Characterizing Design Cognition of High School Students:

Initial Analyses Comparing those With and Without Pre-Engineering Experiences

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Background

Engineering design used as an instructional strategy at the PK-12 level is increasingly being embraced as a core learning method and pedagogical tool for integrative STEM education (Kolodner, 2002, Wells, 2010). As a key stakeholder in this trend toward integration of engineering design in K-12 STEM education curricula, it is critical that the elementary and secondary technology and engineering (T/E) education community understands the impact such experiences have on student development of design practices. Few studies have examined the cognitive characteristics of K-12 students during T/E design-based learning (T/E DBL) activities. Moreover, the way in which secondary students approach the engineering design process is not well understood (Katehi, Pearson, & Feder, 2009; Silk & Schunn, 2008), nor whether that approach differs between students who have engaged in formal engineering experiences through pre-engineering course work and those who have not. Within the context of increasing opportunities for K-12 students to engage in both formal and informal T/E design activities, investigations regarding the extent to which such high school experiences contribute to a student's capacity for design thinking (cognition) are needed. The intent of the research reported in this paper was to characterize the design cognition of high school students, and specifically to compare the design practices between high school students with and without formal pre-engineering design experiences.

Though few would argue that the design literature in engineering education has been somewhat singularly focused on pedagogical issues, there is a growing body of literature from studies that seek to understand the characteristics of design thinking behavior from a cognitive viewpoint (Cross, 2004; Lawson, 2004). Among these studies protocol analysis is the research method of choice (Atman & Bursic, 1998; Dorst & Cross, 2001) for investigating design cognition and has been the basis for many of the more recent design cognition studies (Adams, Turns, & Atman, 2003; Atman, *et al.*, 2007; Christensen & Schunn, 2007). The research study presented in this paper followed a verbal protocol analysis based on the Function-Behavior-Structure (FBS) ontology developed by Gero (1990), and its extension, the situated FBS (sFBS) ontology (Gero & Kannengiesser, 2004) as a design-based coding scheme. The FBS protocol analysis employs a task-independent approach, which is distinct from a task-based or an ad hoc approach. This approach to protocol analysis is applicable across any process-based view of designing and generates results based on a common comparative measure independent of the design challenge (task). In this way the FBS protocol analysis addresses the underlying cognitive processes, as opposed to the standard behavioral-based analysis, and therefore provides a uniform basis for comparisons between students with different educational preparation and backgrounds, and from different educational environments (Jiang, Gero, &Yen, 2014; Williams *et al.*, 2011).

Function, Behavior, Structure Verbal Protocol

FBS Ontology

The FBS ontology presents designing as the process of converting a set of functions into a set of design descriptions whereby those descriptions accurately convey an artifact capable of such functions (Gero, 1990). The design process is characterized in the FBS ontology (Fig. 1) using three classes of ontological variables: function, behavior, and structure, plus external design requirements given the designer and a final description of the designed structure. Modeled in this way *function* (F) is defined as the teleology of a designed object and the *behavior* of that object is either what is expected (Be) from the structure or derived (Bs) from the structure. The *structure* (S) of an object represents individual components and the relationships among them. The external design requirements the designer is given are designated by R, and the resultant set of design descriptions designated by D. These six ontological variables in the FBS model map onto design issues and serve as the basis for design cognition.

