Comparing Design Cognition of Undergraduate Engineering Students and High School Pre-Engineering Students

Matthew D. Lammi, John S. Gero
mdlammi@yahoo.com, john@johngero.com

Abstract - **This paper presents the results of design cognition studies of two groups of students: high school juniors and seniors who have taken pre-engineering courses and sophomore university students in a mechanical engineering department. Both groups carried out design sessions designing for the same design challenge. Data were collected using the protocol analysis technique through video and audio recordings of design sessions. The students' design cognition was measured by segmenting and coding the transcribed videos using the Function-Behavior-Structure (FBS) ontologically-based design issues and design processes coding scheme that provides a uniform basis for analyzing design protocols. Differences in design cognition were found and tentative explanations provided to account for them.**

Index Terms – Design cognition, design education, engineering education, protocol analysis.

ENGINEERING DESIGN IN EDUCATION

Engineering design has been researched at the post-secondary level through diverse studies [1-4]. These studies have ranged from design cognition of individuals and teams, service learning, ethnography, mentor programs, to collaboration. Design cognition data has been collected and analyzed using verbal and/or video data [5-8]. However, few studies have addressed engineering design related to high school students. How undergraduate and high school students employ cognitive processes and strategies within engineering design is not adequately identified or understood. Hence, there is a need for research into engineering design cognition at the K-12 level [9]. Part of that research needs to include how high school students compare to university students. The results from this study have potential implications for university and high school-level engineering design education.

Engineering design is more than the manipulation of numbers and the solving of scientific equations. The processes employed in engineering design encompass a broad variety of topics and fields of study. Design, among other things is dynamic, recursive and iterative, therefore, it is not easily represented by linear models [10]. Jonassen [11] placed design in a distinct type in his "problem type taxonomy." Design is not only listed as complex and ill-structured, but it also requires higher order problem solving skills. Designing is designing, not an example of something else.

Design has been studied using verbal protocol analysis from the early 1970s [12] . However, the study of design in engineering using protocol analysis began in earnest in the 1990s with Gero and his colleagues [13] and Atman and her colleagues [6]. Although Hayes [14] claimed that verbal protocols were typically incomplete for capturing all cognition, he also claimed that under controlled conditions there was no evidence that verbal protocols detrimentally distorted or interfered with the participant's thinking while engaged in a task or solving a problem.

METHODOLOGY

Data were collected from two separate sites: a large public university on the East Coast and a public high school in the Intermountain West. The participants from the university were mechanical engineering students in their sophomore year. The high school students were juniors and seniors who had taken two or more pre-engineering courses. A retired professional engineer taught the pre-engineering courses based on Project Lead the Way (PLTW) curriculum. There were six PLTW pre-engineering courses offered through the high school that culminated in an engineering design course.

Participants were given the same open-ended engineering design challenge. The university and high schools students worked in teams of two for 45 minutes and one hour, respectively. The unit of analysis was a team of two students in order to have natural verbalization between the participants. The design scenario was set in an assisted living facility and the students were tasked with designing an assistive device for opening windows without using electrical power. Being a design task there was no set or best solution. As the challenge was authentic to the students, it engaged them in frequent verbalizations.

Verbal reports, as part of the video record, were collected to capture the students' utterances. The utterances were treated as source data for a protocol analysis [15]. The data were transcribed, segmented, and coded using a coding scheme based on Gero's Function-Behavior-Structure (FBS) ontology [16]. The transcribed utterances were broken into segments. Each segment was assigned only one unique FBS

code producing a morphism between the segmentation and the coding. The coding was performed by trained analysts. The analysts' coding results were arbitrated to reach a satisfactory percent agreement of over 80% for both groups of students. The resulting coded segments are termed design issues and their transitions are termed design processes. The design issues and the resulting design processes capture the cognition in design terms – the design cognition – of the participants. Analyzing the design cognition, expressed, through these concepts, allows for comparisons of the design cognition of high school and university students.

