AC 2012-5094: EXPLORING THE EFFECT OF DESIGN EDUCATION ON THE DESIGN COGNITION OF SOPHOMORE ENGINEERING STUDENTS

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Exploring the Effect of Design Education on the Design Cognition of Sophomore Engineering Students

Abstract

In this paper, we report on 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, we are working with engineering students to characterize their design cognition as they progress through engineering curricula. To observe potential effects of design education, 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 a theoretical orientation that focuses on mathematical modeling based on first principles and 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. In order to provide a uniform basis for comparing students across projects and years, the authors use a task-independent protocol analysis method grounded in the Function-Behavior-Structure (FBS) design ontology. This paper presents results from the first-year of the study, which included students at the beginning and the end of their sophomore 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. We analyze and compare the percent occurrences of design issues and syntactic design processes from the protocol analysis of both cohorts. These results provide an opportunity to investigate and understand how sophomore students' design ability is affected by a design course.

1. Introduction

Design has long been considered a central component of engineering education, and a number of recent publications have called for an increase focus on design education not only in capstone or cornerstone experiences but across the curriculum[1-3]. To date, however, design education research has few studies that examine how students' educational experiences influence their design cognition. That is, we know very little about how students' engineering education affects their engineering design work. Yet such examinations are critical not only to our understanding how curricula can effect design cognition, but to the process of effectively sequencing a design curriculum that addresses misconceptions and ineffective practices, leverages students' zone of proximal development[4], and provides the appropriate scaffolding at each stages.

Some work has been done in this area, most notably by researchers at the Center for Engineering Learning and Teaching (CELT). The CELT team has employed verbal protocol analysis using a coding scheme grounded in the engineering design process to study differences between first-year and senior students [5, 6] and between students and experts[7]. The studies have highlighted differences surrounding the nature and kinds of iteration, the number of alternatives, and the time spent on task. In addition, because the studies included paired students who participated in both their first and senior years, with the seniors consistently showing higher quality solutions, increased transitions between design activities, and spent more time modeling. In related work CELT researchers have compared first-year and senior students' behavior in design scoping [8, 9].

Such studies provide an important foundation for more detailed work that follows students longitudinally across the curriculum. Building on that work, the research presented here is part of a longitudinal study that aims to answer the fundamental research question, "*How does design education impact students' design cognition?*" To accomplish this goal, the researchers are studying students from two distinct curricula – one firmly rooted in design (the experimental group) and one more focused on engineering analysis (the control group) – and comparing their approaches as they proceed through their curricula. Specifically, the study uses verbal protocol methods to capture design cognition at four points: the beginning of the sophomore year, the end of the sophomore year, the end of the junior year, and the end of the senior year. Although students have a broad array of experiences that can affect their approach to design (e.g. internships, extracurricular teams for national design competitions), by considering students from only two majors and tracking them annually, the research team can develop a better understanding of how specific curricular features affect design cognition.

Importantly, the research team has chosen to employ a task-independent coding system grounded in the Function-Structure-Behavior ontology (Section 2) for this analysis rather than adopting the engineering design process method used in other research. Although the design process has particular relevance for engineering, and particular for mechanical engineering, the degree to which it is bound to this particular field can limit cross-field comparisons. By adopting the task-independent FBS approach, the study seeks to focus on more generalizable components of design cognition rather than on field-dependent design behaviors and thus can provide the basis for understanding how a wide array of curricular practices affect design cognition.

In this paper, we focus on the changes in the two populations from the beginning to the end of the sophomore year, comparing the findings both within and across majors.

2. The FBS Ontology and Coding Scheme

The FBS ontology models designing in terms of three classes of ontological variables: function, behavior, and structure plus a design description, Figure 1[10]. In this view, the goal of designing is to transform a set of requirements and functions into a set of design descriptions (*D*). The *requirement (R)* of a designed object is defined as constraints 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. This ontology is used to code the recorded utterances of the design experiment participants (Table 1).

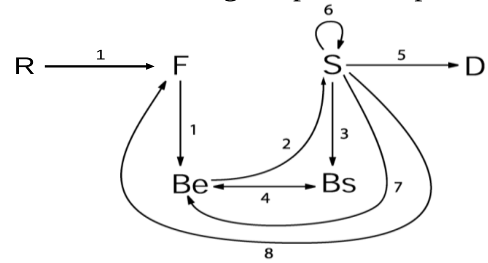


Figure 1: The FBS ontology

Table 1: FBS Coding Examples

(R)	"And here they've got 'you are not allowed to… you can't exert more than 3 pound force'"; "Doesn't rely on electricity"
(F)	"to make it… eh-hm… much easier for the elder…"; "Cause like the main, well the main objectives I mean has to lift and lower it."
(Be)	"Yes, something that just gives them more mechanical advantage."; "Ah-hmm… Somehow it would need to be strong across, so that it will lift up like both sides at the same time. Because, like you saw, it kind-a like…"
(Bs)	"When this goes clockwise this is gonna go counterclockwise, right? So, if that's going counterclockwise, then that would be pulling it down, right? That'll be pulling the window down?"
(S)	"So, instead of going on the bottom, how about we just wrap around couple of times and come down here like that [shows how the string wraps around pulleys and comes down to the bottom of the window]"
(D)	"(WRITES: can be used by elderly/weak person)"; "(drawing some kind of attachment on one of the pulleys)"

These six 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 (Table 2). 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 [11-15].

