Quest for Efficiency: Examining Cognitive Processes Underlying the Use of 3D Modeling Tools

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Abstract. *In this paper we examine the strategies used in 3D modeling for their efficiency. Our study explores the underlying cognitive process that drives design thinking as well the choice of strategies for using specific features in a given CAD software. We take a cognitive task analysis approach to examine our question. Of a total sample of 19 participants, the strategies of the fastest and slowest users are compared to identify areas of improvement for software development as well as user training.*
Keywords. *Modeling strategies; task-analysis; CAD; design cognition; efficiency.*

INTRODUCTION

Computers Aided Design (CAD) tools for design visualization are common place today, making manual graphic techniques take a back seat. This results from an overt focus on the efficiency of CAD tools for content creation from a human-computer interaction (HCI) point of view. Since the beginning, CAD tools have focused on providing efficiency over manual drafting. Optimum efficiency is seen as an important development goal for many CAD tools. Many additional features are included in every new version, purportedly with the intention of improving efficiency. Optimum efficiency is seen as driving the thought process while using CAD tools, particularly in 2D drafting (Bhavnani and John, 1996; 1997). Previous work by Balakrishnan et al. (2005) has indicated this extends to 3D modeling as well. In this work, we investigate the role of CAD tools in architectural modeling by examining the underlying cognitive process as well as individual differences in design cognition. This study specifically explores the underlying cognitive process and the choice of strategies for use of specific features in given 3D CAD software. Our research takes a cognitive task analysis approach to design visualization strategies used by design students. This is achieved by examining modeling strategies employed by design students against the backdrop of their cognitive skills and design intelligence.

Efficiency in Computer-Aided Design Tasks

While the design of CAD software as well as its use are both motivated by efficiency, previous research have shown that users don't always adopt efficient strategies. D'souza and Talbott (2003) have shown that designers are not highly concerned with efficiency, as their strategies are influenced by other factors such as personal preference for specific methods of content creation, reliance on known features in a given CAD tool or the choice of input devices. Despite the goal of efficiency, there is evidence to the contrary as described by Bhavnani and John (1996). As Carroll and Rosson (1987) point out, difficulty and inefficiency in using software are influenced by factors beyond the design and interaction

features of current systems. The users themselves are an important source of inefficient strategies. Many users bring with them procedures and knowledge gleaned from prior experiences to new applications. These practices and knowledge may have been acquired from manual techniques or from knowledge of other CAD applications. This approach of sticking to known procedures reduces the motivation to explore new procedures more appropriate to the new application and its underlying logic (Carroll and Rosson, 1987). Applying their existing knowledge can be helpful for users to be productive when the logic underlying the new tools is compatible with the logic of tools already familiar. However, this can be counterproductive when the similarities are superficial and the underlying issues are vastly different. Carroll and Rosson (1987) point out these mutually reinforcing motivational and cognitive paradoxes which can affect how users learn and use complex applications.

Prior Research on Efficient Strategies in CAD

When learning complex software including CAD packages, knowledge of the tools alone are not sufficient to guarantee productivity or modeling accuracy. It has been pointed out that users need to be taught efficient strategies beyond knowledge of required operational commands (Bhavnani, 2000; Bhavnani at al., 2001). Bhavnani (2000, p. 339) points out four general categories of strategies that improve efficiency:

- Iteration or aggregation strategies that exploit a given application's ability to create and operate on groups (e.g. copy, array, etc.) to avoid repeating identical steps
- Propagation strategies that exploit relational dependencies between objects in a given application (e.g. reference copies in 3D Studio Max; components in SketchUp, etc.)
- Organization and visualization strategies which take advantage of a given application's ability to organize the elements or objects in the scene and to isolate out elements or features as needed at hand (layer features, scenes and views, etc.)

Earlier studies by Bhavnani and John (1996, 1998) have focused on aggregation strategies that allow one to collect and manipulate disjoint elements. These include *detail-aggregate-manipulate* (e.g. creating one shape from multiple elements, grouping all items forming that shape, multiple copies of group), *aggregate-drop-modify* (shapes selected, exceptions removed from selection, and selected shapes modified as a group) and the *aggregate-modify* all-modify exceptions (shapes selected, selected shapes modified as a group, exceptions modified in the group) (Bhavnani and John, 1996; 1997). These efficient strategies can be contrasted against those that don't take advantage of the applications ability for aggregation of tasks and rely on mindless repetition of tasks.