Both the design issues and design processes were analyzed with descriptive statistics in three equal contiguous fractions of the original protocol (beginning, middle, and end) and overall as a whole. T-tests were performed on the design issues and the syntactic design processes between the undergraduate and high school student groups for comparison purposes. The remainder of the paper presents the data on the design issues and the design processes as well as their analyses for both cohorts of students.

RESULTS

Issues

The design issues, derived from the FBS ontology, used for coding were: requirements, function, expected behavior, structure, behavior derived from structure, and description. Figure 1 shows the overall percentages for both the university and high school students' design issues. Differences between the percentages of the university and high school students for both expected behavior (Be) and behavior derived from structure (Bs) were statistically significant, $p < .05$.
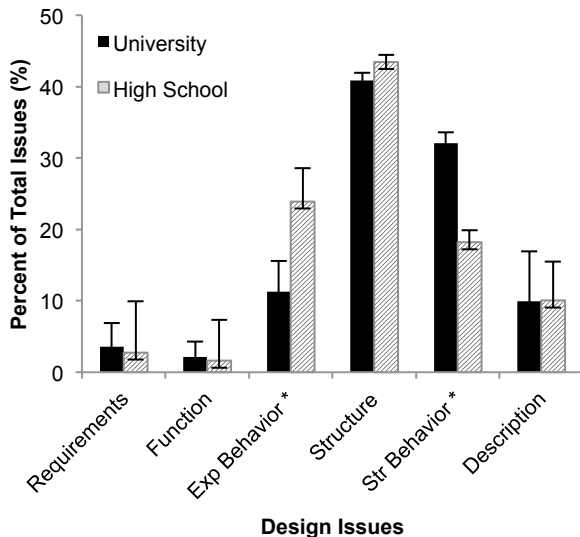

FIGURE 1
DESIGN ISSUES OF UNIVERSITY AND HIGH SCHOOL STUDENTS
NOTE: ERROR BARS REPRESENT STANDARD DEVIATION. STATISTICAL SIGNIFICANCE OF $p < .05$ IS REPRESENTED BY *.

The design issues from the design challenge were also evaluated over three equal contiguous fractions for both sets of participants. Figure 2 shows the percent of expected behavior issues (Be) over all three fractions for the university and high school students. Differences between
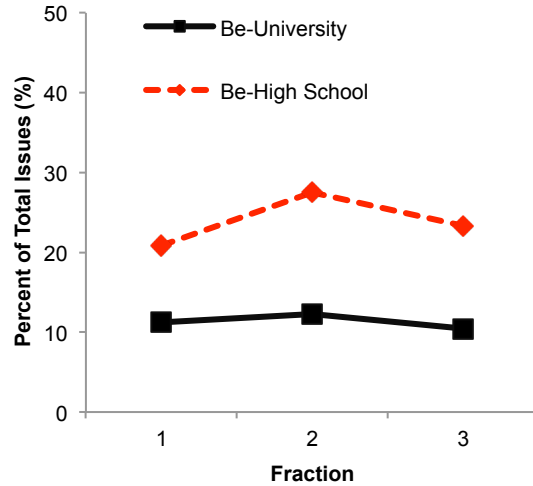

FIGURE 2
PERCENT OF EXPECTED BEHAVIOR ISSUES (Be) OVER ALL THREE FRACTIONS

the percentages of Be for the first two fractions for the university and high school students were statistically significant, $p < .05$. The percentage of Be was consistently higher for the high school students throughout all fractions. Figure 3 shows the percent of derived behavior issues (Bs) over all three fractions for the university and high school students. The differences between the percentages of
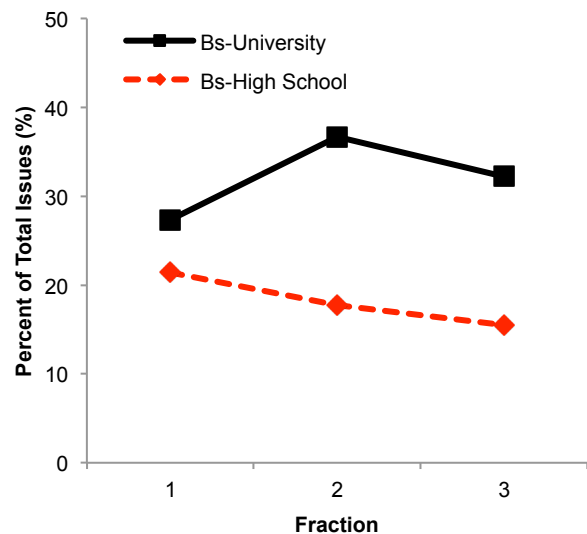