Table 2: FBS Process

Formulation (1)	R>F,F>Be
Synthesis (2)	Be>S
Analysis (3)	S>Bs
Evaluation (4)	Be<>Bs
Documentation (5)	S>D
Reformulation I (6)	S>S
Reformulation II (7)	S>Be
Reformulation III (8)	S>F

3. Experimental Methods

3.1 Participants

Participants in this study were drawn from mechanical engineering (ME) and engineering mechanics (EM) departments at a large mid-Atlantic land grant university. The EM students 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 (17 MEs, 3 EMs) and 16 (13 MEs, 3 EMs) participants were recruited in the first and second semesters, respectively. The participants are a representative sample of their peer group, as determined by a series of spatial reasoning ability tests [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 sets of students matriculate into their chosen major at the beginning of their sophomore year following a common general-engineering first-year program. In this program, the students were exposed to 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 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 wherein 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).

3.2 Experimental Design

In the first year of this longitudinal study, participants attended two 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. In these experiments, students were randomly paired with other students from within the same discipline and 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 (Table 3). 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], Table 4).

Table 3: Fall 2009 Session (Semester 1) Design Brief: Double-Hung Window Opener

Your design team has been approached by a local nursing home to design a new product to assist its elderly residents. The nursing home administrators have noticed that changes in humidity during the summer months cause the windows of the 65-year old building to "stick," thus requiring significant amounts of force to raise and lower the window panes. The force required to adjust the windows is often much too large for the nursing home tenants, making it very difficult for them to regulate their room temperature. *Your team has been tasked with designing a device that will assist the elderly tenants with raising and lowering the building's windows.* Since each window is not guaranteed to be located near an electrical socket, this device should not rely on electric power.

Table 4: Spring 2010 Session (Semester 2) Design Brief: One-Handed Door Opener Device

Your design team has been hired by the Metropolitan Rehabilitation Institute, the leading rehabilitation hospital in the country, to *design a new device to help stroke patients open doors*. Many individuals who have had a stroke are unable to perform bilateral tasks, meaning they have limited or no use of one upper extremity (arm/shoulder). It is particularly difficult for these people not only to unlock and turn the knob but also to push/pull the door open. Your design team has been asked to create a system that allows a person to unlock and open the door at the same time with one hand. (adapted from Atman et al., 2008)

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.

3.3 Protocol Analysis

A protocol analysis was conducted using the video and audio recordings of the design sessions. The research team manually transcribed all the participants' verbalizations as they proceed through the design sessions. The verbalizations were then segmented and coded based on the FBS coding scheme. Two research 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].

The figures reported in the results section were generated by calculating the mean percent values of each design issue and process from the protocol analysis results of all design teams. Due to a low number of participants in the control group (i.e., the EM students), the statistical significance of group differences could not be determined. The results presented in this paper provide general insight into potential differences between the students and their curricula.

4. Results

To investigate the effects of design education on design practice, we compared the design behaviors between Mechanical Engineering (experimental group) and Engineering Mechanics majors. The focus of this paper is in the design issues and processes using the entire arbitrated protocol (Section 4.1). To provide a detailed understanding of how a design session progressed, we divided each session's arbitrated protocol into halves (Section 4.2). The division of the protocol into halves provides a preliminary look at participants' design processes through time.

4.1 Global Changes by Semester

We begin this analysis by looking first at changes in the distribution of issues and processes from Semester 1 (fall) to Semester 2 (spring) to identify potential effects of the ME design course.

4.1.1 Issue Distribution Across the Entire Protocol

The Semester 1 and 2 design issue distributions for both ME and EM majors are illustrated in Figures 2 (fall semester) and 3 (spring semester).

In both semesters, students expended the majority of their cognitive effort discussing design structure (33%~41%), followed by the behavior from structure (24%~32%). These two design issues accounted for more than half of students' cognitive effort. Much less cognitive effort was spent on the design issues of description (10%~18%), expected behavior (6%~14%), function (2%~7%), and requirement (3%~5%). These trends correspond with earlier research which suggests that novice designers spend more time on solving the problem than in properly framing the problem [5, 6].

Some differences in students' cognitive efforts on design issues were identified between majors. In Semester 1, ME majors expended 8% and 4% more cognitive efforts on discussing design issue of behavior from structure and structure, respectively, than EM majors. In contrast, EM majors expended 8% and 3% more cognitive efforts on description and expected behavior than their ME counterparts. These differences correlate with perceived differences between the majors: ME students seem to be more focused on identifying a solution and its necessary specifications, as might be expected for a major typically perceived to focus on designing artifacts, whereas the EM students are more focused on discussing the general behaviors required of a solution, as might be expected for a major oriented more toward intensive mathematical modelling.