We can expect the knowledge of efficient strategies gained from research in 2D computer-aided drafting to be applicable to 3D modeling. However, the introduction of the third dimension introduces additional challenges and even more diverse approaches to arrive at the same model. Balakrishnan et al. (2005) has shown that for a 3D modeling task, novices rely on more commands using basic tools than more sophisticated tools that require less user effort and which can reduce task time. The study also pointed to the large percentage of time spent in view manipulation tasks during the modeling task. Also, in a 3D modeling task, it is more difficult for an icon, button or a drop down menu to provide heuristic indication regarding the efficient use of a tool for 3D operation. This study is an important first step in improving our understanding of efficient strategies for 3D modeling, and identifying commonalities and distinctions with efficient strategies reported in previous studies involving 2D CAD tasks.

METHODOLOGY

Participants

Nineteen undergraduate students, eleven females and eight males, from an Architectural Studies undergraduate program volunteered to participate.

Figure 1
Pavilion modeling task.

The participants were all juniors and seniors who were familiar with using 3D programs for design. The participants ranged from 2-5 years of experience with 3D modeling computer software with an average of 30 hours a week using the computer for course related activities. In addition to the 30 hours, the participants averaged 14 hours a week using the computer for leisure. They were briefed about the study procedures, tasks to be accomplished and each informed consent was obtained.

Modeling Task

The problem used was a pavilion structure which incorporated several unique shapes (Figure 1). The pavilion structure was chosen for the sufficient complexity allowing for multiple modeling strategies to be used to accomplish the same solution. Specifically, these shapes were meant to encourage the use of different tools in SketchUp. The handout used as the main component for the participants to use included details and dimensions of the pavilion shape in section view. To increase the challenge of the problem, some dimensions had to be deduced from the information provided.

Procedure

We took a Cognitive Task Analysis (Crandall et al., 2006) approach to achieve the objectives of the proposed research. An important objective was to collect and analyze information pertaining to cognitive processing during the modeling task. The study gathered both concurrent and retrospective protocols using procedures elaborated by Ericsson and Simon (1993). Participants were asked to externalize their cognitive process by 'thinking aloud' while working in SketchUp. Following set protocols, students were provided an explanation by the researcher of what 'think aloud' meant, then given a practice exercise. After completing the practice exercise, the students were asked to give a retrospective summary of their modeling process. Upon completion of the summary, if the students performed the practice exercise well, the main modeling problem was introduced.

The participant was then provided with the handout containing the dimensions and details of the expected model. The participant would then begin working on the model using SketchUp while 'thinking aloud'. While the participant worked on the provided problem, we automated the collection of HCI data using LogSquare – a software that logs user interactions including all mouse clicks, buttons pressed on the keyboard, and mouse movement on the screen. In addition to screen capture, LogSquare also recorded the participant's verbal reports synchronously with the HCI data. Once the modeling task was complete, the participant was asked to recall and verbalize their modeling process in the sequence in which it occurred.

DATA ORGANIZATION AND META-LEVEL ANALYSIS

This paper reports the findings and implications from our meta-level analysis of the verbal protocols and human-computer interaction analysis. We started by transcribing all the verbal protocol data and

performed hierarchical task decomposition to reveal the user strategy for the modeling task. We also organized the empirical data we collected including task completion time. Based on the task decomposition of individual cases we identified a few distinct strategies for modeling the pavilion. From the empirical data we identified the slowest and fastest cases for a more detailed comparison.

Observed approaches to the modeling task from meta-level analysis

The strategies employed by the participants can be broadly classified into three categories. Given that our task involved 3D modeling, we found it more meaningful to organize the strategies at the macro level before discussing them at the more nuanced level as undertaken by Bhavnani and John (1996, 1998). We distinguished three approaches, which are summarized below.

Object Approach: Participants taking this approach broke down the pavilion conceptually into 3D objects (column, base, gutter and roof). Each unique object was then constructed using elementary shapes and the push-pull tool. These objects were then replicated as needed and connected to form the final model. Here the subjects seemed to demonstrate their cognitive ability for task decomposition and use the perspectival views of the pavilion as the starting point for their cognitive process. Participants using this approach appeared to perform better than others overall.