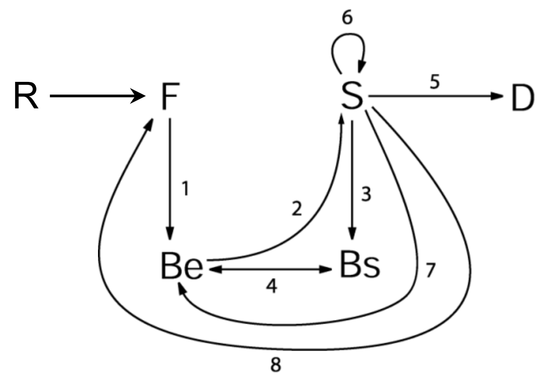

Figure 1 The FBS Ontology

A design description is the result of a designer having progressed through a set of eight distinct processes each of which reflects their movements (Numbers 1-8, Fig. 1) among the ontological variables. The first five processes reflect an implied linear sequence of movements that include *formulation* (1) whereby requirements are transformed into functions and functions into a set of expected behaviors; *synthesis* (2) which results in a proposed structure to satisfy expected behaviors; *analysis* (3) of the proposed structure producing derived behaviors; *evaluation* (4) where both expected behavior and behavior derived from structure are concurrently assessed; and *documentation* (5) which generates the design description. The iterative nature of designing is captured in the movement among three types of reformulation processes also denoted numerically in Figure 1: *reformulation I* (6) which is the reformulation of structure; *reformulation II* (7) as a reformulation of expected behavior; and *reformulation III* (8) indicating reformulation of function.

FBS Coding Scheme: Design Issues and Processes

The coding scheme adhered to in this research is based on this FBS ontology whereby the ontological variables are translated into six design issues. These design issues are coded using the FBS ontology as exemplified in the sample of participant utterances and associated codes seen in Table 1. The selected utterances were drawn from an engineering design session where high school participants were asked to design a device that would assist elderly clients in opening a stuck double-hung window.

Transformations between the six codes used to label the design issues reflected in participant utterances generates the eight distinct design processes (Table 2).

Table 1
FBS Coding Examples

Design Issues	Respective Utterance Example
Design Requirements (R)	"so they need help in trying to…. for the elderly to raise windows"; "it says a significant amount of force to raise and lower the windows…"
Function (F)	"but it'd have to be something that is really easy to twist."; "causes the window to expand on the frame"
Behavior Expected (Be)	"that will increase mechanical advantage"; "that may help the elderly lift or…";
Behavior from Structure (Bs)	"so if they like pull the string it actually lifts it"; "so the longer this is the more mechanical advantage you'll have so the easier it will be"
Structure (S)	"So one thing I came up with is to cut a notch in the bottom frame of the window right there"; "and have the strings coming back down"
Design Description (D)	"let's draw a right side view of this thing to explain it okay I'll let you do that..."

Unidirectional transformational movements are indicated by the "→" symbol, the "↔" symbol indicates transformational comparisons, and the numbers associated with each design issue correspond to those depicted in the FBS model (Fig. 1).

Table 2
FBS Design Processes

Progression	Design Process	Transformational Movement
(1)	Formulation	R → F, F → Be
(2)	Synthesis	Be → S
(3)	Analysis	S → Bs
(4)	Evaluation	Be ↔ Bs
(5)	Documentation	S → D
(6)	Reformulation I	S → S
(7)	Reformulation II	S → Be
(8)	Reformulation III	S → F

Method

The research design followed a two-by-two factorial investigation across two exogenous variables, design experience and maturity, where experience is formal pre-engineering coursework and maturity was the time between data collected fall of the junior and senior years of high school. The full scope of the research was to characterize the design cognition and cognitive design styles of high school pre-engineering students over a two-year period, and to compare them with undergraduate engineering students as well as high school students without such design experience. Presented in this paper are year one results comparing only the high school participants and only addressing the following one of six hypotheses posed:

> High school pre-engineering students have a stronger focus than high school students with no design experience on the design process of synthesis; i.e., the process of producing solutions.

Using purposeful selection high school students in their junior year were assigned to experiment (those having formal pre-engineering course experience) and control (those not having formal pre-engineering course experience) groups. In teams of two (dyads) students engaged in a predefined engineering design task where they were to develop a design-only solution. A dyad configuration was used as it has been found to naturally promote authentic verbal interactions during collaborations on developing acceptable engineering design solutions (Kan & Gero, 2009; Purzer, Baker, Roberts, & Krause, 2008).

Participants

Participants were drawn from a convenience sample of high school juniors attending one of three rural mid-Atlantic high schools all offering the same 9th through 12th grade Project Lead the Way (PLTW) pre-engineering course sequence. Student populations at each of the participating schools were of similar size. Two groups of participants, those with (experiment) and those without (control) formal PLTW pre-engineering course experience, were recruited from each high school using a small monetary incentive. Prior PLTW course experience for the experiment group ranged from those enrolling in their first PLTW course at the start of their junior year, to those with one full year of prior PLTW coursework. Within groups students self-selected into dyads, 60% of which were mixed-gender. Of the

40 students participating in year one, the gender distribution within the experiment group was 64% male and 36% female, and for the control group 65% male and 35% female.

