**Proceedings of the ASME 2011 International Design Engineering Technical Conferences &
Computers and Information in Engineering Conference
IDETC/CIE 2011
August 29 – August 31, 2011, Washington, DC, USA**

DETC2011-48357

EXPLORING THE EFFECT OF DESIGN EDUCATION ON THE DESIGN COGNITION OF MECHANICAL ENGINEERING STUDENTS

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ABSTRACT

In this paper, the authors report on progress of a 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 authors are working with engineering students to characterize their design cognition as they progress through engineering curricula.

In this paper, the results from a protocol study of sophomore Mechanical Engineering students are presented. Specifically, data gathered from two experimental sessions (conducted before and after the students' introductory design course) are analyzed to identify changes in design thinking cognition. Design cognition is determined using protocol analysis with the coding of the protocols based on a general design ontology, namely, the Function-Behavior-Structure (FBS) as a principled coding scheme (as opposed to an ad hoc one).

Preliminary results indicate that statistically significant changes in students' design cognition occur over the course of their sophomore year. The change manifests itself in an increase in focus on the purposes of designs being produced, which is often a precursor to the production a higher quality designs, and an increase in the design processes associated with the introduction of purposes of designs.

1 INTRODUCTION

1.1. Design Education and Design Cognition

What is the effect of design education on students' design cognition? While most of the current design education research focuses on describing approaches to engineering design teaching (a review is presented in Williams et al., 2010), there is little existing work that moves towards identifying the relationship between it and student learning.

To address this need, the authors are exploring the cognitive progress and development of design thinking of engineering students through a three-year longitudinal study. A control group of student participants are enrolled in an engineering mechanics program that adopts a first-principles approach and emphasizes computational analysis and a theoretical understanding of solids, fluids, and dynamics. The experimental group of students is from a mechanical engineering program that includes hands-on design experiences, machine design principles, and courses dedicated to design methods and product realization techniques.

To observe potential effects of engineering education on design cognition, the same group of students is studied at the end of each of their sophomore, junior and senior years. During these experimental sessions, participants are paired together and asked to design a solution to a speculative scenario. To determine design cognition, the authors conduct protocol analysis of the video-taped design sessions.

1.2. Protocol Analysis in Design Research

While engineering education research in design has been dominated by explorations of design teaching, there have been numerous cognitive studies of designers that have been aimed at elucidating design thinking behavior. They have fallen into five methodological categories: questionnaires, interviews (Cross and Cross 1998); input-output experiments (where the designer is treated as a black box which produces the behaviors in the outputs for changes in inputs) (Purcell et al 1993), anthropological studies (Lopez-Mesa and Thompson 2006), 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 study of designers.

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 (Crutcher 1994; Ericsson and Simon 1993; Van-Someren et al 1994). It has been used extensively in design research to assist in the development of the understanding of the cognitive behavior of designers (Adams and Atman 1999; Atman et al 1999; Atman and Bursic 1999; Badke-Schaub et al 2007; Christensen and Schunn 2007; Cross et al 1996; Ennis and Gyeszly 1991; Gericke et al 2007; Gero and McNeill 1998; Goldschmidt 2003; Kavakli and Gero 2002; McDonnell and Lloyd 2007; McNeill et al 1998; Purcell and Gero 1998; Purcell et al 1996; Suwa and Tversky 1997; Suwa et al 1998; Suwa et al 2000; Tang and Gero 2002).

There are two classes of protocol studies: think-aloud and retrospective (Ericsson and Simon 1993; Van-Someren et al 1994). 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 (Gero and Tang 2001). 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. Effects of Design Education on Mechanical Engineering Students

Given the demonstrated value of protocol studies, the authors use this approach as the tool for their exploration of changes in design cognition. In order to provide a uniform basis for comparing design students across projects and years, the authors use a task-independent protocol analysis method that is grounded on a design ontology-based coding scheme. This scheme, described in Section 2, is based on a general design ontology, namely, the Function-Behavior-Structure (FBS) ontology (Gero 1990). The power of this approach lies specifically in its move from the analysis of design behaviors, which may be tied to a single domain, to the elucidation of design cognition; this move is critical to furthering the ability of design researchers to make robust comparisons across a wide variety of settings.