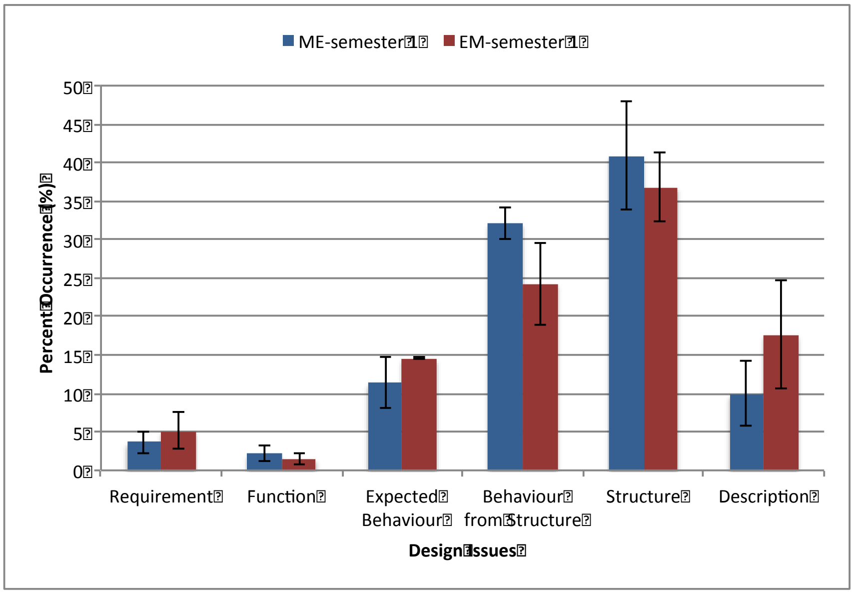


Figure 2: Semester 1 (Fall) Issue Distribution by Majors.

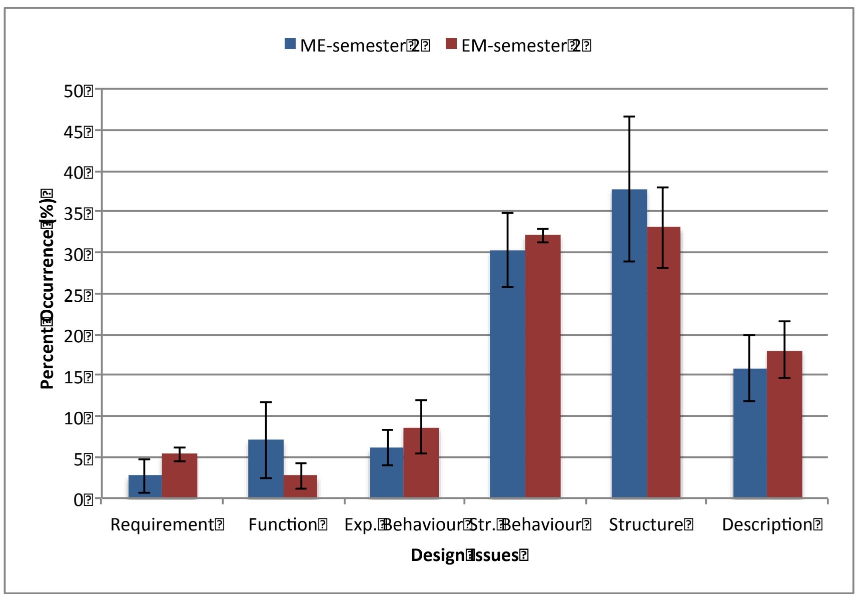


Figure 3: Semester 2 (Spring) Issue Distribution by Majors.

In general, similar results are seen in Semester 2. ME majors spent 5% and 4% more of their cognitive efforts on design issues of structure and function than EM majors, and EM majors spent 3% and 2% more of their cognitive efforts on design issues of expected behavior and description than those of ME majors.

The change in effort spent on each design issue between semesters by major is illustrated in Figure 4. ME majors expended about 6% and 5% more of their cognitive effort on design issues of description and function in Semester 2. Although the data cannot confirm causation, it is critical to note that these changes in cognitive behavior do correspond with learning objectives in the sophmore ME design class. Specifically, in the course, students engaged in several activities that emphasized the importance of identifying specifications, and in documenting design decisions [19]. Thus, increases in their attention to both function and description are desired outcomes from the course.

In contrast, the most significant change for EM majors was in the effort spent on behavior from structure, which increased about 8%. Addressing behavior from structure is a highly analytical process; again, though the data does not support causation, the sharp increase in this activity aligns with the increased focus on analyzing the mechanics of solutions in the EM major. This analytical approach directly correlates with the analytical modeling focus of their sophomore curriculum.

