Cognitive Styles and Design Strategies of Engineering Students During a Hands-on Model-Building Design Task

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Introduction

Design is a fundamental aspect of engineering and is important in preparing students for industrial demands [4]. There has been a growing interest in the relationship between design strategy and cognitive style. Cognitive style describes the way individuals solve problems, think, perceive, and remember information [6]. Investigating if a particular cognitive style results in a more efficient engineering design process (EDP) is important in order to implement effective teaching of design courses**.**

A number of studies [11, 13, 22] have noted the importance of problem representation during engineering design. Design problems are often ill-defined because detailed specifications may be incomplete or not available. Because design problems involve unknown elements, they are more complex and have numerous solutions. Design problems may also incorporate multiple domains and have non-engineering constraints [18]. Significant effort is required in understanding or representing the structure of ill-defined problems and Jonassen [17] argued that this mental representation of the problem space is the most critical aspect of problem solving.

In a meta-analysis of forty studies, Mehalik and Schunn [22] found that how a problem was construed had an impact on what aspects of the design were emphasized as well as the solution paths chosen. A number of researchers have noted that experienced designers tended to spend more time exploring, analyzing, and developing multiple representations of the problem space than inexperienced designers [2, 8, 22]. Developing a creative solution is often a matter of restructuring the problem space by reorganizing existing knowledge or transforming concepts [1, 10, 24, 28, 29].

Theoretical Framework

Newell and Simon's [25] Information-Processing Theory of human problem solving is the lens used for our observations. Their theory describes problem solving behavior as an interaction between a task environment and an information-processing system (the problem solver). The problem solver (PS) represents the task in terms of a problem space where significant information about the task environment is encoded. In other words, the PS must encode components of the problem. Problem solving takes place within this problem space. The ability to solve the problems is a function of how one views the task environment or how the problem is represented.

The structure of the task determines the possible structures of the problem space. The structure of the problem space determines the possible strategies that can be used for problem solving. The problem space holds the full range of possibilities and solutions of the problem. It is the PS, the

task environment, and the problem space that establishes the framework for problem solving behavior.
An important issue in problem representation is the fidelity of that representation [17]. The ease or difficulty of solving a problem will depend on how successful the PS has been in representing critical features of the task in the problem space. Finding a solution requires exploration and manipulation of the problem space. It is an odyssey through the problem space, from one piece of retrieved knowledge to another. The solution will depend on what the PS knows about the problem at a particular point in time, and selectively searching for information on which to build upon.

Exploring the problem space is done by using operators, which are established at the onset when the PS encodes components of the problem. The number of active operators can be likened to the branches of a tree, with possibilities for many operators to be produced and active. The problem space can be highly volatile as it is constructed spontaneously by using information as it becomes available to the PS [13]. Providing more alternatives (multiple problem states) and identifying a greater number of issues (more operators to choose from) can help PS reach solutions of higher quality. However, one of the reasons problem solving can be so difficult is that mapping the complete problem space is complex and can lead to an explosion of operator combinations.

There are many different ways of searching the problem space. The simplest is to use operators that do not make changes leading away from the goal. Another strategy is to use operators that will make the largest improvement towards the goal. Another strategy is to set sub-goals instead of concentrating on the main goal, and compare alternate approaches. The discovery of new operators is a vital part of problem solving. If the strategy is simply to avoid moving away from the goal state, it can become stuck in a non-goal limbo or lead to a sub-optimal solution [8].

Information processing is fundamentally serial in its operation. Searching is sequential, making small, incremental accretions to the store of information about the problem. Although the PS may see many things at once, it only does one thing at a time, i.e. only a small set of operators are active at any one time. If a PS follows a sequence of moves down an unsuccessful path, the PS will retreat to a previous position and search in a new direction. Problem solving then, can be viewed as a goal directed sequence of cognitive operations [17].

Although Newell and Simon based their theory on well-defined problems, they posited that their theory can be applied to ill-structured problems as well. The process used to solve ill-defined problems is the same as those used to solve well-structured ones. The difference is that complex, ill-defined problems require more cognitive operations and the problem space undergoes more alterations as new elements of relevant information are retrieved and processed.