Procedures

Participant recruitment was conducted using typical modes of school communication. Student demographic data (age, gender, pre-engineering course experience, etc.) were collected as students arrived at their session and before dyads engaged in the design task. The design task dyads addressed was that of designing a solution to assist physically impaired elderly nursing home residents with opening difficult-to-open double-hung windows. Instructions for completing the design task were provided, as were basic information resources regarding construction and operation of a double-hung window. Dyads were allowed 45 minutes to collaborate on their design task, and instructed to include a detailed sketch of the final solution on a whiteboard.

Data Collection and Protocol Analysis

The following sequence of tasks presents the basic set of procedures used for data collection and protocol analysis.

Video Capture. Each design task session was captured using two video recording devices arranged at two distinct vantage points ensuring sufficient recording of dyad interactions and their development of a final design description (Figure 2). Additionally, the dual recording devices safeguarded against potential technological issues or difficulties encountered by either device. The Camera-1vantage point directly captures the white board and dyads engaged in progressive design development and sketching of their solution. The Camera-2 vantage point recorded a general view of the entire design session. Both members of a dyad were equipped with a high sensitivity, wireless microphone to ensure quality audio was captured for successful transcription of student verbalizations into text. The resulting videos provide a time-stamped recording of the entire design session.

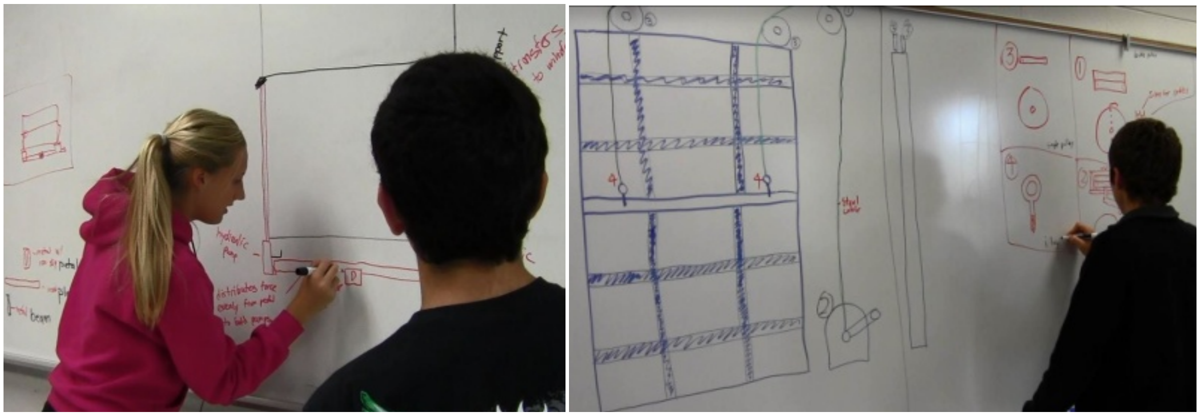

Figure 2. Participants Sketching Final Design Solution Descriptions

Transcription. Video recordings of dyad design sessions were transcribed manually with individual utterances from each dyad member entered verbatim into alternating rows of a spreadsheet. Timestamps were inserted every three minutes to establish reference points throughout the entire video. This approach to transcription resulted in a written version of the verbalizations between participants with time-stamps throughout.

Segmentation and Coding of Text-Based Verbalizations. The method used to segment the text-based version of dyad verbalizations was conducted on the basis of FBS coding previously described. This method involved concurrent analysis of a given transcript by independent coders. A total of six coders were involved with coding the 40 protocols. All coders participated in training using practice protocols until consistently achieving sufficient inter-coder reliability. Coders segmented and coded simultaneously dividing the utterances until each individual segment contained a single code that reflected only one of the six possible design issues (Kan & Gero, 2007). The use of two independent coders ensured robustness and demonstrated an inter-coder reliability ranging from 85 and 95 percent which was consistent with prior research (Williams, Gero, Lee, & Paretti, 2011).

