various algorithms. The final characteristic executive control, or metacognition, has gained considerable support in recent research into expertise (Brown, 1975; Card, Moran & Newell, 1983; Evans, 1991; Gott, 1989; Newell & Simon, 1972; Resnick 1976; Sternberg, 1990; Stevenson, 1984). Metacognition or executive control is viewed as the process whereby decisions are made regarding the selection and order of individual procedures utilized in the process of problem

solving. Gott (1989) describes strategic control knowledge as “how-to-decide what-to-do-and when) knowledge” (p. 100).

CAD researchers such as Bahavnani (2000), Bhavnani and John (1997, 1996), Bhavnani, John and Flemming (1999), and Lang, Eberts, Gabel and Barash (1991), have identified two types of CAD knowledge, commonly referred to as command knowledge and strategic knowledge, as being critical to performance. Lang et al. (1991) describe declarative knowledge for CAD work as being knowledge of “the facts of the situation and would include knowledge on the object being designed and knowledge about the particular commands which can be used on a particular CAD system” (Lang et al., 1991, p. 257). However CAD researchers include in their conceptualisation of declarative CAD knowledge, knowledge about features, commands and algorithms, which include elements of procedural knowledge in order, for example, to invoke specific commands or algorithms. This conceptualisation of declarative CAD knowledge is therefore a mixture of both declarative and procedural knowledge.

Research by Chester (2006) reconceptualised 3D-CAD knowledge to include three types of knowledge. The first two types of knowledge, declarative command knowledge (knowledge that) and specific procedural command knowledge (knowledge how) are based on Ryle’s (1949) classical differentiation and its application in contemporary cognitive theory (e.g. Anderson, 1990). The third category, strategic CAD knowledge is an outcome of the fact that in CAD, as with other complex computing applications, there are often multiple methods available for the completion of a single task. According to Bhavnani (2000) strategic knowledge is “knowledge of these alternative methods and how to choose between them” (p. 339). The knowledge of these alternatives is declarative command knowledge and the knowledge of how to execute the relevant procedures is specific procedural command knowledge. Chester (2006) proposed that 3D-CAD strategic knowledge be reconceptualised to include, in addition to choosing between alternative algorithms, a range of metacognitive processes such as planning, predicting, checking, monitoring and analysing. According to Chester (2006) 3D-CAD knowledge should therefore be reconceptualised to include three types of knowledge: declarative command knowledge, specific procedural command knowledge and strategic (or metacognitive) knowledge.

- Declarative command knowledge is knowledge about the commands or algorithms that are available within 3D-CAD. Thus, an individual may know for example that it is possible to mirror lines, copy objects and create a solid by extrusion. This knowledge is general in nature and is applicable across the majority of CAD software. You need to know about these algorithms before you can do them and you need to know they exist so that you can find them in a new piece of software.
- Specific procedural command knowledge is knowledge that enables the operator to execute the necessary commands to, for example, mirror lines, copy objects and create a solid by extrusion within specific CAD software. Specific procedural command knowledge thus varies from one CAD software package to another and may also vary from one version of a CAD software package to another. This is the type of knowledge concentrated on in 3D-CAD instruction however this type of knowledge changes and may therefore become redundant and need to be relearned.
- Strategic 3D-CAD knowledge includes a range of metacognitive processes. Metacognition is generally accepted to include process such as planning, monitoring and revising and I have confirmed this in 3D-CAD experts. In addition my findings indicate that due to the parametric nature of much of today’s 3D-CAD software experts engage in more predicting. This occurs in order to ensure that the choice of

algorithms will enable the construction a model that will maintain its integrity during subsequent production and allow for later ease of design modification. In the words of one expert the choice of modelling strategy depends on whether “it is easy to change”. For this reason it was also found that 3D-CAD experts tend to minimise the use of geometry in favour of the use of algorithms. For example, they will round the edge of a solid rather than fillet the geometry used to develop the solid. (Chester, 2006)

What are the implications of this reconceptualisation for 3D-CAD pedagogy? There is a need to rethink the way we teach 3D-CAD to place more emphasis on the development of strategic knowledge at the same time as specific procedural knowledge is learned. In this manner students will be better able to cope with changes; changes in the design of the object as technology education problem solving progresses, changes from one 3D-CAD package to another and changes from one software version to another.

