DO HIGH SCHOOL STUDENTS BENEFIT FROM PRE-ENGINEERING DESIGN EDUCATION?

Udo Kannengiesser[1], John S Gero[2], John Wells[3] and Matthew Lammi[4]
[1]Metasonic GmbH, [2]UNCC, [3]VPI and [4]NC-State

ABSTRACT

This paper tests the hypothesis that the design cognition of high school students who have taken pre-engineering courses will be different to those who have not. The test is based on analysing and comparing two sets of design protocol studies for the respective groups of students. All design protocols are coded uniformly using the Function-Behaviour-Structure (FBS) ontology. The analysis in this paper focuses on three aspects: design issue distributions, cumulative design issues and cumulative design processes. The results show that there is no statistical support for the hypothesis that differences exist between the pre-engineering and non-engineering student groups. These unexpected results potentially have profound implications for high school pre-engineering education.

1 INTRODUCTION

Elementary and secondary students are engaging in engineering activities in formal and informal settings across the United States. Engineering has also been making its way into elementary and secondary classrooms through numerous curricula and standards with design as the primary focus (Douglas 2001; Rogers 2006; Wells 2014). Although engineering design is becoming more common and accessible in K-12 venues, how these students go about design in engineering is not readily understood (Katehi et al. 2009; Schunn 2009; Silk and Schunn 2008). The aim of this research study was to further characterize student design cognition when engaged in engineering design problems.

While engineering education literature in design has largely been dominated by discussions of pedagogical approaches, there have been several cognitive studies of designers aimed at elucidating design thinking behaviour. The most prevalent research method currently being used for such work is protocol analysis (Atman and Bursic 1998), which has become the basis of many recent cognitive studies of designers (Adams et al. 2003; Christensen and Schunn 2007; Cross et al. 1994; Kavakli and Gero 2002; Atman et al. 2007). The present study used protocol analysis as the experimental approach, founded on a design-ontology-based coding scheme derived from innovations in cognitive science. The coding scheme is based on a general design ontology, the Function-Behaviour-Structure (FBS) ontology (Gero 1990), which provides a design-based coding scheme (rather than either a task-based or an ad hoc scheme).

This paper tests the foundational teaching and learning hypothesis that the design cognition of high school students who have taken pre-engineering courses will be different to those who have not. This test is based on a design cognition study involving two groups of high school juniors: those who have taken pre-engineering courses and those who have not. Equal numbers of dyad teams from both groups engaged in design-only sessions in which they generated solutions in response to the same design challenge. The design sessions were video- and audio-recorded. The recordings were transcribed and then segmented and coded using the Function-Behaviour-Structure (FBS) ontologically-based design issues coding scheme. The students' design cognition was measured from the cumulative occurrence of the design issues and design activities. Both the design issues and the resulting design processes were compared between the two high school student groups.

The paper is structured as follows. Section 2 presents the collection of protocol data from design experiments with the high school students, and the subsequent coding of the protocols in terms of sequences of design issues and the resulting sequences of design processes. Section 3 describes the statistical and cumulative occurrence analysis that was run over the datasets. Section 4 presents the results of the analysis including a comparison between engineering and non-engineering students. Section 5 concludes the paper with a discussion of the implications of the study.

2 DESIGN PROTOCOLS

2.1 Experiments with High School Students

2.1.1 Participants

Participating high school juniors in this longitudinal study were drawn from three rural mid-Atlantic high schools, all of which offered the same pre-engineering course series. Participants were solicited in the fall of their junior year and assigned to experiment and control groups, comprised of those with (experiment) and without (control) formal pre-engineering course experiences. Formal experiences ranged from one previous year of coursework to being enrolled in a pre-engineering course at the start of their junior year. Students in the control group had no such prior experiences. Both groups had the same number and gender distribution of students. Each group had 20 students in dyads, randomly assigned, with a group gender distribution of 35% female and 65% for each of the two groups.

2.1.2 Research Design

This longitudinal study used a two-by-two factorial research design across two exogenous variables (design experience and maturity) to investigate high school student design practices over two years. This paper reports initial results of year one data collected from participating high school juniors. In this first year pairs of students (dyads) collaborated at a whiteboard to arrive at a solution to an engineering design challenge. The challenge asked students to design a device to assist physically impaired elderly nursing home residents in opening a stuck double-hung window without the use of an external energy source. This scenario has been used in prior studies and thus provides a meaningful basis for comparing findings across studies and populations.

Student dyads collaborated on the design challenge for 45 minutes and were instructed to provide a detailed sketch of their solution on the whiteboard. Each member of the dyad was equipped with a lapel microphone to ensure capture of quality audio. Two video recording devices located at different vantage points (whiteboard and general) captured student interactions. Video recordings captured student dyad engagement throughout the entire design-only session.