Arbitration. Adhering to the FBS coding scheme, once independent coders completed the segmentation and coding of a given transcript, they meet to arbitrate - compare, discuss, and justify - the FBS codes they assigned to each segment. Where agreement of independently coded segments occurred a final code is assigned. Segments that differed in assigned codes require coders to engage in arbitration to dispute the assigned coding and reach agreement on the design issue addressed. Where coders were unable to agree on an arbitrated code, that segment was left un-coded and highlighted for subsequent final arbitration among the lead researchers. The final arbitration resulted in a final protocol data set that was readied for use in statistical analyses. The number of segments typically generated from the final protocol for a 45 minute design session was between 200 and 700. Since there are 6 codes this implies than on average each code will likely appear at least 33 times. This provides a statistically significant data set. Analyses of final arbitrated protocols were conducted using LINKODER (www.linkoder.com) to generate descriptive statistics and probability analyses of the FBS ontology. Data were analyzed to determine statistical differences among design issues and processes between the control and experiment groups.

Results

We are only reporting on the analyses of the first year data collected from design sessions of participating high school juniors. These data were analyzed for comparison of design issues and processes between experiment and control groups, pre-engineering (ENG) and non-engineering (NON) respectively.

Design Issues

A comparison of design issue distributions between ENG and control NON groups is illustrated in Figure 3, with descriptive statistics presented in Table 3. The percent occurrence reflects the average within group frequency of segments associated with each of the six design issue for both groups. The data indicate that both groups expended the majority of their cognitive efforts and to about the same degree (~ 40%) in discussions of the design structure (S), which is typical for most designers. Relatively similar total percent effort (~26-28) was expended on behavior from structure (Bs) and expected behavior (Be) (~14-18) combined. Comparisons of control and experiment group data using a *t*-test (Table 3) revealed no significant differences among any of the design issues, though expected behavior approached it. Similarly, comparison of total effort expended in the problem versus the solution space (P-S Index) (Jiang, Gero, & Yen, 2014) indicated there were no significant differences.