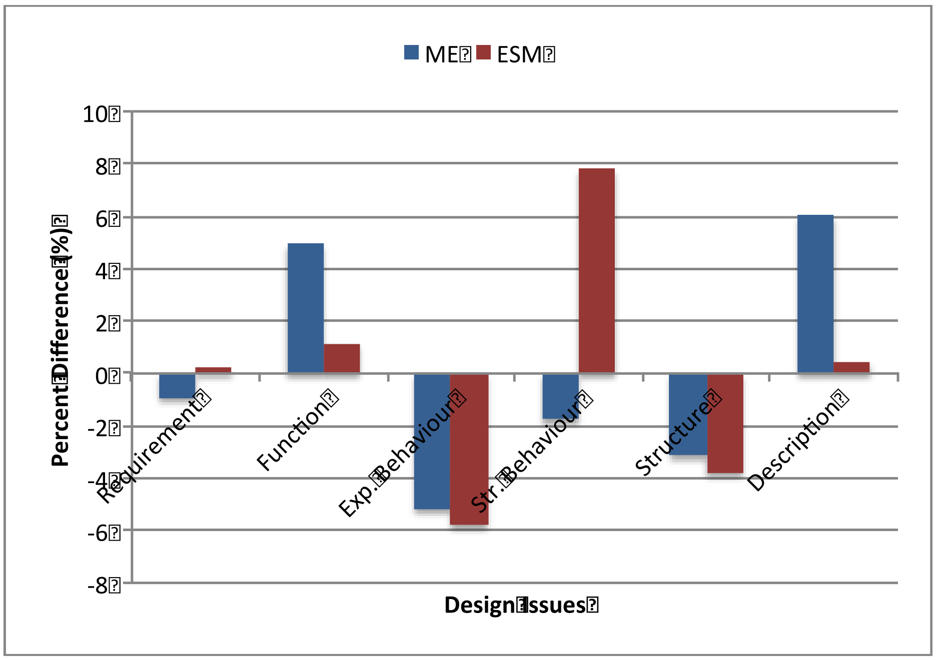


Figure 4: Percent Difference of Issue Distribution between semesters.

Of special interest are design issues where the students of the different majors had opposing changes between semesters. Most notable is that the EM students more frequently discussed issues relating to behavior from structure (*Bs*) in Semester 2 than in Semester 1, whereas ME students had fewer *Bs* utterances between semesters. As mentioned earlier, the upward trend for EM students correlates well with the curriculum's focus in modeling. The ME student's decreasing focus in *Bs* issues can be attributed to an increase in their focus on the "function" (*F*) of the design problem, which correlates well with the design course's focus in problem framing.

4.1.2. Syntactic Process Distribution Across the Entire Protocol

Figures 5 and 6 illustrate syntactic process distributions for each semester by majors. In both semesters, the majority of students' cognitive effort was expended on Reformulation 1 (30~33%) and Analysis (23~30%), which accounted for more than half of their cognitive effort. Much less cognitive effort was spent on the design process of Documentation (11~20%), Evaluation (8~17%), Synthesis (6~9%), Reformulation 2 (3~7%), Reformulation 3 (1~4%), and Formulation (~2%). This focus in Reformulation 1 and Analysis suggests significant amount of focus and iteration on the structural components of the design product– a hallmark of novice designers.

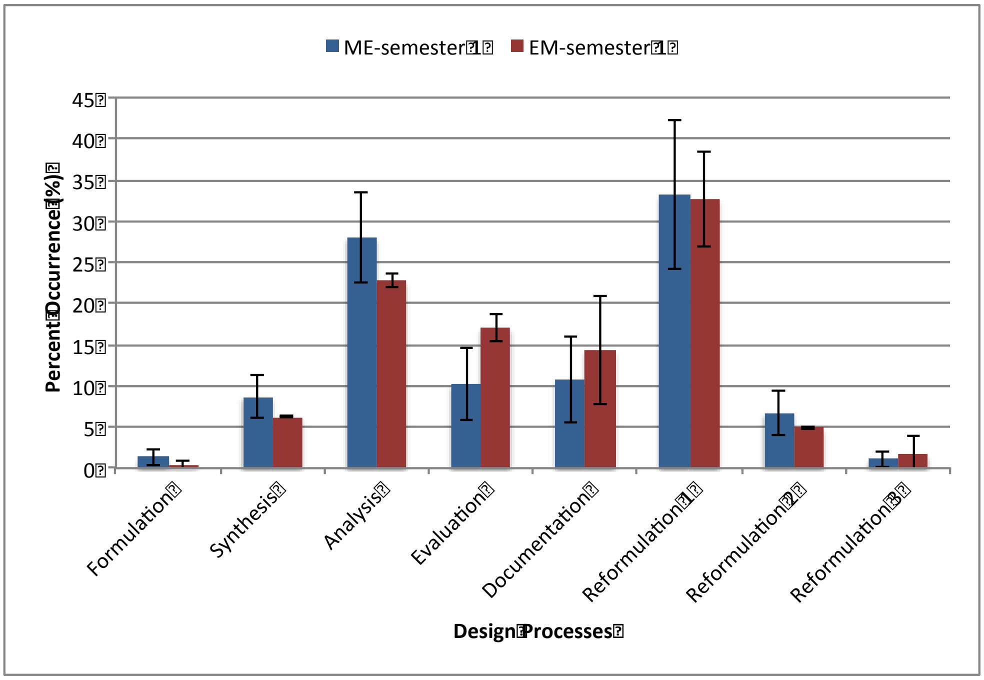


Figure 5: Semester 1 Syntactic Process Distribution.

