Examining the Effect of Design Education on the Design Cognition: Measurements from Protocol Studies

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Abstract – This paper reports the progress of a three-year longitudinal study on the impact of design education on students’ design thinking and practice. Using innovations in cognitive science and new methods of protocol analysis, the study characterizes engineering students’ design cognition as they progress through engineering curricula. Students from two curricula at a large research-intensive state university are being studied. The control group is a major focused on engineering mechanics, which has little formal design education prior to the capstone experience. The experimental group is a mechanical engineering major that uses design as a context for its curriculum. A task-independent protocol analysis method grounded in the Function-Behavior-Structure (FBS) design ontology is utilized to provide a common basis for comparing students across projects and years. This paper presents results of two years of the study, which included students at the beginning and the end of their sophomore year, and at the end of their junior year. Students in the experimental group completed an introductory mechanical design course, while students in the control group had no formal design component in their curriculum. The results of analyzing and comparing the percent occurrences of design issues and problem-solution index from the protocol analysis of both cohorts are presented. These results provide an opportunity to investigate and understand how students’ design cognition is affected by a design course.

Index Terms – Design cognition, verbal protocol studies, design education

BACKGROUND

How does design education affect design cognition? To answer this fundamental question, the authors are embarking on a longitudinal study of two groups of students as they progress through their undergraduate curricula. The students of the experimental group are enrolled in a mechanical engineering curriculum that contains several design courses throughout the 4-year curriculum. The students in the control group are enrolled in an engineering mechanics curriculum, which has a core focus on engineering science and theory.

To analyze effects of design education on students’ design cognition, the authors compare the results of think-aloud protocol analysis of students’ participation in controlled design experiments across several years. The use of verbal protocol analysis to study design behaviors is primarily found in prior work from the Center for Engineering Learning and Teaching (CELT) at the University of Washington [1]. Atman and her colleagues at CELT used a coding scheme derived from representations of the design process in engineering texts [2]. With this methodology, CELT researchers have examined differences across experience levels (freshmen, seniors, experts) [3-5], the influence of reflection [6], team self-evaluations versus observed performance [7], and the ability to effectively contextualize design problems [8-10]. However, further research is needed to explore potential differences across engineering curricula and students’ experiences throughout.

To fill this research gap, the authors in this study use the Function-Behavior-Structure (FBS) ontology as a principled coding scheme to determine design cognition [11], [12]. This coding scheme is applicable across all process-based views of designing and therefore produces results from different sessions by different designers using different design methods in such a way that the results are comparable and commensurable. In their previous work, the authors have explored the effect of a sophomore design class on the experimental group [13, 14] and a comparison of the two groups in their sophomore year [15]. In this work, the authors present a comparison of the two groups in their sophomore and junior years.

ANALYZING DESIGN COGNITION: THE FBS ONTOLOGY

I. FBS Ontology

The FBS ontology models the design process based on three classes of ontological variables: function, behavior, and structure, plus a design description [11]. It posits that the
purpose of design “is to transform a set of functions into a set of design descriptions (D). The function (F) of a designed object is defined as its teleology; the behavior (B) of that object is either derived from the structure (Bs) or expected (Be) from the structure, where structure (S) represents the components of an object and their relationships.” In addition, R is used to designate external requirements given to the designers (Figure 1).

These ontological variables, in turn, help define a set of processes that reflect the transformations from one variable to another. In this case, the FBS ontology identifies eight separate processes. These design processes, denoted numerically in Figure 1, include 1) formulation which transforms requirements and functions into a set of expected behaviors; 2) synthesis, where a structure is proposed to fulfill the expected behaviors; 3) an analysis of the structure produces derived behavior; 4) an evaluation process acts between the expected behavior and the behavior derived from structure; and 5) documentation, which produces the design description. The remaining processes are types of reformulation: 6) reformulation I – reformulation of structure, 7) reformulation II – reformulation of expected behavior, and 8) reformulation III – reformulation of function.

II. FBS Coding Scheme

In this project we use a principled, design-based coding scheme based on the FBS ontology that translates the ontology into six design issues that map onto the ontological variables. Each design issue is coded using the FBS ontology. The six codes for the six cognitive design issues, which are used to label segments in protocol analysis, can be combined to produce eight design processes, as seen in Table 1, where “>” indicates unidirectional transformation and “<>” indicates comparison. The numbers listed next to each design issue corresponds with the labels presented in Figure 1.