3D-CAD Pedagogy

Recent CAD research has identified that while much may have changed in CAD technology, little has changed in the instructional methodologies employed, with the majority of current instruction, text support, software manuals and tutorial material still concentrating on step-by-step acquisition of command or content knowledge. Bhavnani and John (1996), in their review of the manuals provided with CAD software, concluded that these manuals include detail regarding specific commands but not the strategies required for their efficient use. Bhavnani and John (1996) maintain that this practice is often reinforced in the introductions to software manuals where CAD is described as an expansion of the drawing process. The introduction is then followed by command descriptions that further reinforce the link between manual and CAD operations. In this manner, command knowledge is expanded but strategic knowledge is not (Bhavnani & John, 1996). They conclude “in training CAD operators, either through the use of manuals or coursework, most of the emphasis is on teaching declarative knowledge with little emphasis on procedural knowledge” (Lang, Eberts, Gabel, & Barash 1991, p. 257).

This instructional strategy makes the assumption that the acquisition of specific procedural command knowledge will subsequently enable the user to create all the 3D models they require efficiently. However, it is clear from the research of Bhavnani and his associates that the development of strategic 3D-CAD knowledge does not occur as a natural outcome of the acquisition of specific procedural command knowledge. Bahavnani (2000) argues, “knowledge to use direct manipulation tools does not seem to aid users to perform complex tasks efficiently. Several studies have shown that despite training and many years of experience, many users with basic command knowledge do not progress to an efficient use of applications” (p. 338).

A synthesis of effective approaches to CAD instruction is therefore still needed, especially since there is clear evidence that specific procedural command based instruction does not provide the expected advances in efficiency. In relation to these types of command and strategic CAD knowledge three important factors have emerged. First, as already outlined, is that the majority of current CAD teaching concentrates almost exclusively on the acquisition of specific procedural command knowledge. This has been a consistent finding by Bhavnani and his associates (Bahavnani, 2000; Bhavnani, Flemming, Forsythe, Garrett & Shaw, 1995; Bhavnani & John, 1996; Bhavnani, John & Flemming, 1999). This conclusion is supported by Lang, Eberts, Gabel, and Barash (1991), Rodriguez, Ridge, Dickinson, and Whitwam

(1998) and Yue (1999), who point out that there are in excess of 1,100 commands in some CAD packages making the acquisition of command knowledge a major focus of manuals and training programs at the expense of strategic knowledge. “Students are so busy learning the commands that little time is available for acquiring other kinds of information such as procedural knowledge” (Lang et al., 1991, p. 257). A second factor that relates to the use of both command knowledge and strategic knowledge is that inefficiencies in the strategic use of the software are not always evident in the final product (Bhavnani & John, 1996). For instance two models may be identical in appearance but one may have taken considerably longer to produce, and in the case of 3D-CAD, be much more difficult in which to effect subsequent design change than the other. The third factor is that there is emerging evidence that, when specifically taught, strategic knowledge may improve CAD performance (Bhavnani, John & Flemming, 1999; Bhavnani, Reif & John, 2001; Lang, Eberts, Gabel, & Barash, 1991).

The major development of CAD technology occurred in the 1970-1980's and, although this was also the period when a major transition from behaviourism to cognitive psychology occurred in education, the majority of instructional practice was yet to adopt the cognitive approach comprehensively. The dominant instructional technique, under the influence of behaviourism, remained didactic and transmissive, and as such this was the approach adopted for CAD teaching. Behaviourism advocated the didactic approach whereby content was broken down into individual behavioural steps that were then presented to learners in a carefully sequenced order. It was assumed under this method that learning all the individual steps, and providing sufficient practice, would lead to mastery of the domain. What does the CAD research tell us? It highlights a number of things:

1. The didactic approach is still the dominant pedagogy in both education and industry. Bhavnani and John (1996) Lang, Eberts, Gabel, and Barash (1991) (Bhavnani, 2000; Bhavnani & John, 1996 & 1997; Bhavnani, John & Flemming, 1999; and Bhavnani, Reif & John, 2001) Wilss (1994) Sadat-Hossieny (2001) Sexton (1996) Rodriguez, Ridge, Dickinson, and Whitwam (1998) and Yue (1999)
2. Initial teaching plus experience does not lead to the development of expertise – experienced CAD users still use sub-optimal modelling methods that are often time consuming and difficult to modify. Bhavnani (2000) Lang, Eberts, Gabel, and Barash (1991)
3. Expertise in CAD is not differentiated by levels of command knowledge (e.g. knowledge of the steps involved to extrude – most people can learn the steps in a sequence) but by the application of strategic knowledge (knowing what alternative modelling strategies are available and how to choose between them). (Bhavnani, John & Flemming, 1999; Bhavnani, Reif & John, 2001; Lang, Eberts, Gabel, & Barash, 1991)

The following section describes research into a pedagogical approach that has been shown empirically to improve the strategic 3D-CAD knowledge of novice users.

Developing and testing a new 3D-CAD Pedagogy.