In this paper, the authors present the results of protocol analyses from the first year of the study. The focus in this paper is the Mechanical Engineering (experimental) group. Two design sessions were conducted during their sophomore year: one before, and one after, an introductory design course. Using the protocol analysis techniques described here, the change in design cognition of the students is analyzed.

Following the description of the protocol analysis, and the ontology on which it is based, the authors present the experimental approach in Section 3. Results from the protocol analysis are analyzed in Section 4. Conclusions and next steps appear in Section 5.

2 THE FBS ONTOLOGY AND CODING SCHEME

2.1 The FBS Ontology

The FBS ontology (Gero 1990) 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 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.

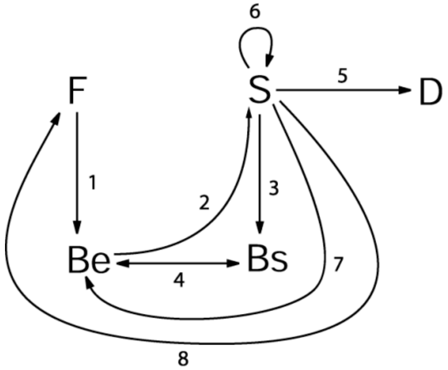

Figure 1. The FBS ontology

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 (Branki 1995; Gero and Kannengiesser 2004; Gero and Kannengiesser 2007; Robin et al 2007; Van Wie et al 2005).

2.2 FBS Coding Scheme

In typical protocol analyses, researchers commence with a pre-existing coding scheme and modify it based on the task and events in the current protocol. In this project we use a principled, design-based coding scheme based on the FBS ontology (Section 2.1) to code participants' utterances during design sessions.

Examples of the FBS coding scheme are provided in this section for each of the ontological variables in the context of the double-hung window opener design brief (Box 1, Section 3.2). Coded samples of participants' utterances are presented in italics.

Function (F). The students' utterances associated with the following issues were considered as the *function*:

- The scope of design: Designers must identify and determine the boundaries of their design outcome. In the window opener example, some students were confused on whether they had to redesign the existing window or to design a device. The following excerpt is an example of when the scope of design is determined.

  "I was saying you can't design the whole new window, we got to design a device"

  The design brief does not include the exact specifications of a double-hung window. Therefore, students had to either assume the window specifications, or design a device that would work for any kind of double-hung windows.

  "*Yeah. Definitely want it (the design solution) to be the most… as universal as possible"*

- Design functionalities: The design functionality refers to what the design outcome would achieve. In case of window opener design, opening and closing a double-hung window is the primary objective of what the design solution must accomplish.

  "*Well the main objectives I mean (the device) has to lift and lower it (double-hung window)"*

- User characteristics: User characteristics refer to the attributes of the users that need to be incorporated in the design. The window opener design brief describes the users as elderly tenants who live in a nursing home. Therefore, attributes associated with the physical capabilities of elderly tenants would be the relevant user characteristics that must be considered in the design. The following excerpts are examples of how user characteristics are incorporated as the *functions*.

  "*for people who would be weak on upper body)*"
  "but I was just thinking like a lot of people are in wheelchairs when they are old."
  "*can be used by a person with weak arms*"

- Value adding features: Some examples of the value adding design features can be the aesthetics, ease of use, or product reliability of the final design. The following excerpt is an example of considering the ease of use of their design.

  "*to make it much easier for the eldery…*"

Expected Behavior (Be). The *expected behavior* includes utterances that are associated with design issues to accomplish the function, yet without considering the structural component of the design.

"*… to reduce the amount of force that they would need… to do.*"

In the above excerpt, the students are transforming the design *function* (design for elderly people) into *expected behavior* (reducing the required force).