FIGURE 3
PERCENT OF DERIVED BEHAVIOR ISSUES (Bs) OVER ALL THREE FRACTIONS

Bs for the last two fractions for the university and high school students were statistically significant, $p < .05$. The percentage of Bs was consistently higher for the university students throughout all fractions. The university students had their lowest amount of Bs at the beginning fraction. Conversely, the high school students had their peak of Bs in the first fraction.

Figure 4 displays the percent of structure issues (S) over all three fractions for the university and high school students. Although there were no statistical differences, the graph displays a difference between the two groups in the middle fraction.

Figure 5 displays the percent of description issues (D) over all three fractions for the university and high school students. The number of description issues converged in the middle fraction and differed in the first and last fractions, although these differences were not statistically significant.

Figure 6 displays the requirement issues (R) and function issues (F). Both sets of students had comparable results. The first fraction had the highest number of occurrences of requirement and function issues. The occurrence of these issues decreased over the second and third fractions for all student teams. The students dedicated more cognitive effort in the first fraction reviewing the design challenge briefing.
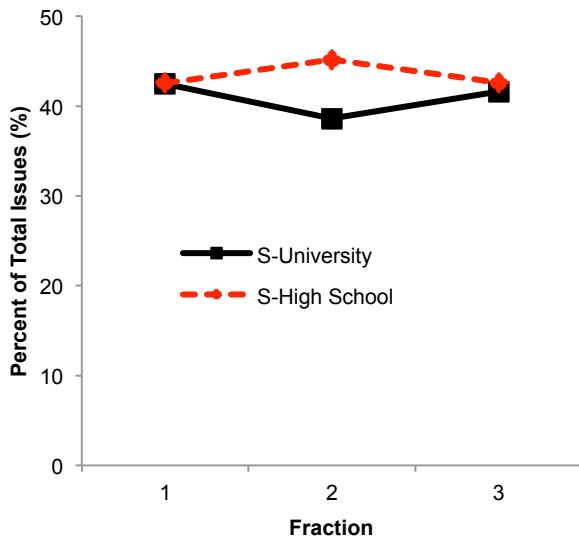

FIGURE 4
PERCENT OF STRUCTURE ISSUES (S) OVER ALL THREE FRACTIONS

SYNTACTIC DESIGN PROCESSES

Syntactic processes are derived from the transitions from one coded segment to the next coded segment in the chronological sequence of segments. It is based on Asimov's model of design [17]. It is considered a weak model of design.

The syntactic design processes between the university and high school students were compared across the entire design session, Figure 7, as well as divided over the three fractions.
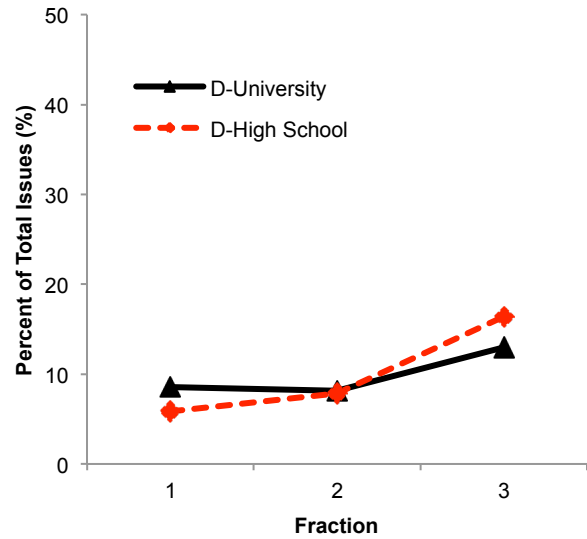