Extrusion Approach: Participants in this approach seem to take the opposite of the *object* approach. In these cases, they started by recreating the complete 2D footprint and then extruding surfaces (push/pull). Participants taking this approach seemed to start with the floor and roof plans provided as part of the task brief for the starting point rather than the cognitively sophisticated approach taken by those in the *object* approach. Participants using the extrusion approach appeared to fare poorly with task completion times compared to those using the *object* approach.

Hybrid Approach: Some of the participants took

a hybrid approach with elements of both approaches described above. These participants performed in the average of task completion times as switching approaches tended to come as a second attempt at completing the model.

### Detailed comparison of the strategies adopted by the fastest and slowest cases

We identified the two fastest cases (16 minutes and 58 seconds for both) and the slowest case (51 minutes and 52 seconds). For a more detailed analysis, we did a hierarchical task analysis to identify the underlying modeling strategies and compare them to previous research regarding efficient strategies. The inferences from the fastest and slowest cases are described below.

Inferences from the fastest cases

The two fastest cases took an object approach to the modeling task as described earlier. Both participants laid out an overall strategy, identifying the key components of the model – column, base, gutter and the roof. In both cases, the objective was to model each of those components and assemble them. They worked with larger components before minor details and organized their actions for efficiency. In both cases, the objective was to identify the most basic 3D form in a given component, and then model it, even though it required more sophisticated cognitive analysis. The modeling process of gutters revealed in the images from one of the fastest users is a case in point.

In modeling the components, the efficient users relied primarily on a detail-aggregate-modify strategy with minor variations. Fastest users extensively re-used elements wherever possible using copy/paste while using translational move/rotate tools. Both users indicate awareness of more advanced features in SketchUp such as the "intersect with solid" as revealed by example of the fastest user given below to model the roof. The fastest users also extensively utilized many of the built-in features within the software for precision including guidelines and "inferring" from already modeled geometry.

Figure 2
Strategy for the fastest users.
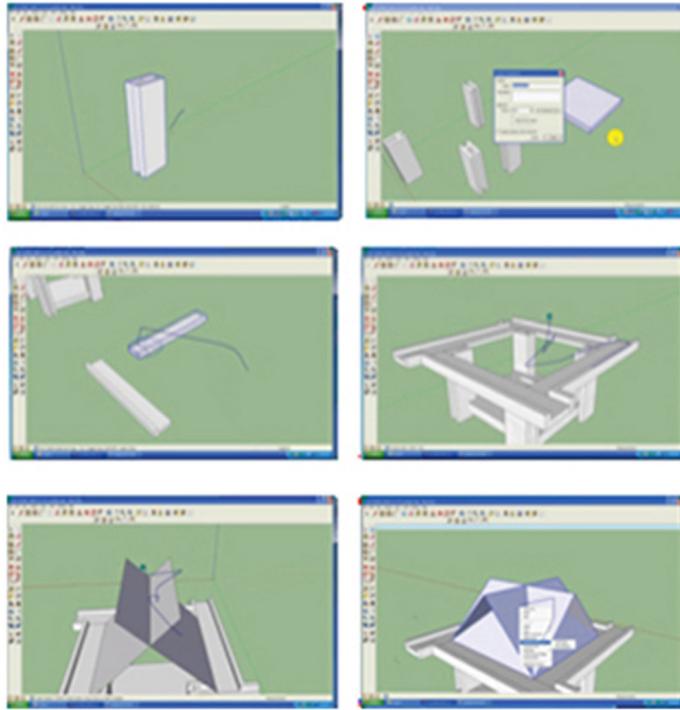
The fastest users made fewer dimensioning mistakes and even when they made mistakes, they were quick to identify them before advancing further. The fastest cases did not indicate production biases or incompatible strategies influenced by their knowledge of other software. Figure 2 summarizes the strategy employed by one of the two fastest users, demonstrating clear goal decomposition, reliance on detail-aggregate-modify strategy and utilization of advanced features in SketchUp.

Inferences from the Slowest Cases
The slowest cases performed quite differently from the fastest cases. In starting the modeling task, the slowest cases began immediately marking out dimensions for details of the objects. This indicated a lack of clear strategy in breaking down the model before beginning. At the beginning of the problem,

the two users each started out with the sequence-by-operation strategy. As the parts of the model began to develop, the users started noticing mistakes they had made several steps earlier. These mistakes ranged from wrong dimensions, to alignment issues. When mistakes were noticed, the users would immediately stop moving forward on the section they were working, and address the errors. In addressing the errors, the users would try to select and manipulate the erroneous objects several times.