The methodology for the study involved a two group post-test design using self allocation of subjects to groups and random allocation of ‘treatment’ and ‘control’ groups. Group randomization was established through analysis of a prior experience questionnaire administered before the commencement of the intervention. Teacher exposition and

demonstration of specific procedural command knowledge was consistent for both groups and in order to ensure consistency further, the same worked examples and student exercises were presented to both groups. In addition specific strategic knowledge, parsing and mental imagery training were provided for the ‘treatment’ group. This training was embedded into the specific procedural command training while the additional time for the ‘control’ group was devoted to procedural command practice.

Since the production of 3D-CAD models is essentially a cognitive activity it is appropriate that a cognitive apprenticeship model be used as a framework through which to develop the strategic thinking abilities of 3D-CAD users. Metacognitive training was embedded into the training of declarative command knowledge and specific procedural command knowledge, in a manner consistent with the arguments of Gott (1989) and Sternberg (1990). Consideration was given to specific instructional strategies to develop parsing (the ability to deconstruct a model into the component parts that may be modelled using the algorithms availability within 3D-CAD software), mental imagery and metacognition through: outlining of parts, explicit verbal description of perceptual differentiation, sketching, image manipulation, expert teacher modelling, scaffolding, cooperative and group problem solving. The inclusion of each of these instructional strategies is addressed in the following sections.

Parsing

The development of CAD expertise requires not only that algorithmic salience (which parts can be modelled using each 3D-CAD algorithm) can be recognized but also that alternative algorithms can be identified within a particular shape so that procedural decisions can be made. This implies the need for explicit teaching of the parsing process to novice 3D-CAD users. Two techniques by which the process of parsing may be taught are suggested by the literature. Firstly Braunstein (1989) and Schyns and Murphy (1991) argue that outlining parts with either a pen or a computer mouse is effective in identifying relevant parts following categorization instruction. The second parsing instructional method is suggested by Norman, Le Blanc, and Brooks (2000) who cite evidence in the medical field that;

“noticing these supposedly obvious features is difficult and is strongly influenced by contextual factors. Both experts and students gained 20% in diagnostic accuracy by having the key, clearly visible features verbally described for them. Both experts and students reported seeing from 15% to 30% more of these features when diagnosis was suggested to them. The informal report by experts and students alike was that they had simply not noticed features that seemed clear when they were pointed out” (p. 112).

It was decided therefore that the intervention should adopt both of these suggested approaches. That is, instruction in the process of parsing for algorithmic salience should involve pre-exposure to perceptual differentiation, teaching the specific features that identify instances of a shape that can be modelled by an algorithm, verbally describing these features during the process of parsing and then giving student the opportunity to practise the process of parsing through outlining of parts.

Mental imagery

Anecdotally, teachers report that many students cannot recognize how to model individual parts thus they have difficulty with basic command knowledge. Nor are they able to ‘see’ alternative modelling methods that may enable them to be strategic and therefore efficient in

their 3D-CAD use. Both of these problems appear to be related to the inability to visualize possible approaches to the modelling process. This suggests that there could be a relationship between an individual's spatial ability and their ability to use 3DSM-CAD. The relationship between mental imagery ability and CAD is a complex one. Alias, Black, and Gray (2002), Sorby (1999) and Yue and Chen (2001) argue that a positive relationship exists between an individual's spatial ability and their ability to use 3DSM-CAD. There is also an assumption (Ault, 2003) that visualisation skill will be improved through the use of solid modelling. However the research of Ault (2003), Gaughran (2002), Sorby (1999) and Yue and Chen (2001) conclude that working with CAD does not necessarily improve spatial ability. It was decided therefore to include specific instructional strategies aimed at improving mental imagery ability in the intervention.

Improvement of individual spatial skills has been previously achieved through the use of a number of strategies including pre-exposure to perceptual differentiation (Norman et al., 2000), the use of sketching (Sorby, 1999) and experience with manipulative tasks (Duesbury & O'Neil, 1996; Harman, Humphrey & Goodale, 1999; Sorby & Baartmans, 1996). Pre-exposure to perceptual differentiation has already been proposed above as a strategy for improving parsing ability and should thus also have a positive effect on the development of mental imagery ability.

The use of sketching as a technique for the improvement of mental imagery (spatial) ability has been the subject of research by Alias, Black and Gray (2002), Lord (1985), Sorby (1999) and Sorby and Baartmans (1996). Sorby (1999) found that the sketching activities involved in traditional graphics courses (orthographic projection, isometric drawing) led to improvements in spatial ability. The research was also able to differentiate between CAD courses and those graphics courses involving sketching, finding "in each case the gain scores in the courses that emphasized sketching and hand drawing were higher than those obtained in either of the CAD courses" (Sorby, 1999, p. 1). It was decided that the inclusion of a variety of sketching techniques, including those aimed at developing parsing ability, might thus be an effective approach in improving mental imagery ability and through it helping to develop expertise in 3D-CAD.