FIGURE 5
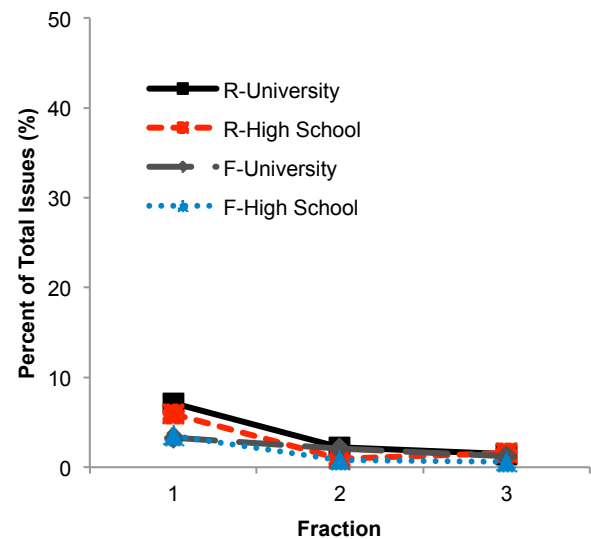PERCENT OF DESCRIPTION ISSUES (D) OVER ALL THREE FRACTIONS

FIGURE 6
PERCENT OF REQUIREMENTS ISSUES (R) AND FUNCTION ISSUES (F) OVER ALL THREE FRACTIONS

There are eight design processes: formulation (F=>Be), synthesis (Be=>S), analysis (S=>Bs), evaluation (Bs<=>Be), documentation (S=>D), reformulation I (S=>S), reformulation II (S=>Be), and reformulation III (S=>F).

Three syntactic design processes will be discussed in further detail. The remaining processes were similar to corresponding findings for design issues. Figure 8 displays the three fractions for the analysis process for both the university and high school students.
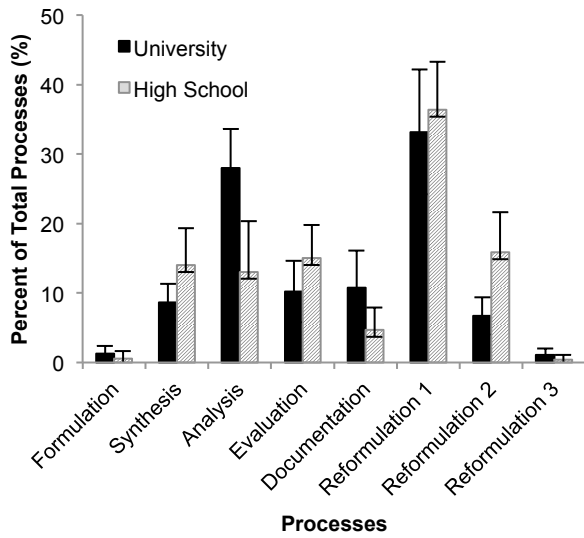
FIGURE 7
SYNTACTIC DESIGN PROCESSES OF UNIVERSITY AND HIGH SCHOOL
STUDENTS

FIGURE 9
PERCENT OF SYNTHESIS PROCESSES OVER THREE FRACTIONS

The university students spent more of their cognitive effort on analysis, nearly twice as much as the high school students. Figure 9 shows the three fractions for the synthesis process for both student sets. The high school devoted more cognitive effort to synthesis than the university students. Figure 10 shows the three fractions for the evaluation process for both student sets. The high school students had a marginally higher number of evaluation processes than the university students, particularly in the first and third fractions of the sessions.
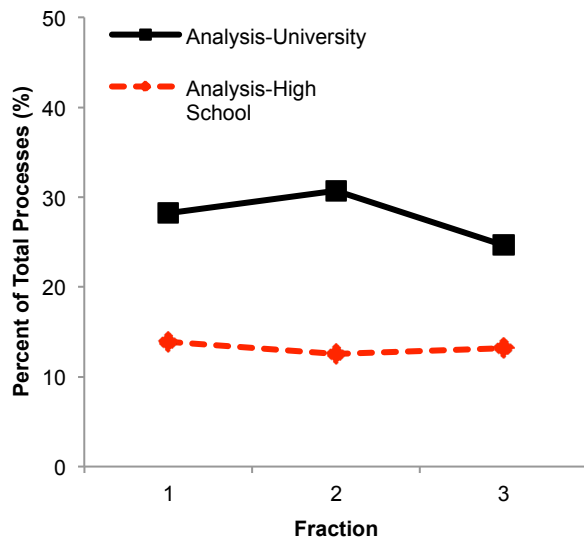
DISCUSSION AND CONCLUSIONS