2.2 Coding the Design Protocols

The FBS ontology (Gero 1990) represents designing as a process that takes externally given requirements (R) as input and produces design descriptions (D) as output, using a set of transformations operating on function (F), expected behaviour (Be), behaviour derived from structure (Bs), and structure (S). These six ontological design issues (R, F, Be, Bs, S, and D) are defined as follows:

- *Requirements (R)*: includes all requirements and constraints that are explicitly provided to the designer by the client or through formal societal codification in terms of codes of practice.
- *Function (F)*: includes teleological representations that can cover any expression related to potential purposes of the design.
- *Expected Behaviour (Be)*: includes attributes of the design used as assessment criteria or target values for potential design solutions. They may include technical, economic, ergonomic and other characteristics.
- *Behaviour derived from structure (Bs)* (or, shorthand, "structure behaviour"): includes attributes of the design that are measured, calculated or derived from observation of a specific design solution.
- *Structure (S)*: includes the components of a design and their relationships. They can appear either as a set of general concept solutions or as detailed solutions.
- *Description (D)*: includes any form of external representation produced by a designer, at any stage of the design process.

The design processes operating on these six design issues are defined in the FBS framework (Gero 1990), shown in Figure 1. They include:

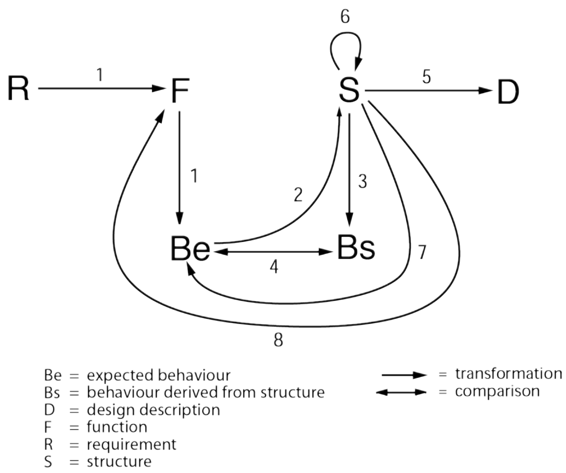

Figure 1. The Function-Behaviour-Structure Framework

- *Formulation*: transforms requirements into functions (R → F), and functions into expected behaviour (F → Be).
- *Synthesis*: transforms expected behaviour into structure (Be → S).
- *Analysis*: transforms structure into structure behaviour (S → Bs).
- *Evaluation*: compares expected behaviour with structure behaviour (Be ↔ Bs).
- *Documentation*: transforms structure into a description (S → D).
- *Reformulation type 1*: transforms structure into new structure (S → S').
- *Reformulation type 2*: transforms structure into new expected behaviour (S → Be').
- *Reformulation type 3*: transforms structure into new function (S → F' via Be).

The FBS design issues form a principled coding scheme for segmenting and coding transcripts of the experiment videos (i.e., design conversations and gestures, etc.) into a sequence of design issues denoted by semantic symbols, i.e., the FBS codes. An arbitration method (Gero and McNeill 1998; Purcell 1996) was applied to increase the reliability of protocol segmentation and coding. It consists of two separate codings undertaken by two independent coders, and an arbitration session to resolve the coding disagreements identified in the previous coding results. The average inter-coder reliability across all protocols is 83%. The arbitrated result, namely, a sequence of design issues, becomes the foundational data for subsequent analyses that characterise the design cognition of the participants.

Sequences of design processes were extracted from the coded and arbitrated protocols using the LINKODER tool (http://www.linkoder.com/). This tool generates the syntactic relations between design issues of two consecutive segments, based on the FBS framework in Figure 1. An example is provided in Table 1. It shows that for some syntactic relations (or transitions) between design issues no design activity is defined in the FBS framework; these transitions are represented using the term "blank" in Table 1. As a final step of preparing the protocol data for analysis, all "blanks" are removed from the datasets.

