EXPLORING THE EFFECT OF DESIGN EDUCATION ON THE DESIGN COGNITION OF TWO ENGINEERING MAJORS

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ABSTRACT
This paper presents the results of two years of a three-year longitudinal study on the impact of design education on students' design thinking and practice. Two engineering majors in a large research-intensive state university are being studied. The control group is a major focused on engineering mechanics. 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 design ontology is utilized to provide a common basis for comparing students across discipline and year. This study reports data collected at the beginning and at the end of students' 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 processes 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.

1 INTRODUCTION
1.1. Design Education and Design Cognition
Much of engineering education research in design has been dominated by explorations of design teaching with a focus on the effects of educational interventions on the results of designing. These studies have treated the design students as a black box [1]. Recently, there has been an increase in the number and scale of cognitive studies of designers that have been aimed at elucidating design thinking behavior. These studies have fallen into five methodological categories:
- questionnaires,
- interviews [2],
- input-output experiments (where the designer is treated as a black box which produces the behaviors in the outputs for changes in inputs) [3],
- anthropological studies [4], and
- protocol studies.

Whilst each of these methods has produced interesting results, the most promising is protocol studies and it has become the basis of the current cognitive studies of designers.

1.2. Protocol Analysis in Design Research
Protocol analysis is a rigorous methodology for eliciting verbal reports of thought sequences as a valid source of data on thinking. It is a well-developed, validated method for the acquisition of data on thinking [5-7]. It has been used extensively in design research to assist in the development of the understanding of the cognitive behavior of designers [8-25].

There are two classes of protocol studies: think-aloud and retrospective [6, 7]. In a think-aloud protocol the subject verbalizes while carrying out the task, while in a retrospective protocol the subject verbalizes after the task has been completed. Often the retrospection is carried out while viewing the video of the subject performing the task. It has been shown that there is a statistical agreement between them for the same task under controlled conditions [26]. Where there is more than a single subject involved, there is a natural verbalization between them. As a consequence most protocol studies of groups and teams use think-aloud protocols.
1.3. Context

In this paper, the authors use protocol analysis and an ontology-based coding scheme (described in Section 2) to research the potential effects of design education on students’ design cognition. Specifically, protocol analysis is used to compare and analyze the experimental design sessions of two student groups: a control group that is enrolled in a curriculum with a theoretical engineering science focus, and an experimental group that has a curriculum focused in design (Section 3). To fully explore the effects of these two curricula on design cognition, the authors are in the midst of a longitudinal study that researches student design cognition from their sophomore to senior years [1, 27].

In this paper, the authors compare the design cognition of the two student groups for their sophomore and junior years (totaling three experimental design sessions, Section 4).

2 THE FBS ONTOLOGY AND CODING SCHEME

2.1 The FBS Ontology

The FBS ontology [28] models designing in terms of three classes of ontological variables: function, behavior, and structure plus a design description, Figure 1. In this view, the goal of designing is to transform a set of requirements and functions into a set of design descriptions (D). The requirements (R) of a designed object are intentions that come from outside the designer. 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.

![Figure 1. The FBS ontology](image)

These five variables map onto design issues that are the basis of design cognition. A design description is never transformed directly from the function but is a consequence of a series of design processes among the FBS variables. These design processes include: formulation which transforms functions into a set of expected behaviors (process 1 in Figure 1); synthesis, where a structure is proposed to fulfill the expected behaviors (process 2); an analysis of the structure produces derived behavior (process 3); an evaluation process acts between the expected behavior and the behavior derived from structure (process 4); documentation, which produces the design description (process 5). There are three types of reformulation: reformulation I – reformulation of structure (process 6), reformulation II – reformulation of expected behavior (process 7), and reformulation III – reformulation of function (process 8). These eight design processes are a consequence of the ontology of design issues and form the ontology of design processes. Figure 1 shows the relationships among the eight design processes and the five design issues, which claim to be the fundamental processes for designing.

The FBS ontology has been referenced as an ontology of designing that has been used in multiple disciplines and one that transcends individual designers and design domains [29-33].