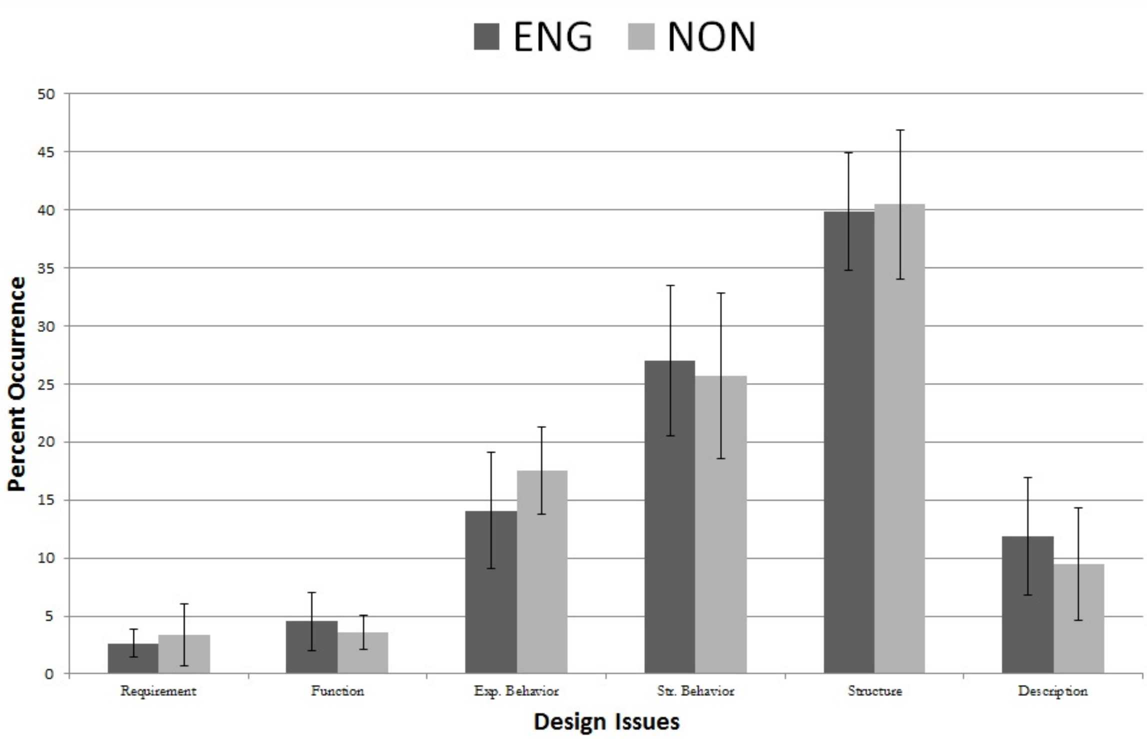

Figure 3. Percent Occurrence of Design Issues: ENG vs. NON High School Juniors
Note: error bars indicate standard deviation

Table 3
Statistical Results of Design Issues (Entire Session): ENG vs. NON High School Juniors

Design Issue	*t* - value (%)	*p* - value
(R) Requirement	-0.78	0.240
(F) Function	1.05	0.153
(B_e) Expected Behavior	-1.7	0.053
(B_s) Behavior from Structure	0.43	0.334
(S) Structure	-0.23	0.410
(D) Description	1.09	0.145
P-S Issue Index	-1.2	0.123

Design Processes

The distribution of syntactic design processes was computed to discern differences in cognitive effort expended between control and experiment groups. Similar to computations of design issues, analytical comparisons of the eight syntactic design processes between groups showed no statistically significant differences between ENG and NON groups (Table 4). As well, no statistically significant differences were observed in the P-S Processes Index between these two groups.

Table 4
Statistical Results of Design Processes (Entire Session): ENG vs. NON High School Juniors

Design Process	***t* - value (%)**	***p* - value**
Formulation	1.22	0.118
Synthesis	-1.01	0.163
Analysis	1.48	0.077
Evaluation	-0.16	0.436
Documentation	0.82	0.211
Reformulation I	-0.5	0.311
Reformulation II	-1.59	0.064
Reformulation III	0.55	0.295
P-S Process Index	-0.92	0.183

Percent occurrences for the eight design processes (Fig. 4) indicate that roughly 30% of their cognitive effort was invested in Reformulation *I* (S > S) and between ~17- 21% on Analysis (B_e<>B_s).