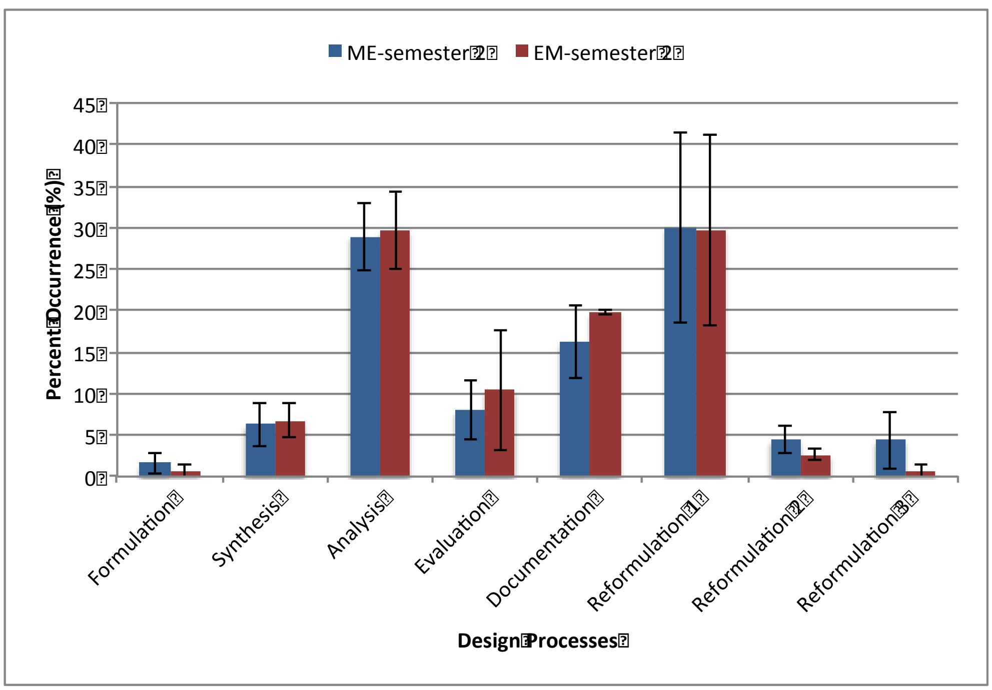


Figure 6: Semester 2 Syntactic Process Distribution.

Some differences in students' cognitive efforts on design processes were identified between majors. In Semester 1, EM majors expended more cognitive effort on the design processes of Evaluation (7%), Documentation (4%), and Reformulation 3 (1%) than those of the ME counterparts. On the contrary, ME majors expended more cognitive effort on the design processes of Analysis (5%), Synthesis (2%), Reformulation (2%), Formulation (1%), and Reformulation 1 (0.5%). The ME students' longer discussions related to Anaylsis and Synthesis point again to their strong focus on proposing and evaluating solutions to the problem.

In Semester 2, EM majors spent more cognitive effort on the design processes of Documentation (4%), Evaluation (2%), Analysis (1%), and Synthesis (1%) than those of the ME majors. Whereas, ME majors spent more cognitive effort on Reformulation 3 (4%), Reformulation 2 (2%), Formulation (1%), and Reformulation (1%).

The changes in effort for each design process between semesters by majors are illustrated in Figure 7. Both ME and EM majors expended more cognitive efforts on the design processes of Analysis (1%~7%), Documentation (6%), and Formulation (0.2~0.3) in Semester 2. Likewise, both majors expended less cognitive efforts on the design processes of Evaluation (2~7%), Reformulation 1 (3%), Reformulation 2 (2%) in Semester 2. As noted in the previous section, the EM students' large increase in having discussions related to Analysis correlate well to the "identity" of their major.

Interestingly, ME majors spent more cognitive effort on the design process of Reformulation 3 (3%) in Semester 2, while EM majors spent about 1% lower. Reformulation 3 corresponds with iteration between discussions of the structure of the solution and the functions that it should satisfy (Section 2). This increase suggests that ME students are more likely to verify their design before finalizing its documentation, which was a core focus in their sophmore design class.