<table>
<thead>
<tr>
<th>Table 1: FBS Processes</th>
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<tbody>
<tr>
<td>Formulation (1) R&gt;F,F&gt;Be</td>
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<tr>
<td>Synthesis (2) Be&gt;S</td>
</tr>
<tr>
<td>Analysis (3) S&gt;Bs</td>
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<tr>
<td>Evaluation (4) Be&lt;&gt;Bs</td>
</tr>
<tr>
<td>Documentation (5) S&gt;D</td>
</tr>
<tr>
<td>Reformulation I (6) S&gt;S</td>
</tr>
<tr>
<td>Reformulation II (7) S&gt;Be</td>
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<tr>
<td>Reformulation III (8) S&gt;F</td>
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</tbody>
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METHODS

1. Participants

Participants were recruited from mechanical engineering (ME) and engineering mechanics (EM) departments at a large mid-Atlantic land grant university. The EM majors are considered the control group in this research, as the EM curriculum has a theoretical orientation that focuses on mathematical modeling based on first principles but has little formal design education. The ME curriculum, and its focus in design, is the experimental group. A total of 20, 16, and 14 students participated throughout the first, second, and third experiments, respectively. The breakdowns by major are provided in Table 2.

<table>
<thead>
<tr>
<th>Table 2: Participation in Each Semester by Majors</th>
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<tbody>
<tr>
<td>Semester 1 (n=20)</td>
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<tr>
<td>ME</td>
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<td>EM</td>
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The participants are a representative sample of their peer group, as determined by a series of spatial reasoning ability [16]. Students with significant design experience (either professionally or through prior academic experience), as identified through a preliminary interview, were not selected as participants for this study. Those who agreed to participate in the study were compensated with a gift card to an online retailer.

Both groups had had a brief first-year design experience that emphasized the engineering design process. At the time of the first data collection, the first semester of the sophomore year, the primary difference between the EM and ME students’ coursework was a focus in design. During the sophomore year, the EM students had no specific course related to design, but the ME students had a fall semester course that focuses in exposing students to engineering design and design methodologies at the beginning of their entry into the major. This 3-credit sophomore-level design course provides students with several hand-on team-based activities, which include a semester design project, product dissections, and designing products for various speculative
scenarios. Further, the ME students were enrolled in a hands-on laboratory course focused on manufacturing processes (welding, machining, casting, etc.).

At the time of second and third data collection, in the second semester of participants’ sophomore and junior years, neither group was enrolled in design-related courses. Both sets of students were involved in engineering science courses (e.g., dynamics, mechanics of materials). In this regard, the two curricula are very similar aside from a handful of courses from their respective major’s core technical areas (e.g., an introductory thermal/fluid course for ME students and a computational methods course for EM students).

II. Experimental Design

Participants attended three out-of-class experiments: at midway through the fall semester (Semester 1) and just after spring break (roughly mid-semester) in the spring semester (Semester 2) of their sophomore year, and late March or early April in their junior year (Semester 3). In these experiments, pairs of students worked together at a whiteboard to solve a speculative design task. In the first session, students were asked to design a device to help disabled users open a stuck double-hung window without relying on electric power. In the second session, students were asked to design a device to help stroke patients who are unable to perform bilateral tasks with opening doors (adapted from [17]). In the third session, students were asked to design an add-on device to a hand/arm-powered wheelchair, so that paraplegic users can easily traverse over a standard roadside curb.

Student pairs worked together on the assigned design tasks for 45 minutes. Working in pairs provided for natural verbalization that could be recorded, transcribed, and analyzed. Two digital camcorders, one recording the whiteboard and the other recording the students, were used to video record the session. In addition, each student was provided a remote microphone to ensure the recorded quality of their conversation was high.