"*Somehow it would need to be strong across, so that it will lift up like both sides at the same time.*"

In this excerpt, the students identified that proper lifting of a window (design *function*), requires strong enough force that can be equally applied to the windowpane (*expect behavior*). No mechanical or structural properties are determined, yet it is expected to behave in such manner to fulfill the design *function*.

Behavior from Structure (Bs). The *behavior from structure* includes utterances that describe the motions of the structures that form the design. In the window opener design example, physical effects, such as lever and pulley are used to amplify the force. To analyze whether those mechanical properties are effectively synthesized to the design, a mental simulation of the expected behaviors of structures is necessary. The following excerpt is a description of how two gears with a rope can pull down the window.

"*When this goes clockwise this is will go counterclockwise, right? So, if that goes counterclockwise, then that would be pulling it down, right? That'll be pulling the window down*"

Structure (S). The *structure* involves utterances that are associated with an object's property, location, and relationships. The following excerpt describes how a gear, crankshaft, and pulleys are physically located and connected to one another.

"If there is like a gear attached to the side of the window, you can have just like a crank shaft and like two pulleys and this would be like linked."

The description (D) refers to when design related issues are written or sketched, as depicted in the Figure 2.

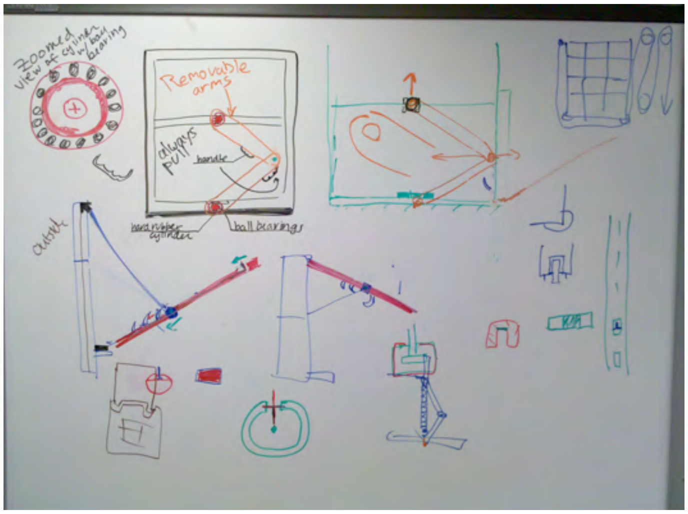

Figure 2. Participant white-board sketch examples, coded as *description* (D)

The FBS coding scheme can be summarized, using the design terminology embodied in Figure 1, with the addition of the symbol *R* for Requirements. Requirements come from outside the designer. This produces six codes for the six cognitive design issues (labeled events or segments in protocol analysis) and those six codes can be combined to produce eight design processes, as seen in Table 1, where ">" means unidirectional transformation and "<>" means comparison.

Table 1. FBS Syntactic Processes (Numbers Refer to Labels in Figure 1)

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 METHOD

3.1 Participants & Context

Participants for the study described in this paper were drawn from the Department of Mechanical Engineering (ME) of a large mid-Atlantic land grant university. 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 is 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 (Williams et al., 2010).

At the time of the study described in this paper, the student participants were enrolled in a second-year ME design course, "Engineering Design and Economics," that focuses in exposing students to engineering design and design methodologies at an early stage in their professional development. This 3-credit 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 (IC engines, air compressors, electric drills, disposable cameras, etc.) to various speculative design scenarios. These activities provide an opportunity for the instructor to perform individual mentoring and instruction. In addition to these in-class activities, student design teams work together out-of-class on a semester project wherein they design a novel consumer product.

The data collected in this phase of the study represents the beginning of the students' formal design education and experience. At this stage in their education, the students' design education is limited to a four-week "Introduction to Engineering Design" module in their first-year introductory engineering course. 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

Once participants were successfully identified, they were asked to attend two out-of-class experiments: one at the beginning of the fall semester of their sophomore year; the other in the middle of the spring semester of the same academic year. In these experiments, pairs of students worked together at a white board to solve a speculative design task. Total 28 students (16 in fall 2009 and 12 in spring 2010) participated the design session. The problem statements of these design scenarios are presented in Boxes 1 and 2.