Table 1. Excerpt from a coded design protocol

<table>
<tr><th>Segment number</th><th>Utterance</th><th>Design issue</th><th colspan="2">Design process</th></tr>
<tr><td>46</td><td>So like just in case the grips don't work,</td><td>Be</td><td rowspan="2">Synthesis</td><td></td></tr>
<tr><td>47</td><td>like something</td><td>S</td><td rowspan="2">Reformu-lation type 2</td></tr>
<tr><td>48</td><td>has to catch it</td><td>Be</td><td rowspan="2">Synthesis</td></tr>
<tr><td>49</td><td>Oh, have a net. Can we click on that? No. Okay</td><td>S</td><td rowspan="2">[blank]</td></tr>
<tr><td>50</td><td>All right so one of our ideas is I guess the rainbow grip</td><td>R</td><td rowspan="2">[blank]</td></tr>
<tr><td>51</td><td>with the suctions?</td><td>S</td><td rowspan="2">Analysis</td></tr>
<tr><td>52</td><td>Ok, I think that's a good idea</td><td>Bs</td><td rowspan="2">[blank]</td></tr>
<tr><td>53</td><td>Yeah, or the, what about the indoor silicone cup, since it's like indoor</td><td>S</td><td rowspan="2">Analysis</td></tr>
<tr><td>54</td><td>Should we do that one or the other?</td><td>Bs</td><td></td></tr>
</table>

3 DATA ANALYSIS

3.1 Statistical Analysis of Design Issues

A t-test was performed on the experiment and control groups' design issues across an entire design session to determine whether the differences between them are significant as one test of the foundational hypothesis.

3.2 Cumulative Occurrence Analysis

The analysis of the coded protocols follows recent studies applying quantitative measures to the cumulative occurrence of design issues (Kannengiesser et al. 2013; Gero et al. 2014). The cumulative occurrence of a design issue is calculated across all segments in a design protocol as follows: the cumulative occurrence (c) of design issue (x) at segment (n) is $c = \sum_{i=1}^{n} x_i$ where (x_i) equals 1 if segment *(i)* is coded as (x) and 0 if segment (i) is not coded as (x). Plotting the results of this equation on a graph with the segments (n) on the horizontal axis and the cumulative occurrence (c) on the vertical axis yields a visual representation of the cumulative cognitive effort represented by the occurrence of the design issues in a protocol, Figure 2. This analysis is performed for each of the six design issues.

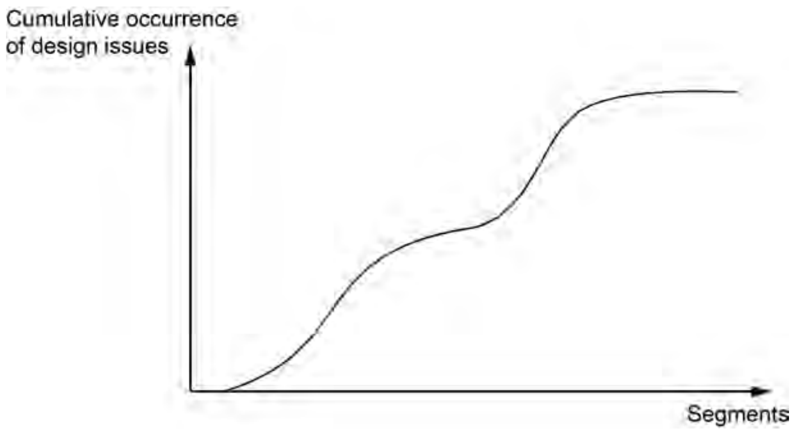

Figure 2. Graphical representation of the cumulative occurrence of a design issue in a design protocol

In this paper we generalise this analysis to also capture the cumulative occurrence of design activities. It is calculated in an analogous way: The cumulative occurrence (c) of design activity (y) at transition (n) is $c = \sum_{i=1}^{n} y_i$ where (y_i) equals 1 if transition *(i)* is coded as (x) and 0 if transition (i) is not coded as (x).

In this paper we use two quantitative measures that characterise the graphs of the cumulative occurrence of design issues and design processes. The first measures whether the cumulative occurrence is linear. This tests whether a particular design issue's cognitive effort is expended uniformly during the design session; if it is then the line of best fit will be linear. If the graph is linear then its slope can be measured and compared between groups.

- *R-square (RSQ):* is the variance of the graph from a first-order polynomial fitting curve. If RSQ ≥ 0.95, the graph is linear. Linear graphs indicate that the rate at which the design issues or design activities are generated is constant and that the cognitive effort is uniformly distributed across the design session for that issue or activity.
- *Slope:* is calculated for all graphs that are found linear. Its numeric value quantifies the rate at which the design issues or design activities are generated and the rate at which cognitive effort is expended.

4 RESULTS

4.1 Design Issue Distributions

For each group, the percentage of total segments associated with each design issue is shown in Figure 3.