2.2 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 2, 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>Code</th>
<th>Label</th>
</tr>
</thead>
<tbody>
<tr>
<td>R&gt;F,F&gt;Be</td>
<td>Formulation (1)</td>
</tr>
<tr>
<td>Be&gt;S</td>
<td>Synthesis (2)</td>
</tr>
<tr>
<td>S&gt;Bs</td>
<td>Analysis (3)</td>
</tr>
<tr>
<td>Be&lt;&gt;Bs</td>
<td>Evaluation (4)</td>
</tr>
<tr>
<td>S&gt;D</td>
<td>Documentation (5)</td>
</tr>
<tr>
<td>S&gt;S</td>
<td>Reformulation I (6)</td>
</tr>
<tr>
<td>S&gt;Be</td>
<td>Reformulation II (7)</td>
</tr>
<tr>
<td>S&gt;F</td>
<td>Reformulation III (8)</td>
</tr>
</tbody>
</table>

Table 1. FBS Syntactic Processes (Numbers refer to labels in Figure 1).

3 EXPERIMENTAL METHOD

3.1 Participants & Context

Participants for the study described in this paper were drawn from the Departments of Mechanical Engineering (ME) and Engineering Mechanics (EM) of a large mid-Atlantic land grant university. The EM majors are 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, with its focus in design, is the experimental group. A total of 20, 16, and 14 students participated throughout the first, second, and third semesters, respectively. The breakdowns by major are provided in Table 2.

The participants were solicited during their sophomore year and agreed to participate in the 3-year longitudinal research study. For their participation in the study, each volunteer was compensated with a gift card to an online
The participants were solicited during their sophomore year and agreed to participate in the 3-year longitudinal research study. For their participation in the study, each volunteer was compensated with a gift card to an online retailer. The participants are a representative sample of their peer group, as determined by a series of spatial reasoning ability tests, as described in [1].

Both groups 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 on 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 on exposing students to engineering design and design methodologies at the beginning of their entry into the major. This 3-credit sophomore-level design course is centered on active-learning opportunities that allow students to apply their engineering design learning. Classroom meetings are typically devoted to hands-on team-based activities, which range from product dissections to designing products for various speculative scenarios. In addition to these in-class activities, student teams work together out-of-class on a semester project where they design a novel consumer product. In addition, the ME students were enrolled in a hands-on laboratory course focused on manufacturing processes (welding, machining, casting, etc.).

At the time of second data collection, in the second semester of participants’ sophomore year, neither group was enrolled in design-related courses. Both sets of students were involved in engineering science courses (e.g., dynamics, mechanics of materials) and their respective major’s core technical courses (e.g., an introductory thermal/fluid course for ME students and a computational methods course for EM students).

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.

### 3.2 Design Experiments

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. In the third session, students were asked to design a device to add to an existing hand/arm-powered wheelchair that will allow paraplegic wheelchair users to traverse a standard roadside curb unassisted.

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 lapel microphone to ensure the recorded quality of their conversation was high.

Prior to the design task, students were asked about their prior experiences and courses taken related to design. This was to ensure no significant differences in design skills and knowledge among the participants. Then, student pairs were instructed to collaborate with one another to come up with a design solution that meets the design requirements provided in the design brief within 45 minutes. The entire design sessions were audio and video recorded for later analysis. Specifically, two digital camcorders were used, one recording the whiteboard and the other recording the students. Each student had individual remote microphones to ensure the recording quality of their conversation.

### 3.3 Protocol Analysis

The basic methodology of the protocol analysis consists of the following sequence of tasks.

- **Videoing of subjects.** This involves capturing voice, sketching and gestures of participants during the problem-solving session. The result is a time-stamped video of the design session.
- **Transcription of verbalization into text.** Since success with various voice-to-text programs has been very limited when studying a team of designers (because of the variability of the voices) the research team carries out the transcription manually. The result is a time-stamped, digital version of the verbalizations in a session in the form of entries in a spreadsheet.
- **Segmentation/coding of the verbalization as text.** Segmentation involves collecting into a single unit those verbalizations that cohere with each other. In this project, segmentation occurs on the basis of FBS coding of design issues as described in Section 2.2. Each segment can contain only one design issue [34]. This harmonizes all segmentation when using this coding scheme since there is now an isomorphism between segments and design issues. This is a critically important advance in protocol analysis.
since the two separate processes of segmentation and coding of segments are now linked. The segments can be connected to time through the time-stamped text constituents of the segments.

- **Arbitration of segmentation/coding.** Two segmenters/coders are used to produce the final segmented/coded protocol in order to have robustness, which is measured by inter-coder reliability against the final, arbitrated protocol. Typical inter-coder reliability obtained by this method is in the range 85–95%. Agreement between coders is obtained using the Delphi method [35]. The result is the final, arbitrated protocol. This final protocol is the first data set available for analysis. The final protocol for a 45 minute design session typically generates between 200 and 800 segments. This provides a rich and statistically significant data set.