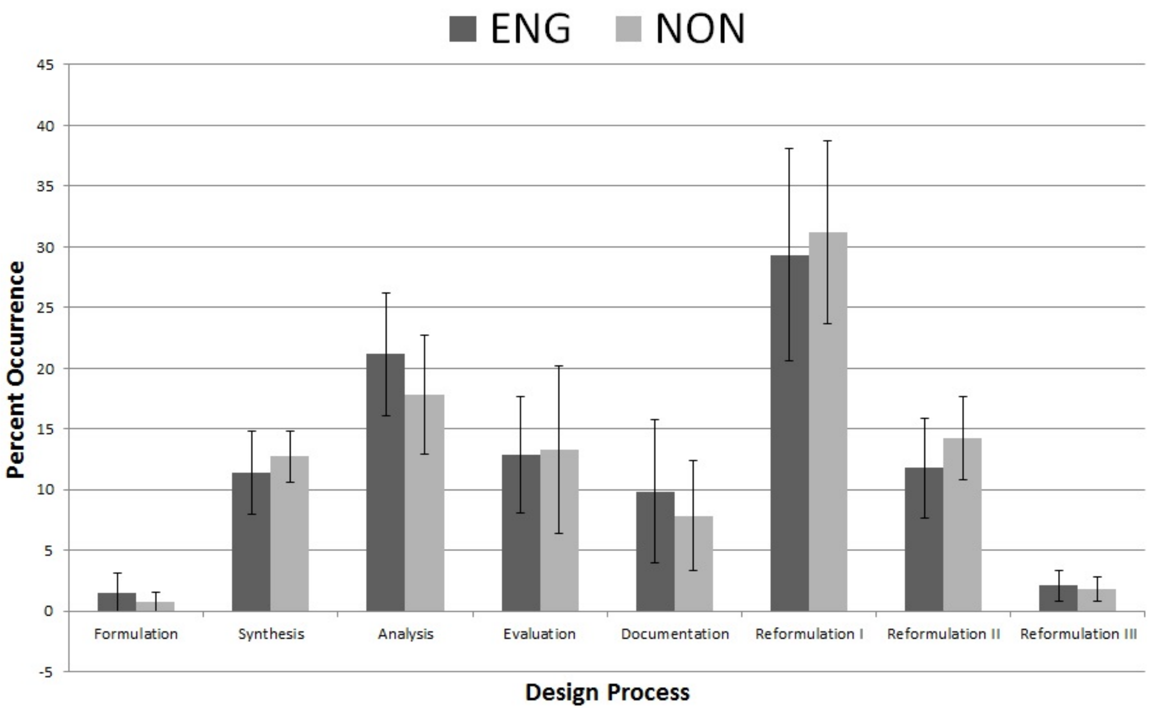

Figure 4. Percent Design Processes Occurrences: ENG vs. NON High School Juniors
Note: error bars indicate standard deviation

Discussion and Conclusions

Analysis of year one data did not reveal any significant differences between the experiment (ENG) and control (NON) groups in engineering design cognition. Based on these results the underlying hypothesis must be rejected: pre-engineering students do not demonstrate a stronger focus on the process of producing design solutions. To further investigate this apparent lack of difference between ENG and NON groups, the following select demographic data related to prior technology/engineering (T/E) design experiences were collected: participation in (a) middle school technology education classes, (b) T/E clubs, (c) other T/E related activities, and because of the rural school settings (d) farm related activities. Analysis of these data indicated that of the ENG students, 59% had previously participated in middle school technology education classes, 14% were or had been involved in T/E clubs, 30% engaged in other T/E related activities, and 30% had T/E related farm experiences. In each of these demographic categories students in the NON group had significantly less additional formal and/or informal T/E related experiences, 33%, 5%, 17%, and 0% respectively. Evident from these demographic data is that students in the ENG group clearly had far more formal and informal T/E related experiences.

Though demographic data indicates some degree of common prior pre-engineering experiences, it does not provide sufficient explanation for finding no significant differences in engineering design thinking between these groups. Other influences such as curricular and pedagogical factors must therefore be considered. Project Lead the Way (PLTW) program documents present entry-level course outlines that do not specifically target design thinking as a learning goal (https://www.pltw.org/our-programs/engineering). This is equally the case for the curriculum used by the middle school technology education programs at participating schools. The initial PLTW course that all pre-engineering participants engaged in was *Introduction to Engineering Design* (IED). A review of the detailed IED curriculum outline indicates that instructional units give attention to teaching the following set of practices and steps in the design process: technical sketching and drawing skills, modeling skills, geometry of design, documentation, and completion of a prescribed design project using Computer Aided Design (CAD) software. Authentic open-ended design challenges are not integral to the learning experience provided students in this entry level pre-engineering course. In light of this, it suggests that the pedagogical preparation provided to educators delivering the earlier courses in PLTW might not be adequate for intentionally incorporating or promoting design thinking as part of the pre-engineering experiences.

Year two data of this longitudinal study are currently being collected. The project anticipates that as the pre-engineering students continue their engagement in engineering design experiences during their final year of high school, differences in design cognition will be demonstrated to some degree.

Acknowledgment

The authors wish to acknowledge and thank Brooke Bellows, Yoon Lee, Tyler Love, and Mick Smythwood for segmentation and coding of data. Appreciation is also extended to Pinelopi Kyriazi for conducting the statistical testing. This material is based upon work supported by the National Science Foundation under Grant No. 1160345. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. This study has been approved by the author's respective Institutional Review Boards.

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Wells, J, Lammi, M, Grubbs, M, Gero, J, Paretti, M and Williams, C (2016) Characterizing design cognition of high school students: Initial analyses comparing those with and without pre-engineering experiences*, Journal of Technology Education* (to appear)