The design cognition behaviors of university engineering and high school pre-engineering students were significantly different and in some areas reversed. The university students had more behavior derived from structure and analysis, while the high school students had more expected behavior and synthesis. The difference in the amount of analysis between the university and high school students could be due to the high school students' lack of skills and training in engineering analysis. This difference was seen when analyzing the entire design session and throughout each of the three time fractions for both derived behavior and analysis.

FIGURE 8
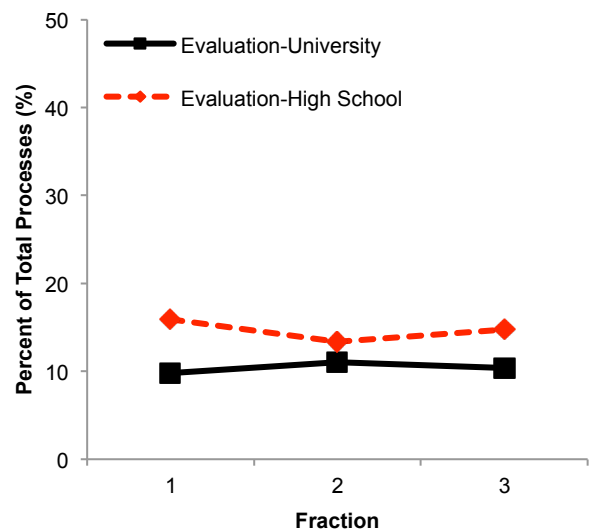PERCENT OF ANALYSIS PROCESSES OVER THREE FRACTIONS

FIGURE 10
PERCENT OF EVALUATION PROCESSES OVER THREE FRACTIONS

These results are consistent with other studies reported in the design research literature. Novices tend to generate more ideas but not to analyze them further [18]. The results for synthesis parallel the findings for the issues of expected behavior and structure since synthesis is the transition of expected behavior to structure. Other studies have found that novices also dwell more on structure [19, 20]. The results from the design process "analysis" agree with this finding. The high school students had more instances of developing ideas, but appeared not to be able to analyze them due to a lack of skills. These findings do not suggest that the undergraduate students were experts, but rather they were further on the continuum towards expertise than the high school students.

The high school students also had more evaluation processes. The high school students performed more evaluation at the beginning and ending fractions. Perhaps, they spent time evaluating their multiple ideas in the beginning while brainstorming and at the end against the design requirements. Both sets of students had a sharp increase in documentation and description in the last fraction. Documentation is generally used to communicate an idea or design concept. The students used the final fraction to prepare drawings or concepts of their final design.

Further analysis could be performed on the data. These analyses might include measures of centrality and Markov analysis of the design processes. Also, the results may be analyzed qualitatively.

The findings from this study suggest that pre-engineering students in high school and engineering students at a university share commonalities in design. However, the high school students performed less analysis on their design ideas. Further studies are needed to determine if the disparity in analysis can be overcome through pedagogical or curricular interventions. This research may also provide further foundations for other design studies in engineering education for both the K-12 and post-secondary areas; serving as a baseline and a springboard.

REFERENCES

[1] Atman, Cynthia J., Deborah Kilgore, and Ann McKenna. 2008. "Characterizing design learning: A mixed-methods study of engineering designers' use of language." Journal of Engineering Education. Vol. 97, pp. 309-326.

[2] Dally, James W. and Guangming M. Zhang. 1993. "An engineering design course for freshman students." Journal of Engineering Education. Vol. 14, pp. 20-27.