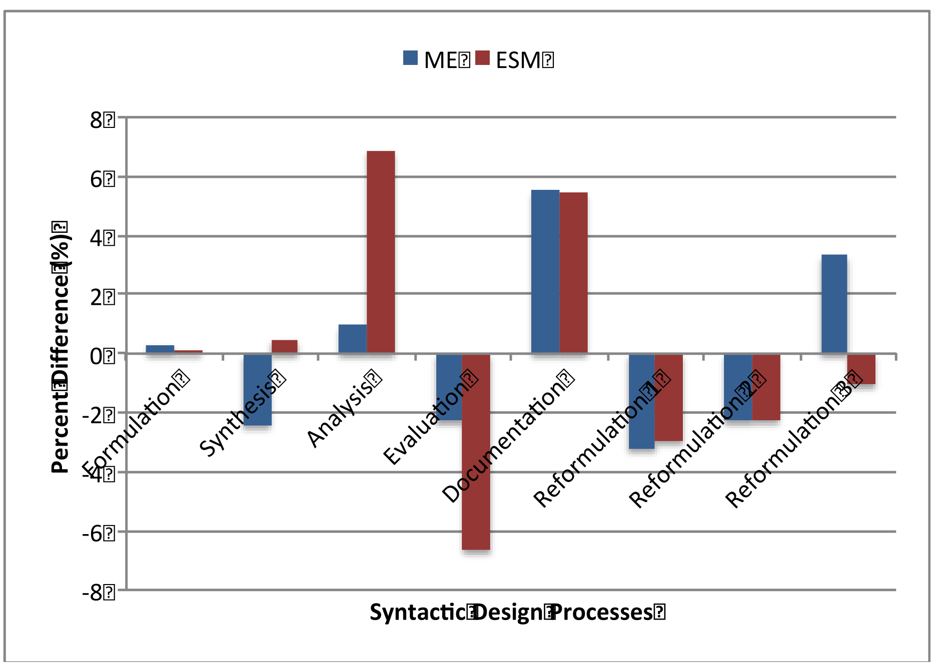


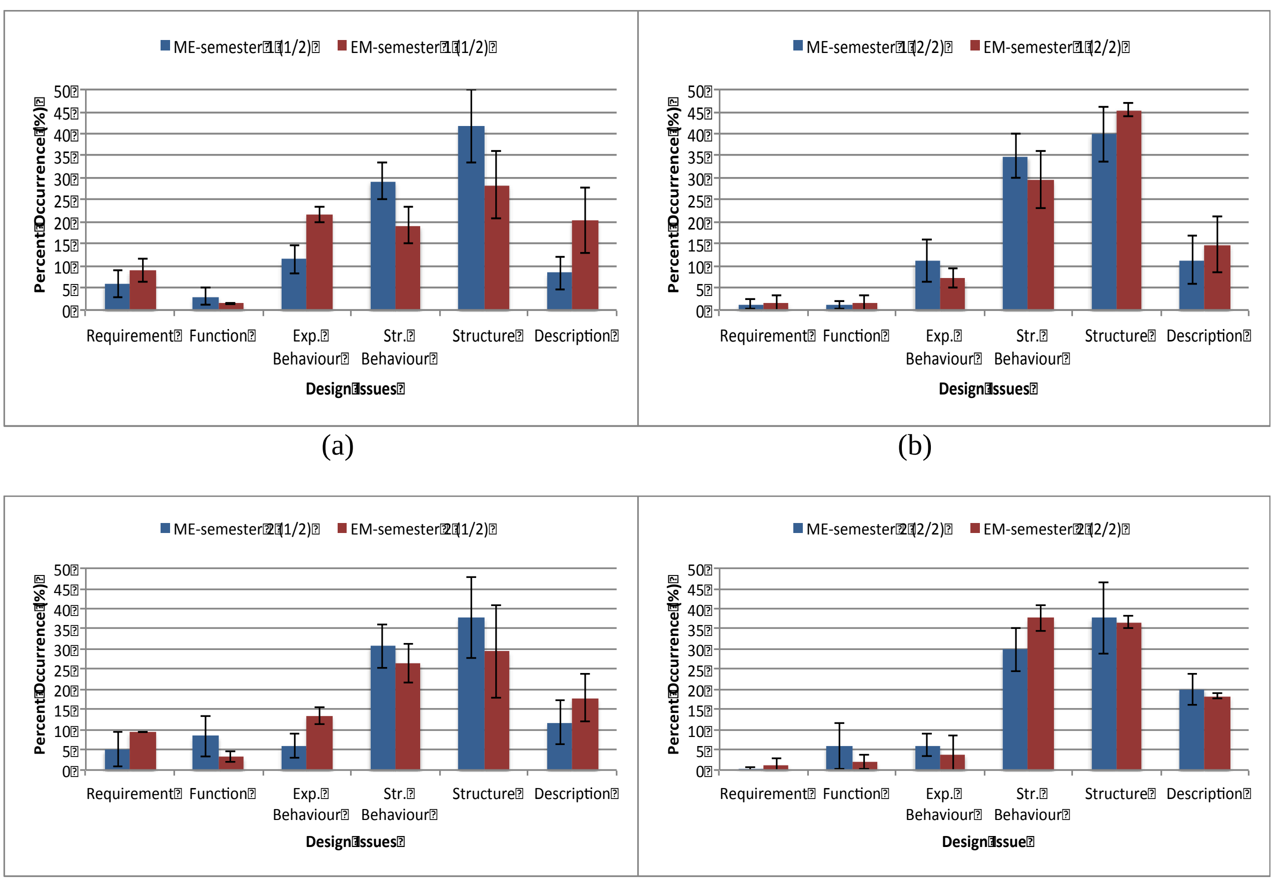
Figure 7: Percent Difference of Syntactic Process Distribution between Semesters

4.2 Designing and Time within Design Sessions: Preliminary Results

To investigate the effect of time on designing we divided each session's arbitrated protocol into sequential halves to provide a more detailed understanding of how a design session progressed. This division of the protocol into halves provides a preliminary look at participants' design activities through time. The percent occurrences of design issues and syntactic design processes from the first and second halves of the two sets of design sessions were then analyzed and compared across majors and across semesters.

4.2.1. Design Issue Distribution Across Time within Design Sessions

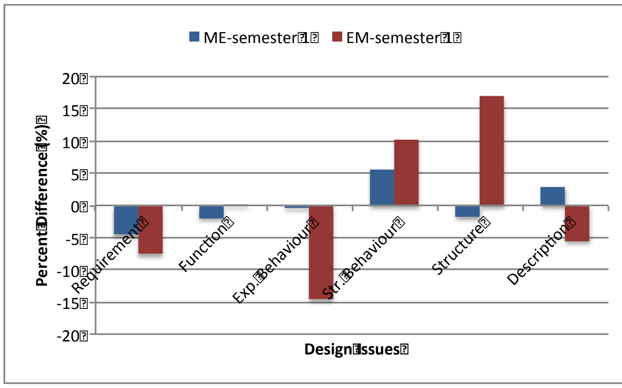
The distributions of design issues for each half of the design sessions, by semester and major, are shown in Figures 8(a) and 8(b) for Semester 1 and in Figures 8(c) and 8(d) for Semester 2. Figure 9 takes the data in Figure 8 and shows the differences between semesters for the first and second halves of the design sessions.