Box 1. Fall 2009 Session: 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.

Box 2. Spring 2010 Session: 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)

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.

- *Video taping 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 completes transcription manually. The result is a time-stamped, typed version of the verbalizations in a session.
- *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 as described in Section 2.2. Each segment can contain only one code (Kan and Gero 2007a). This harmonizes all segmentation when using this coding scheme since there is now an *isomorphism between segments and codes*. 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 (Linstone and Turoff 1975). The result is the final, arbitrated protocol. This final protocol is the first data set available for analysis. The final protocol for a 90 minute design session typically generates between 300 and 1,000 segments. This provides a rich and statistically significant data set.

4 RESULTS AND ANALYSIS

4.1 Design Issues

The distributions of design issues before and after the introductory design course described in Section 3.1 are illustrated in Figure 3, with descriptive statistics reported in Table 2.

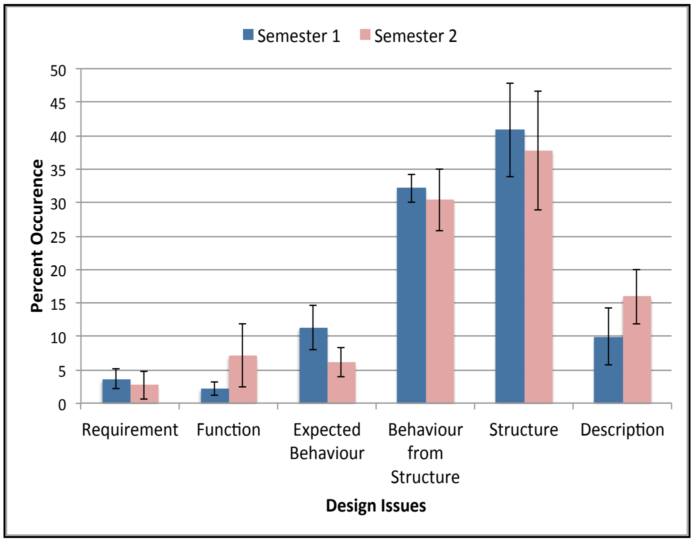

Figure 3. Percent Occurrences of Design Issues Before (Semester 1) and After (Semester 2) Exposure to Design Teaching

Table 2. Means and Standard Deviations of Design Issues Before (Semester 1) and After (Semester 2) Exposure to Design Teaching

Issue distribution	**Semester 1 (*n*=8) *Mean (SD)***	**Semester 2 (*n*=6) *Mean (SD)***
Requirement	3.62 (1.46)	2.70 (2.10)
Function	2.16 (1.07)	7.10 (4.67)
Expected Behavior	11.31 (3.32)	6.13 (2.22)
Behavior from structure	32.13 (2.12)	30.37 (4.58)
Structure	40.88 (7.01)	37.75 (8.83)
Description	9.91 (4.22)	15.93 (4.10)

In both data sets it is observed that students expended the majority of their cognitive effort discussing design structure (37~40%), followed by behavior from structure (30~32%). These two design issues accounted for two-thirds of their cognitive effort. Much less cognitive effort was spent on the design issues of description (9~15%), expected behavior (6~11%), function (2~7%), and requirement (2~3%). The variations between before and after being exposed to the design course have been identified for each design issue. The percentages of their cognitive effort related to design function and design description have increased approximately 5% and 6% respectively, whereas the percentages for all the other design issues have decreased.

JMP 9.0, a statistical software package, was utilized to identify any statistical differences in the percentages of cognitive effort related to individual design issues before and after the course. Statistically significant differences were assumed at a significance level (α) of 0.05. The normality assumption was tested for each design issue using the Shapiro-Wilk W test. Only the percentage of cognitive effort on the design issue of function rejects the null hypothesis, which states that the data are from the normal distribution. Therefore, the Wilcoxon rank sum test, a non-parametric statistical analysis, was used for the design issue of function, whereas two-sample t-tests were used for the rest. The results for these statistical analyses are reported in Table 3.