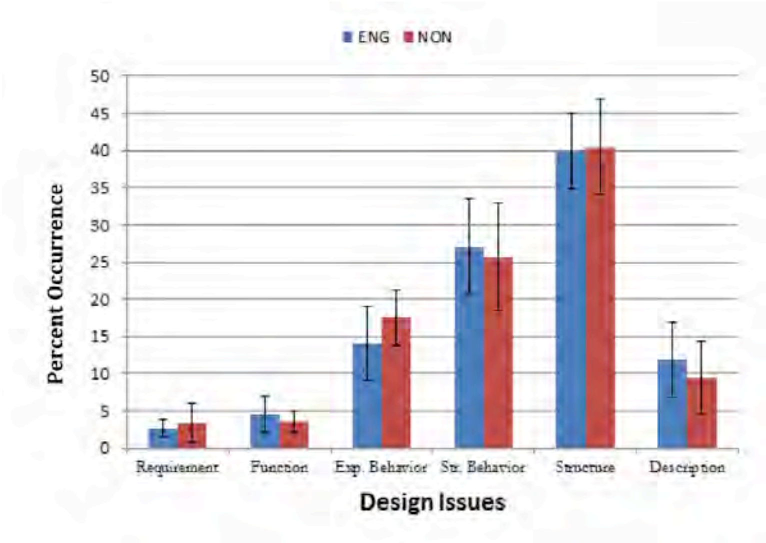

Figure 3. Percent occurrence of design Issues between pre-engineering (ENG) and non-engineering (NON) high schools students.

A t-test was performed on the experiment and control groups' design issues across an entire design session. The *t*-tests show that there is no significant difference between the two groups in terms of their design issue distributions, Table 2.

Table 2. t-test of high school student design issues.

Design Issues: High School ENG vs NON		
Design Issue	**t-value (%)**	**p- value**
Requirement	-0.78	0.2403
Function	1.05	0.1538
Expected Behavior (Be)	-1.7	0.0532
Behavior from Structure (Bs)	0.43	0.3344
Structure	-0.23	0.4100
Description	1.09	0.1453

4.2 Cumulative Occurrence of Design Issues

We limit our analyses to expected behaviour issues, structure behaviour issues, structure issues, and description issues. Requirement issues and function issues had too few occurrences to be able to run statistical analyses on them.

4.2.1 Linearity

Linearity is identified when the mean RSQ value for a design issue across all design protocols in a dataset is at least 0.950 and when at least 90% of the individual RSQ values for the design issue in the dataset indicate linearity. The results are shown in Tables 3, 4, 5 and 6.

Table 3. Expected Behaviour Issues: Linearity

Dataset	Mean RSQ (Stdev)	Linear individual graphs [%]	Linearity
Engineering	0.935 (0.051)	42	No
Non-Engineering	0.921 (0.081)	41	No

Table 4. Structure Behaviour Issues: Linearity

Dataset	Mean RSQ (Stdev)	Linear individual graphs [%]	Linearity
Engineering	0.984 (0.011)	100	Yes
Non-Engineering	0.961 (0.072)	84	No

Table 5. Structure Issues: Linearity

Dataset	Mean RSQ (Stdev)	Linear individual graphs [%]	Linearity
Engineering	0.994 (0.004)	100	Yes
Non-Engineering	0.977 (0.070)	95	Yes

Table 6. Description Issues: Linearity

Dataset	Mean RSQ (Stdev)	Linear individual graphs [%]	Linearity
Engineering	0.920 (0.072)	43	No
Non-Engineering	0.931 (0.084)	59	No

The results show that Engineering and Non-Engineering groups are not statistically different in terms of linearity except for one design issue: structure behaviour. Here the Non-Engineering group, unlike the engineering one, narrowly fails the threshold criterion of 90% of individual RSQ values being linear. For structure issues, both datasets exhibit linearity. For expected behaviour and description issues, there is no linearity in both datasets.

4.2.2 Slopes

The next step is to calculate mean slopes for all linear graphs within a dataset, Table 7. We can use *t*-tests to determine whether differences in slopes across the datasets are statistically significant. The *t*-test results are shown in Table 8, in terms of the *t*-values and p-values for each *t*-test. If the p-value associated with the test statistic t is lower than 0.05, the difference between slopes is statistically significant.

Table 7. Mean slopes (design issues)

Dataset	Expected Behaviour (Stdev)	Structure Behaviour (Stdev)	Structure (Stdev)	Description (Stdev)
Engineering	0.154 (0.027)	0.321 (0.074)	0.421 (0.057)	0.129 (0.052)
Non-Engineering	0.179 (0.059)	0.313 (0.053)	0.423 (0.065)	0.113 (0.042)

Table 8. t-tests comparing mean slopes of Engineering and Non-Engineering datasets (design issues)

Expected Behaviour		Structure Behaviour		Structure		Description	
t-value	p-value	*t*-value	p-value	*t*-value	p-value	*t*-value	p-value
1.027	0.334	0.409	0.687	0.102	0.919	0.719	0.483

The *t*-tests show that there is no difference between the Engineering and Non-Engineering groups. The mean slopes of all design issues analysed in this study are statistically the same.