III. Protocol Analysis

A protocol analysis was conducted using the video and audio recordings of the design sessions. The research team manually transcribed all the students’ verbalizations as they proceed through the design sessions. The verbalizations were then segmented and coded based on the FBS coding scheme. Two researcher assistants independently identified and coded the segments and arbitrated differences to determine the final design protocol for each session. Typical inter-coder reliability obtained by this method is in the range 85–95%. Agreement between coders is obtained using the Delphi method [18].

RESULTS

To begin our exploration of the effects of design education on design practice, we first compare students’ design issues by majors for the three semesters. Then we report the sliding window average results to capture how students’ design cognition progressed in design sessions by semester and major. Finally, we report the Problem-Solution (P-S) issue index, also using the sliding window technique to examine the degree to which students’ cognitive effort was focused on problem or solution.

I. Design Issues

Figures 2-3 illustrate the percent occurrences of design issues by semester and major. In semester 1 (Figure 2), the design issue of behavior from structure and description showed the most difference between majors. ME majors expended about 8% more cognitive efforts on design issue of behavior from structure, while EM and mixed majors spent about 8% more cognitive efforts on the design issue of description.

In semester 2 (Figure 3), the most notable differences between majors were the design issues of structure and function. ME majors spent about 5% and 4% more cognitive efforts on structure and function respectively. EM and mixed majors expended about 3% more of their cognitive effort on the design issue of requirement.

In semester 3 (Figure 4), ME majors spent about 7% more cognitive efforts on the design issue of structure than those of their EM and mixed counterparts. EM and mixed majors expended approximately 6% more of their cognitive effort on the design issue of behavior from structure.
II. Design Issues Sliding Window Results

A sliding window technique was used in order to calculate moving average results, which provide a description of the dynamic behaviors across design sessions. The number of data points that will be produced from each sliding window needs to be the same for each protocol to allow for direct comparisons. In this study, 150 data points were computed from each protocol. Since a 45 minutes design session produced between 200 and 800 segments, each corresponding window size was calculated for each protocol.

For example, in order to produce 150 data points for a protocol that has 400 segmentations, the window size should be 250. A window size of 250 commences at the beginning of the design protocol (segment #1) and moves a single segment at a time until it reaches the end of the protocol (segment #400). Throughout the window movement, an independent calculation of the averages of the design issues in that window is carried out at each window position. By putting the calculated results together, a dynamic model is produced, which shows the changing values of the design issues in the course of a design session.

Figures 5 and 6 show the design issue distribution sliding window results by majors. The x-axis represents 150 segments from the design protocol and the y-axis represents the amount of cognitive effort expended in percentage. For each sliding window result, a linear regression was computed using a statistical software JMP 9.0 to calculate the goodness of fit ($R^2$) and the slopes ($\beta$).

For the design issue of requirement, ME students spent more cognitive efforts in semester 1, followed by semesters 2 and 3. Slight negative trends of slopes ($\beta<0$) were identified for all semesters. For the design issue of function, students spent significantly more cognitive effort in semester 2 than in semesters 1 and 3. Similar to the design issue of requirement, the slopes showed a slight negative trend for all semesters. These results indicate that students generally discuss design functions and requirements more in the beginning and less towards the end of the design session.

For the design issue of expected behavior, a significant difference of cognitive efforts was identified across semesters. Specifically, students expended more cognitive efforts in semester 3 followed by semesters 1 and 2. A slight negative trend was identified for semesters 2 and 3, while a slight positive trend was observed in the 1st semester.

For the design issue of structure, a noticeable difference was identified among semesters. Students spent more cognitive effort associated with structure in semester 1, followed by semesters 2 and 3. The slopes for each semester showed a slight negative trend except in semester 3.

For the design issue of description, students spent more cognitive effort in semester 2, followed by semesters 3 and 1. While the amount of cognitive effort slightly increased towards the end of the design session in semesters 1 and 2, the amount of change in students’ cognitive efforts in semester 3 was negligible.
Figure 6 illustrates the sliding window results for EM and mixed majors. In general, the amount of cognitive efforts varied more across semesters when compared to those of their ME counterparts. The changes in slopes ($\beta$) were also greater when compared to those of ME majors. This result can mostly be accounted by the change of slopes in semester 2.