Table 3. Design Issues Comparisons Between Semester 1 and Semester 2 Statistical Analysis Results

Design issue	***t (z) statistics***	***p-value***
Requirement	-0.925	0.137
Function	2.904	0.003**
Expected Behavior	-3.495	0.004**
Behavior from structure	-0.879	0.409
Structure	-0.717	0.490
Description	2.685	0.021*

*$p < 0.05$, **$p < 0.01$

The statistical analyses indicate that there are significant differences regarding the percentages of cognitive effort on the three design issues of function, expected behavior, and description between the two semesters. In semester 2, students were more engaged in discussions related to the design function, which is the teleology of their design solution. Specifically, many students attempted to jointly optimize their design for two criteria: design for the users (patients) and design for the customer (rehabilitation institute). Students intended to solve the initial problems with their design, yet also aimed to add or modify the functionalities of their design based on criteria such as safety, security, or possibilities to failure.

The percentage of cognitive effort on the design issue of expected behavior significantly decreased from semester 1 to semester 2, after taking a design course. It is possible that this cognitive change could be caused by the design course's three-week focus on problem formulation and functional decomposition. In these portions of the course, students are taught to scope a design problem by identifying customer needs, transforming them into target specifications, completing a needs-metrics matrix and formulating function structures.

The percentage of cognitive effort on the design issue of description significantly increased after taking a design course. This increase could be due to the introductory design course as well – a major learning goal of the course is effective oral and written communication of design outcomes. As a result, students might be more confident in explaining their design innovations.

No significant differences in the percentages of cognitive effort on the design issues of requirement, behavior from structure, and structure between the two semesters were identified.

4.2 Syntactic Design Processes

The syntactic design process distribution was computed to identify differences between before and after an introductory design course. The occurrences of syntactic processes for the two semesters are illustrated in Figure 4, with descriptive statistics reported in Table 4.

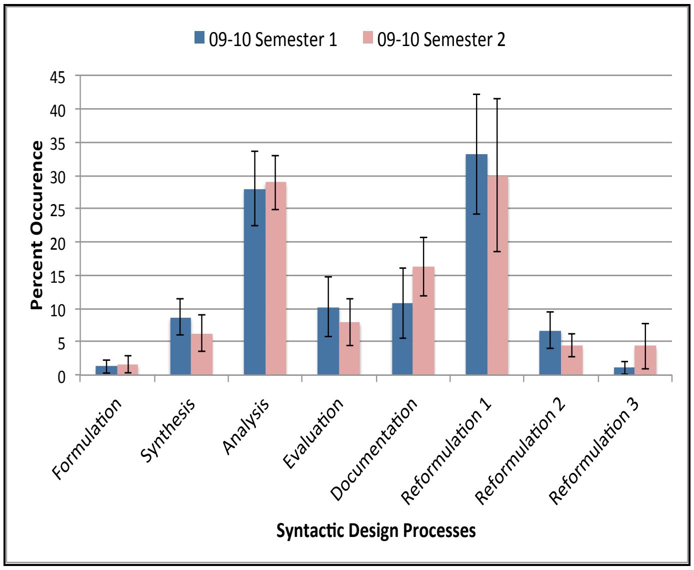

Figure 4. Percent occurrences of syntactic design processes before (Semester 1) and after (Semester 2) exposure to design teaching

Table 4. Means and Standard Deviations of Design Issues Before (Semester 1) and After (Semester 2) Exposure to Design Teaching

Syntactic process distribution	**Semester 1 (*n*=8) *Mean (SD)***	**Semester 2 (*n*=6) *Mean (SD)***
Formulation	1.32 (1.01)	1.65 (1.30)
Synthesis	8.70 (2.66)	6.28 (2.70)
Analysis	28.00 (5.55)	28.95 (4.08)
Evaluation	10.23 (4.44)	7.96 (3.57)
Documentation	10.77 (5.31)	16.30 (4.43)
Reformulation I	33.18 (9.00)	29.98 (11.42)
Reformulation II	6.72 (2.70)	4.45 (1.69)
Reformulation III	1.06 (0.92)	4.38 (3.43)