In this study, we utilized the design strategy framework developed by Kruger and Cross [19, 20] to investigate the EDP of students. They identified the following four design strategies:
1. Problem driven
    - Focuses on defining the design problem
    - Uses only the information needed to formulate the problem
    - Little time is spent enlarging the information space

- Solution reflects specialized problem

2. Information driven
    - Focuses on gathering information
    - Solution reflects the many requirements found in the assignment
    - Strict problem definition
    - Solution is focused
3. Solution driven
    - Scans the problem for basic requirements
    - Little time is spent enlarging the information space
    - Design remains ill-defined
    - Short problem analysis stage
    - More time spent generating solutions and more varied solutions
    - Does not assess the validity of information
4. Knowledge driven
    - Uses prior personal knowledge
    - Compares it to similar problems

The present study extended the research of Kruger & Cross [19, 20] by using students rather than experts, and focusing on the design *process* rather than design *outcomes*. Also, because Information Processing Theory states that problem solving is sequential, we looked more closely at the seriality of the PS's thought processes, rather than establishing a priori categories.

Methodology

Verbal Protocol Analysis (VPA) was used to analyze the cognitive strategies of students as they were solving a design task. During VPA data collection, subjects are asked to think aloud while performing a task [15]. From participants' verbal reports, we can gain insights into how subjects generate and transform information about the problem, as well as how they go about developing a solution.

Verbal Protocol Analysis has been used extensively since the 1970's to study the cognitive processes of engineering students [3, 5, 23, 27] as well as experienced designers [7, 10, 14]. Although VPA is considered the most appropriate method to study the cognitive abilities and processes of designers it is not an assessment tool appropriate for large subject populations due to the copious amounts of data collected and time required for analysis [10, 12, 16]. For this paper, the verbal reports of ten student participants were analyzed.

Subjects

Ten students attending a private university in the northeast of the United States were asked to participate in a design task at the end of the school year. There were six males and four females from diverse engineering disciplines and academic years (Table 1). It was a sample of convenience as the students were all known by one of the co-authors. Each participant was given a code according to gender (male = M, female = F), engineering discipline (chemical, mechanical, etc.), and class level (2 = sophomore, 3 = junior, 4 = senior). Since there were two male mechanical engineering seniors, one was coded as M-ME-4, and one was coded as M-ME-4*.

Participant Code	Gender	Engineering Discipline	Class Level (undergrad)
M-ME-4	M	Mechanical Engineering	4
F-EnE-4	F	Environmental Engineering	4
M-ChE-2	M	Chemical Engineering	2
M-EE-3	M	Electrical Engineering	3
M-ME-4*	M	Mechanical Engineering	4
F-CE-4	F	Civil Engineering	4
M-ME-3	M	Mechanical Engineering	3
F-ME-4	F	Mechanical Engineering	4
M-GE-4	M	General Engineering	4
F-ME-3	F	Mechanical Engineering	3

Table 1. Student Participants

Procedure

The study participants were asked via e-mail if they would be willing to participate in a research experiment on engineering design. After giving consent, students were tested individually in a small conference room on campus. A small audio-video camera was mounted on the ceiling to record speech as well as students' hands. Participants were told that the purpose of the study was to investigate the design process of engineering students. A practice think-aloud project of assembling a 24-piece puzzle was given to the students. When the subjects finished the puzzle, they were given an information sheet that explained the design task. The card read:

Clients at the local rehabilitation center have diverse disabilities and physical challenges. For example, clients may have an amputated limb, cerebral palsy, multiple sclerosis, or they may have had a stroke. However, one difficulty they all face is opening a jar with one hand.
As an engineering student, what can you do to help?

Each participant was presented with a choice of fifteen activities, each offering various pieces of information. The activities were titled: *(1) Talk to Jim (an amputee), (2) Speak with Mary (a stroke victim), (3) Learn about amputees, (4) Learn about stroke, (5) Look at other models, (6) Plan/draw/sketch, (7) View available materials, (8) Read technical descriptions of prototype jar openers, (9) Build a prototype, (10) Review first principles of physics, (11) Talk to jar manufacturers, (12) Examine elementary mechanics, (13) Look at jar variables, (14) Investigate aesthetic options, and (15) View unnecessary nonsense.*