The use of manipulative tasks to improve spatial ability has been proposed by Duesbury and O'Neil (1996), Harman et al. (1999) and Sorby and Baartmans (1996) who conclude that experiencing the opportunity to manipulate an object image actively on a computer screen is sufficient to improve spatial ability. The learning of 3D-CAD presents the opportunity for students to gain considerable exposure to the manipulation of objects on a computer screen throughout the process of learning therefore this was explicitly incorporated into the instructional design.

Metacognitive considerations

A number of researchers and theorists have addressed the acquisition of metacognitive skill through instruction, suggesting instructional strategies that may be effective. These include techniques such as cognitive apprenticeship and collaborative problem solving. Collins Brown and Newman (1989) use the concept of cognitive apprenticeship by drawing on the work of a number of authors including Schoenfeld (1985) to argue the importance of combining both expert teacher modelling of problem-solving heuristics and extensive student practice in collaborative problem solving. They argue that teacher modelling should make explicit the reasoning processes, and for them to be spoken aloud during problem solving. In

the cognitive apprenticeship approach proposed by Collins Brown and Newman (1985) it is proposed that:

"students do not usually have access to the cognitive problem-solving processes of instructors as a basis for learning through observation and mimicry Cognitive apprenticeship teaching methods are designed to bring these tacit processes into the open, where students can observe, and enact, and practice them with help from the teacher and from other students" (p. 458).

This is different to the normal 3D-CAD explanation of the steps involved in specific procedural command knowledge, it involved the reasons why commands were chosen, what characteristics of the model led to the choice, why particular pieces of geometry were positioned on specific work-planes or at origin points etc.

Scaffolding of learning was incorporated into the learning process. Scaffolding, according to Goldman and Petrosino (1999), is important to the development of metacognition as it provides a "support structure for thinking" (Goldman & Petrosino, 1999, p. 607). Collins, Brown and Newman (1989) elaborate on the process of scaffolding of learning pointing out that it involves repeated learner observation of the particular process being attempted in order to be able to mimic that process. While student 3D-CAD practice was occurring, guidance from the teacher was also being provided. This guidance included both direct help and coaching which was gradually withdrawn as knowledge of the target process was gained, much as advocated by Vygotsky (1978) in his Zone of Proximal Development which relates to the difference between a learner's existing problem solving abilities and what the learner is capable of achieving with the guidance of an adult or a more capable peer. Repeat demonstrations were also used during which the students were required to provide the reasoning behind the decisions being made by the teacher. Questions included such things as why was that particular algorithm chosen? Why was the sketch placed there? Why was the extrusion done symmetrically about the work-plane?

The use of cooperative learning or group problem solving activities as a means of developing metacognitive strategy learning is proposed by Collins, Brown and Newman (1989), Resnick (1989) and Goldman and Petrosino (1999). It provides an opportunity whereby teacher intervention can occur in a public environment where all students can observe the process, unlike individual exercises. It also facilitates group decision-making and the need to choose among alternative solutions, which in itself provides discussion regarding the utilisation of various control processes. Seeing other students struggle with the problem-solving process also has the advantage that it may help to overcome some individual student insecurity. Resnick (1989) supports the use of group problem solving activities, drawing on the work of Schoenfeld, stating that through this process students "build self-consciousness and self-confidence in problem-solving" (Resnick, 1989, p. 22) and for this reason it was also incorporated into the 3D-CAD pedagogy.

Results

Due to the predominantly interval nature of the data non-parametric analyses were undertaken in order to provide more robust results. Initial analysis of pre-test data confirmed the effectiveness of the randomization of groups in terms of these prior experiences in computer and CAD use. Post-test analysis of the data from the two groups was undertaken confirmed that the 'treatment' group used more expert strategies than the 'control' group and this difference was significant ($p = 0.00$). The finding that the 'treatment' group used more expert strategies was consistent with the predictions about the development in novices of a

metacognitive approach to 3D-CAD processes and provided support for the design of the intervention. The design of the intervention included a number of treatments included specifically to improve parsing, mental imagery and metacognitive processes. The intention of study was to test the efficacy of this overall intervention. Data analysis thus supported the design of the intervention. It is interesting to note that the new pedagogical approach involved students spending less time on the computer and more time in sketching, discussion and analysis. However the research found that, when compared to students who had command and specific procedural command instruction only, and therefore more time on the computers, those exposed to the new approach had equal command knowledge but greater strategic knowledge.

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