Without success, the objects would finally be deleted and rebuilt using another strategy such as detail-aggregate-manipulate. At times, several strategies would be attempted to not only fix erroneous objects but also to build different parts of the model. Much of this behavior showed a lack of organization for efficiency. To add to the lack of efficiency, the slowest cases continually checked and
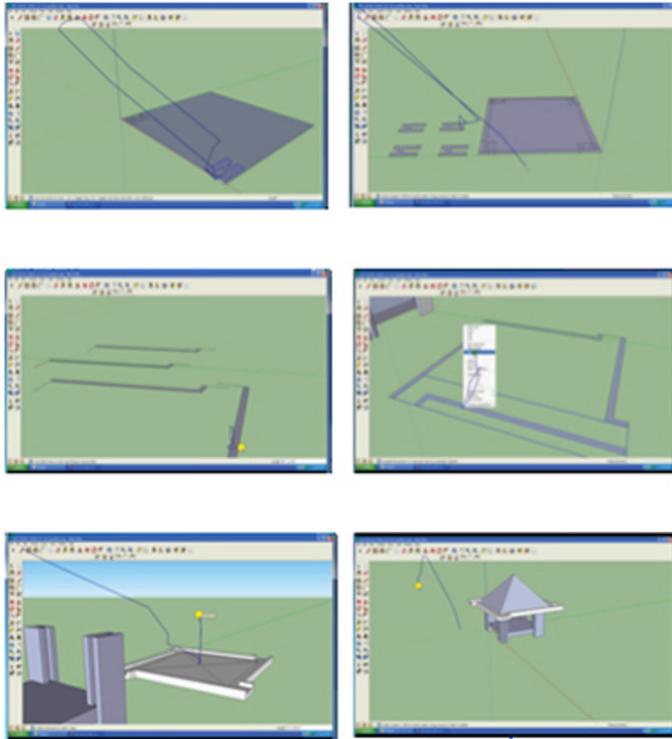
re-checked dimensions while modeling different objects. This not only took time but did not always aid in identifying errors.

In addition to inefficient practices, the slowest cases did not focus on utilizing built-in features of the software, which would have enhanced precision. Built-in features such as guidelines and the measuring tape went unused by both of the slowest cases. In the slowest two cases, the detailed 2D plan used as the starting point indicated a production bias carried over from familiarity with AutoCAD. Figure 3 summarizes the strategy employed by slowest user indicating production bias, lack of clear goal decomposition, inefficient sequence-by-operation approach, and limited utilization of advanced features.

Common Sources of Error

Errors were common among all the participants, though the slowest cases were more significantly affected. The most common type was typographic errors when entering dimensions in SketchUp. For the slowest cases, errors, including dimension inputs were noticed only after a few steps. Beyond the errors of the fastest and average performers, the slowest participants also had errors, which stemmed from misreading the dimensions on the handout. In misreading the dimensions, mistakes were continually made throughout the model. Protocols indicate the slowest users started modeling without a full understanding of the dimensions of all elements in the model and the relationship between them.

IMPLICATIONS OF FINDINGS

Findings from our study are consistent with findings from those exploring strategies in 2D CAD tasks. In both cases, efficient users rely on clear hierarchical goal decomposition and *detail-aggregate-modify* strategies as similarly found in the studies conducted by Bhavnani and John (1996, 1998). Inefficient users rely on *sequence-by-operation* strategies and fail to have clear task breakdown. Inefficient users show indications of production bias (Carroll and Rosson, 1987) – relying on their knowledge of other CAD software even when strategies are incompatible. These findings have implications for both design of CAD systems as well as training users. The study points to the need for software systems to provide more heuristic cues to overcome the production bias. For example, there is no array command in SketchUp, but one can achieve the same effect through multiple copy using rotate or move commands. However, when there is no visible heuristic cue for this process, the users tend to default to a *sequence-by-operation* strategy to achieve the same effect. The study also indicates the need for improving the training and pedagogical approaches to teaching CAD. It is clear that pedagogy should be informed by our understanding of the cognitive processes underlying the use of tools as well as knowledge of efficient strategies. It is important to train the users beyond simple use of tools and train them in efficient strategies and hierarchical goal decomposition. Though we have made good progress in the recent decades, it appears that both the design of CAD systems as well as training has some more ground to cover, before we can exploit its full potential.

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