[3] Hirsch, Penny L., John C. Anderson, J. Edward Colgate, John Lake, Barbara L. Shwon, and Charles Yarnoff. "Enriching freshman design through collaboration with professional designers." In American Society for Engineering Education Annual Conference. June 16-19, 2002. Montreal, Canada.

[4] Sheppard, Sheri, Cynthia J. Atman, Reed Stevens, Lorraine Fleming, Ruth Streveler, Robin S. Adams, and Theresa Barker. "Studying the engineering student experience: Design of a longitudinal study." In American Society for Engineering Education Annual Conference. June 20-23, 2004. Salt Lake City, UT.

[5] Adams, Robin S., Jennifer Turns, and Cynthia J. Atman. 2003. "Educating effective engineering designers: The role of reflective practice." Design Studies. Vol. 24, pp. 275-294.

[6] Atman, Cynthia J. and Karen M. Bursic. 1998. "Verbal protocol analysis as a method to document engineering student design processes." Journal of Engineering Education. Vol. 87, pp. 121-132.

[7] Cross, Nigel. 2004. "Expertise in design: An overview." Design Studies. Vol. 25, pp. 427-441.

[8] Dorst, Kees and Nigel Cross. 2001. "Creativity in the design process: Co-evolution of problem-solution." Design Studies. Vol. 22, pp. 425-437.

[9] Katehi, Linda, Greg Pearson, and Michael Feder, Eds., Engineering in K - 12 education: Understanding the status and improving the prospects. Washington, DC: The National Academies Press, 2009.

[10] Mawson, Brent. 2003. "Beyond `The Design Process': An alternative pedagogy for technology education." International Journal of Technology and Design Education. Vol. 13, pp. 117-128.

[11] Jonassen, David. 2000. "Toward a design theory of problem solving." Educational Technology Research and Development. Vol. 48, pp. 63-85.

[12] Eastman, C. "On the analysis of intuitive design processes." In G. T. Moore Ed. 1970. Emerging methods in environmental design and planning. Cambridge, MA: MIT Press, pp. 21-37.

[13] Purcell, A.T., JS Gero, H. Edwards, and T McNeill. "The data in design protocols: The issues of data coding, data analysis in the development of models of the design process." In N. Cross, H. Christiaans, and K. Dorst (eds.). 1996. Analysing design activity. Chichester, England: John Wiley & Sons, pp. 225-252.

[14] Hayes, John R., The complete problem solver, 2nd ed. Hillsdale, NJ: Erlbaum, 1989.

[15] Ericsson, K. Anders and Herbert A Simon, Protocol analysis: Verbal reports as data. Cambridge, MA: MIT Press, 1993.

[16] Kan, Jeff W. and John S. Gero. "Using the FBS Ontology to capture semantic design information in design protocol studies." In J. McDonnell and P. Lloyd (eds.). 2009. About designing: Analysing design meetings. London, England: CRC Press, pp. 213-229.

[17] Asimov, M, Introduction to design: Fundamentals of engineering design. Upper Saddle River, NJ: Prentice Hall, 1962.

[18] Kavakli, Manolya and John S. Gero. 2002. "The structure of concurrent cognitive actions: A case study on novice and expert designers." Design Studies. Vol. 23, pp. 25-40.

[19] Hmelo-Silver, Cindy E., Douglas L. Holton, and Janet L. Kolodner. 2000. "Designing to learn about complex systems." The Journal of the Learning Sciences. Vol. 9, pp. 247-298.

[20]   Hmelo-Silver, Cindy E. and Merav G. Pfeffer. 2004. "Comparing expert and novice understanding of a complex system from the perspective of structures, behavior, and functions." Cognitive Science. Vol. 28, pp. 127-138.

AUTHOR INFORMATION

Matthew D. Lammi, Assistant Professor, STEM Education, North Carolina State University, mdlammi@yahoo.com

John Gero, Research Professor, Krasnow Institute for Advanced Study and Volgenau School of Engineering, George Mason University, john@johngero.com