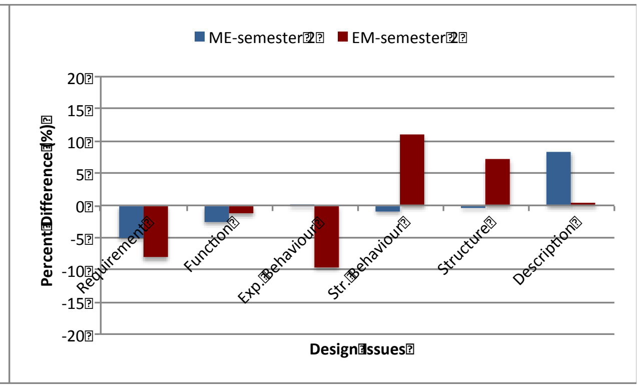


(a) (b) (c) (d)

Figure 8: Issue distribution: (a) 1st half of Semester 1, (b) 2nd half of Semester 1, (c) 1st half of Semester 2, (d) 2nd half of Semester 2.

Figures 8 and 9 show that, overall, time-based behaviors of the teams are generally qualitatively similar across both semesters with quantitative differences. There were significant differences in design issue distributions between the first and second halves of design sessions indicating a change of behavior over time within design sessions. Not all the differences were exhibited uniformly by both majors indicating a difference in design cognition between majors in terms of design issues.





(a) (b)

Figure 9: Percent difference of design issue between 1st and 2nd halves for: (a) Semester 1 and (b) Semester 2

The design issues of requirement and function were much higher in the first halves than the second halves of the design sessions for each semester. This means that both majors expended more cognitive effort on design issues related to requirements and functions in the beginning of the design sessions in both semesters. The cognitive effort expended on the design issue of expected behavior was unchanged between the first and the second halves for ME majors. However, there was a large decrease in the cognitive effort expended on the design issue of expected behavior for EM majors in both Semesters 1 and 2, meaning that EM majors tend to focus less on expected behavior as they progress towards the end of the design session. The cognitive effort expended on the design issue of structure behavior (i.e., behavior derived from structure) changed differentially between the first and the second semesters for ME majors. However, there was a large increase in the cognitive effort expended on the design issue of structure behavior for EM majors in both Semesters 1 and 2, meaning that EM majors tend to focus more on the structure behavior issues of design solutions as they progress towards the end of the design session.

The cognitive effort expended on the design issue of structure was largely unchanged between the first and the second halves for ME majors. However, there was a large increase in the cognitive effort expended on the design issue of structure for EM majors in both Semesters 1 and 2, meaning that EM majors tend to focus more on the structure issues of design solutions as they progress towards the end of the design session. The design issue of description increased for ME majors Semesters 1 and 2. For EM majors, the design issue of description decreased in Semester 1, but there was a marginal increase in Semester 2.

4.2.2. Design Process Distribution Across Time within Design Sessions

The syntactic design processes for each half of the design sessions by semester and major are illustrated in Figure 10.

Figure 11 takes the data in Figure 10 and shows the differences between semesters for the first and second halves of the design sessions. Figures 10 and 11 show that overall time-based syntactic design process behaviors of the teams are qualitatively similar across both semesters with quantitative differences. There were significant differences in design process distributions between the first and second halves of design sessions indicating a change of behavior over time within design sessions. Not all the differences were exhibited uniformly by both majors indicating a difference in design cognition between majors in terms of design processes.

These results, based on dividing the protocols into two halves, point toward further research into time-based design issue behavior and design process behavior. The existing protocols can be divided into a larger number of fractions to provide additional data points across each design session and hence to obtain a better understanding of design issue behaviors and design process behaviors across time.