These activities were presented to eight of the participants using physical sets of cards laid out on a large table. Two participants (M-ME-4* and F-ME-3) were given the design task using a digital workbook supported by Robobooks^{TM} software. Information presented physically and digitally was identical except for the *Talk to Jim* information, which was replaced with videos of an upper limb amputee. The digital medium was utilized during data collection for its ability to take photos and input text. The two digital sessions were also trials to test the software for possible wide scale testing in the future. When participants chose the "Plan, Draw Sketch option, they were handed a kit of LEGO pieces. Participants used the LEGO pieces to build their model. Two researchers (the first two authors) took observational notes during the session. (A more detailed description of the methodology can be found elsewhere [Lemons et al., 2010])

Data Analysis

The transcribed texts with time stamping formed the main data for analysis. A rich representation of thoughts can be formed by identifying patterns used during the design process (Creswell, 1997; Patton, 2002). According to Newell and Simon, information processing is fundamentally serial in its operation. Searching is sequential, making small, incremental accretions to the store of information about the problem. For this reason we looked at the sequence of comments made by students to determine their cognitive strategy. The cognitive design strategy each student used to solve the problem was analyzed. We looked at how students represented the problem space and which operators they identified as being the most important. Each student was then classified according to the design strategies identified by Kruger & Cross (2001, 2006) based on how their process best fit the strategy descriptors.

Results

We found that the classification strategies developed by Kruger & Cross using experienced designers also applied to this sample of engineering students. Within this sample of ten students, six were problem driven, three were solution driven, and one was information driven. We found no student that fit the criteria of a knowledge driven strategy. Following is an example of each category.

Example 1: Problem Driven Designer

M-ME-4 was classified as a problem driven designer, because he focused on defining the design problem, used only the information needed to solve the problem, left little room for alternative solutions, and developed a solution that reflected a specialized problem. While reading about amputees, this student focused on defining the problem. (Total elapsed time in minutes: seconds precedes verbal accounts.)

(2:07) I'm trying to figure out like what, how much control do they have over that one hand. I'm not sure this one (set of cards) *is gonna really get that for me. It just gives some statistics . . . So I'll put that one down.*
(3:00) So there's lots of pain in the limb . . . I'm not sure that gave me exactly the answers I was looking for.

After reading the "Mary" cards, he said:

(4:42) This didn't exactly answer my question of what exactly, what mobility they have with one hand.

While reading technical descriptions, this student commented:
(8:21) That seemed like it would use two hands so that doesn't help so much.

This student evaluated the level of usefulness of the information in answering his search for defining the design problem. He was efficient, focused, and not very interested in enlarging the problem space or developing alternative solutions. He quickly came to defining the problem:
(12:05) So it looks like the things we need are some sort of base to stabilize the jar . . .and then some way to lock it in, and then a third component to turn the lid.

This student focused on the problem, discarded information that was not helpful in defining the problem, and focused on a single solution that reflected a highly specialized problem. As you can see from Figure 1, this student's prototype reflected his representation of the problem, included components to stabilize and lock in different sized jars, and incorporated a gear mechanism to turn different sized lids. Collectively, these elements best fit the Kruger and Cross (2001, 2006) definition of a problem driven designer.

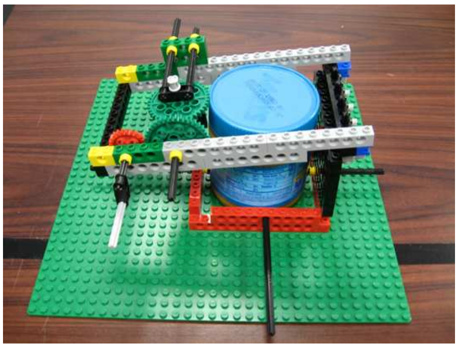

Figure 1. Prototype for M-ME-4

Example 2: Information Driven Designer
This student fit the definition of an information driven designer. He had a compassionate perspective of the clients and their challenges, and spent a good deal of time gathering information and expanding on it. Reading the "Jim" cards he said:
(3:36) He wants to do things for himself . . . especially being like an army guy.
(3:59) Mm. Land mine, One of the many people that were injured . . . infection too, which is too bad.

After reading the "Mary" cards, he summarized
(7:22) Both just wanna continue on with their life. We're not making this a totally encompassing, debilitating design . . . (I want to avoid) just the simple things that may delay (recovery).
(12:15) Stroke. It's gonna damage some of the brain. I know it can go either left or right hemisphere . . . understanding that would be important . . . what kind of disability the stroke caused can target different areas.