## 4 RESULTS AND ANALYSIS

To explore the effects of design education on design practice, we first compare students’ design cognition 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) process index, also using the sliding window technique to examine the degree to which students’ cognitive effort was focused on problem or solution.

### 4.1 Syntactic Design Processes

Figure 2 illustrates the percent occurrences of design processes by semester and major. In semester 1, the design process of evaluation showed the most notable difference between the majors followed by the design process of analysis. EM and mixed majors spent about 7% more of their cognitive effort on evaluation, while ME majors spent about 5% more of their cognitive effort on analysis, Figure 2(a). In semester 2, ME majors spent about 3% more of their cognitive effort on design process of reformulation 3, while EM and mixed majors spent about 4% more of their cognitive effort on documentation, Figure 2(b). In semester 3, EM and mixed majors spent about 14% more of their cognitive effort on design process of evaluation, while ME majors spent about 5% more of their cognitive effort on reformulation 1 Figure 2(c). Much less differences of design processes between majors were identified for the remaining design processes in each semester.

### 4.2 Syntactic Design Process Sliding Window Results

In order to calculate moving average results, which provide a description of the dynamic behaviors across design sessions, a sliding window is used. 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.

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**Figure 2.** Percent Occurrences of Design Processes by Semester and Major: (a) Semester 1, (b) Semester 2, (c) Semester 3.
For example, in order to produce 150 data points for a protocol that has 400 segments, the window size needs to 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 processes in the course of a design session. Figures 3 and 4 show the design process distribution sliding window results by majors and semesters. (A more detailed explanation of sliding window technique can be found in [36]). For each design process, a linear regression was computed using JMP 9.0, a statistical software. The goodness of fit ($R^2$) and the slopes ($\beta$) of each regression line are reported in Figures 3 and 4.

4.2.1 ME Syntactic Design Process Sliding Window Results. The amount of cognitive effort that teams of ME majors expended on each design process is shown in Figure 3. The x-axis represents 150 segments from the design protocol and the y-axis indicates the amount of cognitive effort expended in percentage.

![Figure 3](image-url)

Figure 3. Design Process Sliding Window Percentage of Cognitive Effort for Teams of ME Majors by Semester.

For the design process of formulation, the difference between semesters was almost negligible and the slope of regression lines were all close to zero, meaning students have spent almost equivalent amounts of cognitive effort on formulation throughout the design session. For the design process of synthesis, students spent slightly more cognitive
effort towards the end of the design session in semester 1, whereas their cognitive effort on design synthesis decreased in semesters 2 and 3. Students spent more cognitive effort on the design process of analysis in semester 2 than in semesters 1 and 3. Students’ cognitive effort on the design process of analysis slightly decreased during their design sessions in semesters 1 and 2, and increased in semester 3.

Teams of ME students expended significantly more cognitive effort on the design process of evaluation in semester 3, when compared to semesters 1 and 2. While cognitive effort on evaluation slightly increased as students progressed through the design session in semesters 1 and 2, they expended more cognitive effort around the middle of the design session in semester 3. Such unimodal pattern is also reflected by low goodness of fit ($R^2=0.001$). This trend aligns with the increases in students coursework related to engineering analysis in semester 3.

For the design process of documentation, students’ cognitive effort slightly increased towards the end of the design session in semesters 1 and semester 2, while in semester 3, their cognitive effort decreased around the middle of the design session. When compared across semesters, students’ expended more of their cognitive effort on documentation in semester 2, followed by semester 3 and 1.

For the design process of reformulation 1, students expended more cognitive efforts in semester 1, followed by semester 2 and 3. The slopes for each semester were all positive except for semester 1, which showed a slight decrease towards the end of the design session. This decrease in reformulation 1 suggests that students do less iteration in the structure of their design solution, which is most likely due to their increased focus in evaluation.

For reformulation 2, students spent more cognitive effort in semester 3 followed by semesters 1 and 2. While students’ cognitive effort on reformulation 2 decreased over time in semester 3, semester 1 showed a slight increase and semester 2 showed a decrease towards the middle of the design session. Reformulation 3 showed a relatively flat pattern for all semesters. Students spent much cognitive effort on reformulation 3 in semester 2 then in semester 1 and 3.