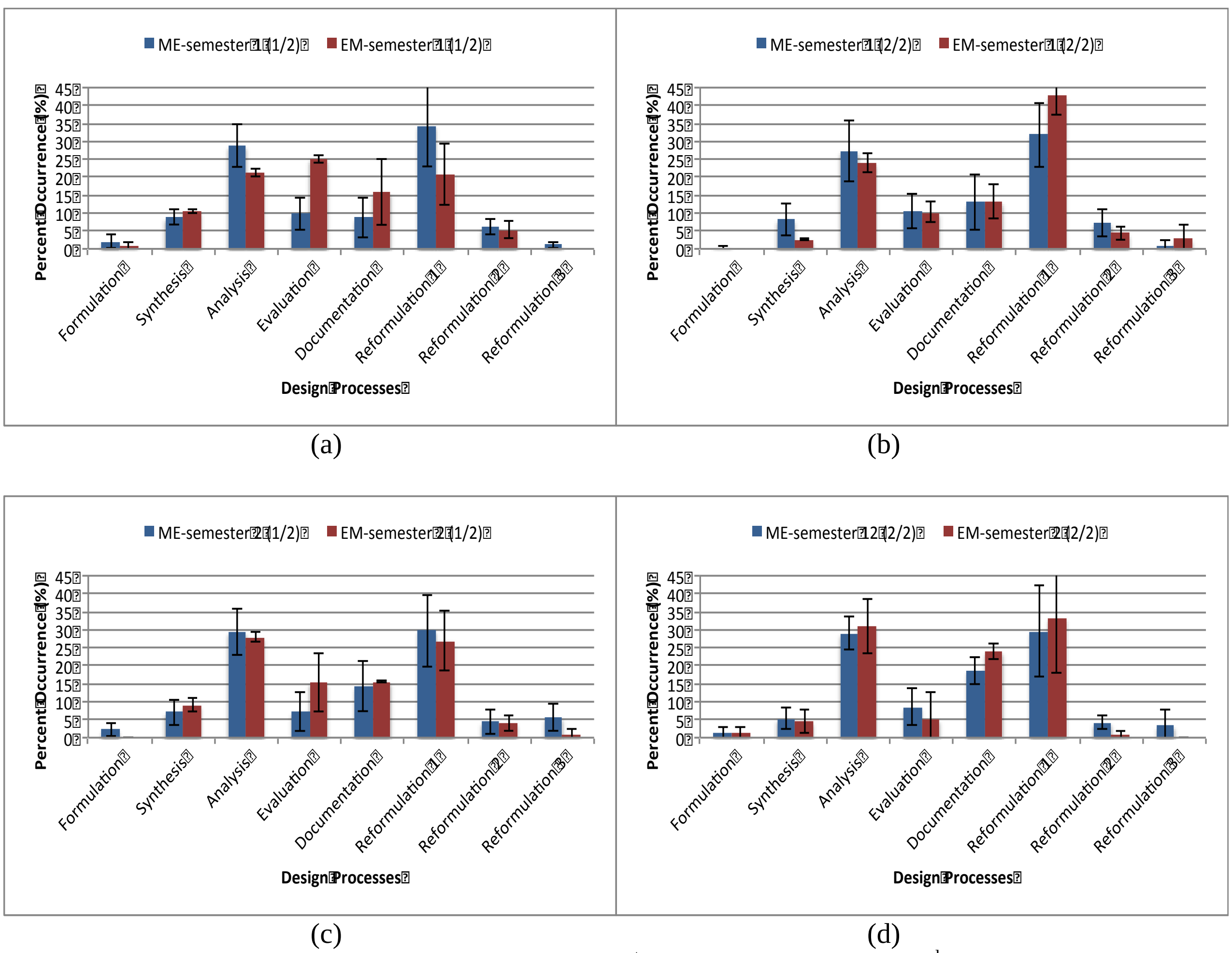
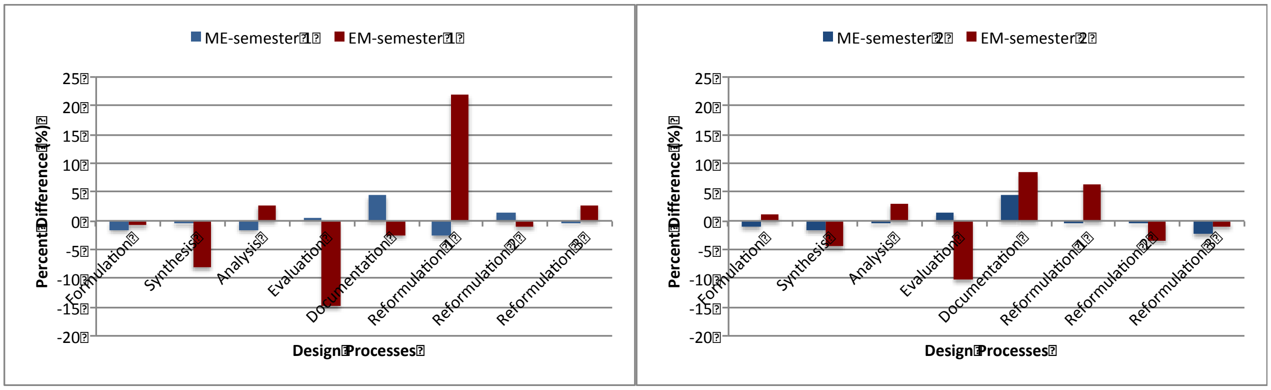


Figure 10: Syntactic design process distribution: (a) 1st half of Semester 1, (b) 2nd half of Semester 1, (c) 1st half of Semester 2, (d) 2nd half of Semester 2.



(a) (b)

Figure 11: Percent difference of design process between 1st and 2nd halves for: (a) Semester 1 and (b) Semester 2

5. Conclusion and Future Work

The results presented here demonstrate notable differences both between semesters and between majors. As noted earlier, the data presented here support correlation (though not causation) between the learning outcomes from design-based education experiences and students' subsequent design cognition. Moreover, because the differences are apparent not only as changes over time but as differences between major, the correlations do appear to have some relationship to students' curricular experiences. This correlation is, of course, the desired effect, but one that remains important to confirm through experimentation. In addition, as noted in Section 4.2, the changes include not only the overall issues and process students attend to, but how they spend their time and the attention issues receive as students move through a design task.

While the correlations demonstrated here are significant, even more useful are the remaining points in the longitudinal study. Analysis from subsequent years can help determine the degree to which student learning persists from year to year (i.e. Will we continue to see strong attention to Function in the ME students?), as well as changes that correlate to additional design experiences. Analysis of data from students' junior year is currently in process and will be presented at future conferences.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. NSF EEC-0934824. 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.

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