The majority of students' cognitive effort was expended on reformulation I (29~33%) and analysis (28%), which accounted for almost two-thirds of their cognitive effort. Much less cognitive effort was spent on the design processes of documentation (10~16%), evaluation (7~10%), synthesis (6~8%), reformulation II (4~6%), reformulation III (1~4%), and formulation (1%). Some differences were identified between the two semesters for each design process. A large increase in the percentages of students' cognitive effort for documentation (6%) and reformulation III (3%) were identified, whereas a slight increase was identified for formulation (0.33%) and analysis (0.95%). The cognitive effort for design processes of synthesis, evaluation, and reformulation II have decreased approximately 2%, whereas, reformulation I decreased in 3%.

Two-sample t-tests were used to identify significant statistical differences in the percentages of cognitive effort related to individual design processes before and after the course, as shown in Table 5. As the percentage of cognitive effort on the design process of reformulation III did not follow the normal distribution, the Wilcoxon rank sum test was used.

Table 5. Syntactic Design Processes Comparisons Between Semester 1 and Semester 2 Statistical Analysis Results

Syntactic process	***t (z) statistics***	***p-value***
Formulation	0.506	0.624
Synthesis	-1.666	0.124
Analysis	0.368	0.718
Evaluation	-1.059	0.155
Documentation	-0.567	0.584
Reformulation I	-0.567	0.584
Reformulation II	-1.931	0.077
Reformulation III	2.070	0.038*

*$p < 0.05$

The results indicate that there is a significant difference of the percentage of cognitive effort on the design process of reformulation III. The design process of reformulation III represents changes in the design function when the actual behavior is evaluated to be unsatisfactory (Gero and Kannengiesser, 2004). The result reveals that the students were more engaged in the design process of modifying design issues of function based on their analysis of design structures. As explained in Section 4.1, the significant increase of discussions related to the design function in semester 2 provides some evidence of such result.

A smaller pattern of difference between the two semesters was identified for the design process of reformulation II. The design process of reformulation II addresses changes in the design behavior when the actual behavior of a design structure is evaluated to be unsatisfactory (Gero and Kannengiesser, 2004). This indicates that the students displayed a tendency of decreased engagement in the design process of modifying design issues of expected behavior based on their analysis of design structures. The result is supported by the significant decrease of discussions of expected behavior reported in Section 4.1.

5 CLOSURE

In this paper, the authors present results from the first year of a three-year longitudinal study. Specifically, results from two protocol analyses of sophomore mechanical engineering students, conducted before and after an introductory design course, are compared to identify changes in design thinking. The protocol analysis technique examines not only students' movements through the steps of a canonical design process, but also their engagement at a cognitive level with the interplay of the more fundamental concepts of product design: identifying and defining product function, structure, and behavior.

The results highlight that there were significant differences in students' design cognition between before and after an introductory design course. Particularly, the design issues of function and description have significantly increased, while expected behavior significantly decreased. The syntactic design process of reformulation III significantly decreased as well.

We cannot yet conclude that the introductory design course was the cause of the change in students' design cognition, without further analysis, and subsequent comparison, of the data from the control group (students enrolled in an engineering mechanics program that does not have design teaching). However, the introductory design course's focus in problem formulation, needs identification, and functional decomposition correlate to the observed cognitive changes.

What this work shows is that it is now possible to quantitatively measure design cognition both in terms of the design issues that designers focus on and the design processes they use to transform one design issue to another. These and other quantitative measures of design cognition, such as the rate at which design issues are brought up by the designer, can be used to compare design behavior before and after being taught a course on design and hence to begin to determine the effects of such an educational intervention.

6 ACKNOWLEDGMENTS

The authors wish to acknowledge Sergey Chernyak and Matthew Dworksy for their work as the primary coders of the experimental sessions.

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.

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