Although he was only a second year student, he demonstrated a sophisticated, more global perspective, commenting:
(9:38) Statistics might be a good thing to have in the background, especially when looking for funding for the design.
(10:55) Probably have to target an upper age (who) may not be as strong as our Jim amputee.
(14:02) It may be important to work with rehabilitation therapy groups . . . It may be helpful to contact them . . . so the design (can) be successful.

Both researchers noted that this student read each card carefully and often referred back to the introduction card. The first researcher wrote, "He tried to incorporate different facets of the individual into the design. I got the sense he was trying to incorporate all the information in a systematic fashion." The second researcher similarly wrote, "He . . . wants to . . . get a feel for who Jim is; building a database of characteristics to design for (looks at all cards)." This student spent more time enlarging the problem space by having a deeper understanding of the client.

Example 3: Solution Driven Designer

This student, F-CE-4 focused on generating solutions and little time was spent on defining the problem.
(12:49) If you're using a long lever arm, that should be simple enough.
(20:20) I guess the gears would make it easier for people to rotate.
(20:52) I guess you could use the bricks to keep the jar in place . . . and you can move them around.
(23:04) I'd have the cone at the bottom and this would be some type of screw type device.
(24:15) I can do the other thing where you just push the can up into a holder and make sure it fits tightly enough.
(24:33) Or for that matter, why can't you just clamp the jar down and then use your hand?
(26:24) I don't know how I'd incorporate a funnel idea.
(32:58) You want to make sure that whatever you're clamping onto the top has some sort of friction pad to make sure that it doesn't slip.
(34:43) I guess you want to provide some lateral support.
(36:51) I would want a heavy base, like a super heavy base.
(37:41) So, you could also have a cone on the base.
(38:26) I like the top cone idea.
(40:19) You could hold the top and rotate the bottom.
(41:48) I guess I can figure out how to use a gear.
(45:53) You can have this post be adjustable somehow.

Although this student generated numerous ideas, little time was spent on defining the problem space and the problem remained ill-defined. Because she never reached a clear representation of the problem, she struggled with selecting and developing a specific design solution. After 50 minutes, she began building a prototype without direction and incorporated much in the way of opportunistic behavior (e.g., "There's lots of wheels [in the LEGO kit] so I'm wondering if I could use wheels somehow").

Discussion

Within this sample of ten students, six were problem driven, three were solution driven, and one was information driven. The solution driven students had very short problem analysis stages. This resulted in poor or incorrect problem representations. From this sample of students and for this particular design task, it appeared that a solution driven strategy was not an optimal design strategy for engineering students. Kruger and Cross [20] noted that solution driven design seems to produce solutions of low overall quality, while problem driven design achieves relatively good results. They wrote that designers who use a problem driven strategy put more effort into the analysis stage, than those using solution driven strategies. We similarly found that students who used problem driven strategies were also more likely to expand the problem space and incorporate more design features and criteria, than solution driven students. Similar to the sample of nine in the Kruger and Cross study, only one designer was identified as using the information driven strategy. This student was the youngest student in the sample (second year), so it is interesting to speculate if his design strategy will change as he progresses through his academic engineering education. No students in our sample were classified as knowledge driven designers. This may be a function of our sample, as students do not yet have the years of experience from which to draw upon.

Conclusion

Individual differences in design strategies emerged within this sample of student engineering students even though they performed the same task under similar conditions. The commonalities in their approach allowed them to be classified according to the design strategies developed by Kruger and Cross [19, 20]: problem driven, information driven, solution driven, and knowledge driven. However, none of the students in our sample was classified as knowledge driven. It appeared that students who used a problem driven strategy put more effort into the analysis stage, than those using solution driven strategies. Although we were more interested in the process, rather than the quality of the results, we found that students who used problem driven strategies were also more likely to expand the problem space and incorporate more design features and criteria in their prototype, than solution driven students.

Common strategies used to teach engineering design often result in instructors describing engineering rather than presenting engineering as a creative process. Students need to understand the importance of thoroughly analyzing and correctly interpreting design problems, in order to prevent shortcuts leading to low quality solutions. The results of this limited qualitative study indicate that a thorough analysis of the problem space is a crucial component of the design process that deserves a greater emphasis in engineering design education.

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