4.2.2 EM Syntactic Design Process Sliding Window Results. The amount of cognitive effort that teams of EM and mixed majors spent on each design process is shown in Figure 4. Similar to ME majors, the difference of students’ cognitive effort on formulation was negligible across the semesters and students spent almost equivalent amount of their cognitive efforts throughout the design session. The cognitive effort spent on design process of synthesis also showed a similar trend to that of ME students. Students’ cognitive effort decreased towards the end of design in all three semesters. There were notable differences between semesters that students expended more cognitive effort on analysis in semester 2 followed by semester 1 and 3. The same order and similar magnitude of cognitive efforts were identified for the ME counterparts. For the design process of evaluation, students’ cognitive effort decreased towards the end of the session in all semesters, except for semester 3 where a slight positive trend was identified.

The amount of cognitive effort that teams of EM and mixed majors spent on each design process is shown in Figure 4. Similar to ME majors, the difference of students’ cognitive effort on formulation was negligible across the semesters and students spent almost equivalent amount of their cognitive efforts throughout the design session. The cognitive effort spent on design process of synthesis also showed a similar trend to that of ME students. Students’ cognitive effort decreased towards the end of design in all three semesters. There were notable differences between semesters that students expended more cognitive effort on analysis in semester 2 followed by semester 1 and 3. The same order and similar magnitude of cognitive efforts were identified for the ME counterparts. For the design process of evaluation, students’ cognitive effort decreased towards the end of design in all semesters, except for semester 3 where a slight positive trend was identified.

The most noticeable differences across semesters were identified in the design process of reformulation 1. Students expended much of their cognitive effort on reformulation 1 in semester 1, followed by semesters 2 and 3. In semesters 2 and 3, students increased their cognitive effort throughout the design, while a slight decreasing pattern was identified in semester 3. Similar results were identified for the ME students. For the design process of documentation, students’ cognitive effort increased only in semester 2, whereas semesters 1 and 3 showed a slight decrease. The results are similar to the ME counterparts, yet the magnitude of increase in semester 2 is much higher.

The most noticeable differences across semesters were identified in the design process of reformulation 1. Students expended much of their cognitive effort on reformulation 1 in semester 1, followed by semesters 2 and 3. In semesters 2 and 3, students increased their cognitive effort throughout the design, while a slight decreasing pattern was identified in semester 3. Similar results were identified for the ME counterparts. For the design process of reformulation 2, a slight negative trend was identified for all three semesters, with students expending more cognitive efforts on reformulation 2 in semester 3 followed by semesters 1 and 2. Likewise, the same order and similar magnitudes for each semester were identified for the ME majors. The design process of reformulation 3 showed the least amount of variance across the semesters with all showing a flat pattern.
4.2 Problem-Solution Process Index Sliding Window Results

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 processes it is called the problem-solution process index. The method to calculate this index is given in Figure 5.

\[
P-S\text{ Process Index} = \frac{\text{SUM (Formulation, Reformulation-2, Reformulation-3)}}{\text{SUM (Synthesis, Analysis, Evaluation, Reformulation-1)}}
\]

Figure 5. P-S Process Index Equation.

The moving averages of the problem-solution process 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 6 shows the P-S process index moving averages for each of the three semesters by major. The behavior of ME and EM students differ markedly in their first two semesters and converge in their third semester of this study. In the first two semesters ME students showed much higher P-S process index value throughout the design, whereas EM and mixed teams showed relatively lower P-S process index value with a decreasing pattern towards the end of design. However, the P-S process index value for both cohorts converge in the third semester.
5 CLOSURE

In this paper, the authors use protocol analysis to characterize the design cognition of two student groups in their sophomore and junior years. While the ME student (experimental) group has engaged in a sophomore-level course dedicated to design, the EM student (control) group has had a more theoretical curriculum focus based in engineering science.

The influence of the curricular design focus on the ME experimental cohort is reflected in their increased discussion of problem formulation and reformulation following their sophomore-level design course. The time spent on these processes doubled following this course experience, whereas the control group’s focus remained unchanged across semesters (Figure 6).

The differences between the two groups are not as significant following their junior year. This corresponds well with the similarities in their coursework (neither group was enrolled in a design course). Specifically, both groups showed dramatic increases in time spent on design evaluation, which corresponds to their curricular focus in engineering analysis (Figure 6).

The research team will next investigate the differences between the two groups following their senior capstone experiences. It is hypothesized that larger differences between the two groups will be observed following this significant design experience.

6 ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No. NSF EEC-0934828. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. The authors would also like to thank the study participants for their participation.

7 REFERENCES


Figure 6. P-S Process Index by Major and Semester.