For the design issue of requirement, a similar negative trend was observed for all semesters. Specifically, students expended significantly more cognitive efforts in the beginning of semester 2, followed by semesters 1 and 3. For the design issue of function, the difference of the amount of cognitive efforts among semesters were almost negligible among semesters and the slopes for each semester were all very close to zero. However, a slight increase of students’ cognitive effort was identified in the middle of design sessions in semester 2.

For the design issue of expected behavior, students spent more cognitive efforts in semester 3, followed by semesters 1 and 2. The amount of cognitive effort remained almost equivalent throughout the design session in semester 3, while a significant decline was observed in semesters 1 and 2.

For the design issue of structure, students spent more cognitive efforts in semester 1, followed by semesters 2 and 3. Interestingly, the amount of cognitive efforts in semesters 1 and 2 increased as students progressed through the design session, while a slight negative trend of cognitive effort was observed in semester 3.

For the design issue of behavior from structure, students expended more cognitive efforts in semester 3, followed by semesters 2 and 1. Although the slopes for all semesters showed a positive trend, semester 2 showed the most variation throughout the design session, and more similar pattern was identified for semesters 1 and 3.

For the design issue of description, students expended significantly more cognitive effort in semester 2, when compared to semesters 1 and 3. The slopes for all semesters showed a slight negative pattern.

II. Problem-Solution Index

One method to measure meta-level design behavior is to divide all cognitive effort into that focused on the problem or focused on the solution. The ratio of cognitive effort on the problem to cognitive effort on the solution is called the problem-solution index. When the cognitive effort relates to design issues it is called the problem-solution issues index. The method to calculate this index is given in Figure 6.

\[
P-S \text{ Issue Index} = \frac{\text{SUM (Requirement, Function, Expected Behavior)}}{\text{SUM (Structure, Behavior from Structure)}}
\]

The moving averages of the problem-solution issue index describes the dynamic meta-level behavior and is calculated in the same way as for design issues themselves. When graphed these provide the basis for observing the qualitative differences between semester and between majors.

Figure 7 shows the problem-solution issue index moving averages for each of the three semesters by major. Two qualitative differences can be observed in Figure 7. First the behavior of ME and EM students differ markedly in their first two semesters and converge in their third semester of this study. ME students commence with a P-S issue index value that declined only slightly in their first two semesters and dropped noticeably in their third semester. The behavior of CM students was the reverse of this. Second the P-S issue index of ME increases in their third semester.
**DISCUSSION**

Due to the lower number of participants in the control group, it is not feasible to quantify differences between the teams using descriptive statistics. However, qualitative observations can be made by comparing the two student groups’ design issues and P-S indices. From these observations, we can note that there are differences between the two groups’ behaviors.

Regarding design issues, it is interesting to note how the design cognition of the experimental group changes according to their involvement in design-related courses. For example, there is a large positive increase in the amount of time spent on function related issues from Semester 2 from Semester 1; however, the time reduces in Semester 3. The increase corresponds to the students’ time in a design course focused in problem scoping and definition. The decrease in the following semester could suggest that students’ behavior is dependent on their current course focus, and might be an argument for a focus in design through the curricula.

Also of interest is that the control group spends very little time on discussing function. This does not change across the three semesters of experiments, which could relate directly to their curricula’s lack of a design focus.

Looking at the two groups’ P-S indices in semesters 1 and 2, the students of the control group spend more time focused in problem definition than those in the experimental group (as seen by the higher P-S value). This is slightly surprising, given that the experimental group has received focused in problem scoping and definition. The students’ behavior is dependent on their current course focus, and might be an argument for a focus in design through the curricula.

While the control groups’ P-S value changes sporadically across the three experiments, the experimental groups’ P-S value regularly increases. As higher P-S values correlate to more expert-like design behavior, this is a positive progression for the experimental group. This progression is also evident in comparing the slopes of the experimental groups’ sessions in semesters 1 and 3. A P-S slope indicates the rate of change of focus, and should be negative as the problem solving process progresses. The experimental groups’ P-S slope is more negative during each semester.

In future work, the authors will close their longitudinal study by capturing the data following the students’ senior years. This dataset will offer valuable insight as both groups will have concluded their capstone design courses and projects. We look forward to exploring how these formative experiences (and the two majors’ varying interpretations) affect student behavior.

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**REFERENCES**


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