4.3 Cumulative Occurrence of Design Processes

We limit our analyses to the design processes of synthesis, analysis, evaluation, documentation, reformulation type 1 and reformulation type 2. For formulation and reformulation type 3, the number of occurrences was too low to derive statistically meaningful results.

4.3.1 Linearity

Linearity of design processes is identified in an analogous way to the linearity of design issues. The results are shown in Tables 9, 10, 11, 12, 13 and 14.

Table 9. Synthesis: Linearity

Dataset	Mean RSQ (Stdev)	Linear individual graphs [%]	Linearity
Engineering	0.937 (0.037)	46	No
Non-Engineering	0.941 (0.055)	54	No

Table 10. Analysis: Linearity

Dataset	Mean RSQ (Stdev)	Linear individual graphs [%]	Linearity
Engineering	0.972 (0.051)	95	Yes
Non-Engineering	0.979 (0.013)	100	Yes

Table 11. Evaluation: Linearity

Dataset	Mean RSQ (Stdev)	Linear individual graphs [%]	Linearity
Engineering	0.941 (0.033)	57	No
Non-Engineering	0.939 (0.064)	55	No

Table 12. Documentation: Linearity

Dataset	Mean RSQ (Stdev)	Linear individual graphs [%]	Linearity
Engineering	0.901 (0.108)	40	No
Non-Engineering	0.938 (0.049)	60	No

Table 13. Reformulation type 1: Linearity

Dataset	Mean RSQ (Stdev)	Linear individual graphs [%]	Linearity
Engineering	0.979 (0.021)	95	Yes
Non-Engineering	0.979 (0.016)	100	Yes

Table 14. Reformulation type 2: Linearity

Dataset	Mean RSQ (Stdev)	Linear individual graphs [%]	Linearity
Engineering	0.928 (0.066)	50	No
Non-Engineering	0.946 (0.050)	69	No

The results show that there is no statistically significant difference between the Engineering and Non-Engineering groups in terms of linearity. For the design activities of analysis and reformulation type 1, the cumulative occurrence graphs are linear. For the other design processes, the graphs are non-linear.

4.3.2 Slopes

The mean slopes for all linear graphs of each design process are shown in Table 15, and the associated *t*-tests are shown in Table 16.

Table 15. Mean slopes (design processes)

Dataset	Synthesis (Stdev)	Analysis (Stdev)	Evaluation (Stdev)	Documentation (Stdev)	Reformulation type 1 (Stdev)	Reformulation type 2 (Stdev)
Engineering	0.110 (0.034)	0.261 (0.072)	0.154 (0.037)	0.134 (0.072)	0.357 (0.099)	0.129 (0.028)
Non-Engineering	0.139 (0.042)	0.266 (0.090)	0.160 (0.055)	0.134 (0.060)	0.341 (0.089)	0.136 (0.054)

Table 16. t-tests comparing mean slopes of Engineering and Non-Engineering design processes

Synthesis		Analysis		Evaluation		Documentation		Reformulation type 1		Reformulation type 2	
t-value	p-value	*t*-value	p-value	*t*-value	p-value	*t*-value	p-value	*t*-value	p-value	*t*-value	p-value
1.338	0.208	0.209	0.836	0.221	0.830	0.008	0.993	0.546	0.589	0.343	0.737

The *t*-tests reveal that the mean slopes between the two datasets statistically do not differ from each other.

5 DISCUSSION

The analysis of the results for design issue distributions, the cumulative design issues and the cumulative design processes all show a lack of support for the foundational teaching and learning hypothesis that the design cognition of high school students who have taken pre-engineering courses will be different to those who have not. In order to investigate this lack of expected difference between these two groups demographic information relating to prior engineering experiences was collected.

Though demographic data indicates some degree of common prior pre-engineering experiences, it does not provide sufficient grounds to explain finding no significant differences in engineering design thinking between these groups. Curricular and pedagogical factors must therefore be considered. The pre-engineering students all participated in the Project Lead the Way (PLTW) program. The PLTW program documents present entry-level course outlines that do not specifically target design thinking as a learning goal. This is equally the case for the curriculum used by the middle school technology education programs at participating schools. In light of this, it suggests that the pedagogical preparation provided to educators delivering the PLTW might not be adequate for intentionally incorporating or promoting design thinking as part of the pre-engineering experiences.

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