ASEE's 123rd Annual • Conference & Exposition • New Orleans, LA • June 26-29, 2016

New Orleans JAZZED about Engineering Education

Paper ID #15463

Cognitive Research: Transferring Theories and Findings to K-12 Engineering Educational Practice

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Design Cognition Research: Establishing Coding Scheme Agreement

Abstract

Engineering design is increasingly viewed as highly beneficial to K-12 education. As a result, engineering continues to be implemented in technology and engineering education classrooms alongside the recent inclusion of engineering within the Next Generation Science Standards. In turn, use of engineering has raised a number of concerns as to what the true intent is and how research can be used for K-12 educational practice. One concern is the identification of engineering content for grades K-12 and how it aligns with professional engineering preparation. Secondly, how can the growing body of engineering design cognition research be used to impact student learning outcomes. As cognitive research in K-12 engineering is being conducted more frequently, it is important to examine the methodologies used, distinguish the proper coding schemes, and develop ways in which the findings of these studies guide educators in the planning of instruction and designing of curricula. Consequently, the article focuses on the influx of K-12 design cognition research related to engineering design. The outcome of this paper is to ground K-12 engineering design cognition research, by making connections with goals of K-12 education.

Introduction

Implementation of design-based learning (DBL) pedagogical approaches has been wide-spread across science, technology, engineering, and mathematics (STEM) education (Crismond & Adams, 2012; Doppelt, Mehalik, Schunn, Silk, & Krysinksi, 2008; Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Grubbs, 2013; Jacobson & Lehrer, 2000; Wicklein, 2006). At the same time however, examination of students' cognitive processes used during such experiences has not been nearly as abundant nor aligned with educational theory and practice. Additionally, a recent meta-analysis and report by the National Academy of Engineering, suggests minimal evidence has been found that integrative approaches do indeed increase students ability to learn content better and develop higher order thinking skills. As a result, minimal consensus has been established for an agreed upon coding scheme to describe students cognitive processes and methods for connecting with effective pedagogical practices. In an effort to reach some degree of agreement regarding such a coding scheme, this paper presents an analysis of multiple coding schemes purporting to describe K-12 students' cognitive activity during engineering design tasks. The purpose was to determine the: (a) focus and intent of each scheme, (b) similarities and differences, and (c) from a cognitive science standpoint those concepts not being addressed. Lastly, research findings using these coding schemes will be aligned with theories and philosophies of education.

Design Cognition: K-12 Coding Schemes, Findings, and Future Directions

As interest in design cognition has steadily grown throughout the past 40 years, researchers have primarily examined the cognitive processes of practicing professionals such as architects, mechanical engineers, and software designers as they complete a design task (Cross, 2001). The main purpose of this line of research is to inform professional designers on how best to prepare future designers (Adams, Turns, & Atman, 2003). Only recently have researchers turned their attention to examining the design cognition of students at the K-12 educational level. The goal for this type of educational research, in addition to improved teaching of design skills, is to enhance the cognitive abilities of K-12 students (Roberts, 1994).

Of the existing studies examining design cognition, at both expert and novice levels, most have been conducted through three research methods: case studies, protocol analysis, and performance tests (Cross, 2001). Of these approaches, verbal protocol analysis is has become the most frequently employed to describe and examine cognitive processes. Using a think-aloud design, researchers capture participants thought processes as they attempt to solve an engineering design task. A transcript is then produced documenting their verbalized cognitive processes. Analysis occurs through application of a coding scheme either created prior to the study or derived from an emerging framework. For the former, researchers have employed a variety of coding schemes to describe students design cognition.

Given the steady increase of explorations into connections between K-12 *design cognition*, (also termed *design thinking*), and development of student cognitive competencies, it becomes increasingly important to understand and choose the most appropriate coding schemes available, as each has its own intent and characteristics. To that end, this article examines recent K-12 design cognition studies from the perspective of the coding schemes used with the purpose of determining the: (a) focus and intent of each scheme, (b) similarities and differences, and (c) from a cognitive science perspective those concepts not being addressed.

Coding Schemes

Focus and Intent

A review of relevant literature revealed five coding schemes used in the majority of cognitive research designed to examine the cognitive processes of K-12 students while engaged in an engineering design task. Table 1 provides a summary of coding scheme elements identified through an examination of those studies. A significant difference between these coding schemes is found in the focus and intent of what is expected to be captured.

General Engineering Design Process. Two of the coding schemes (Welch & Lim, 2000; Wilson, Smith, & Householder, 2013) adopt what is referred to in this study as a general engineering design process (GEDP) model to document the amount of time students perform each of the steps. Though both coding schemes were identified by their authors as being grounded in research related to engineering design, both were also crafted with the intent of being used by teachers as a scaffolding tool for students. Thus, each coding scheme captures broad processes students may work through. This simplification is tantamount to general heuristics one might use during problem solving, with minimal attention to specific engineering design principles. As a result, both coding schemes were classified in this study as being minimally-grounded in the design cognitive science literature.

Table 1

Overview of Coding Schemes

Research Study	**Coding Foci**	**Number of Codes**
Welch & Lim (2000)	General Engineering Design Process (GEDP) *Instructional Tool*	24 *(5)*
Wilson et al. (2013)	General Engineering Design Process (GEDP) *Instructional Tool*	5
Mentzer (2012)	Practitioner Engineering Design Process (PEDP) *Engineering Textbook*	9
Kelley (2008)	Practitioner Engineering Design Process (PEDP) *Engineers' Notebooks*	17
Wells et al. (2014)	Cognitive Science Foundation *Task & Domain Independent*	6 *(8)*

Note. Parentheses indicate broad categories that subsume the codes used during analysis.

Practitioner Engineering Design Process. Although it shares similarity with the two previously discussed models, Mentzer (2012) applies a coding scheme often represented in undergraduate introductory engineering textbooks. This model was largely based on a 1995 model developed through a content analysis of seven introductory engineering design textbooks (Mosborg, Adams, Kim, Atman, Turns, & Cardella, 2005). In contrast to broad, GEDP models, Mentzer applies a coding scheme with explicit attention to core engineering design processes such as modeling and feasibility analysis. Similarly, Kelley (2008) attends to specific, unique processes engineers engage in by using a 1973 coding scheme derived from notebooks of distinguished engineers that identified particular activities they worked through (Halfin, 1973). In comparison to other models that were created from verbal protocol analysis, the Halfin coding scheme was grounded in a content analysis approach, identifying specific processes engineers documented in which were validated through a delphi study. Consequently, the intent of both the Mentzer and Kelley coding schemes is to describe students design thinking in terms of specific practices engineers engage in and has been coined practitioner engineering design process (PEDP) model by the researchers of this study.

Task and Domain Independent. Conversely, the Wells, Lammi, Grubbs, Gero, Paretti, & Williams (2014) study examined students' cognitive processes using the pre-established Function-Behavior-Structure (FBS) coding scheme, which is well-established in the cognitive science literature. Compared to other coding schemes the FBS ontological framework, as developed by Gero and associates (Gero, 2004), presents a significant difference with respect to intent. Specifically, the focus of the FBS coding scheme is to be task and domain independent and center more directly on designers' reasoning processes. Therefore, in this research, the FBS ontological framework was classified as a task and domain independent focus grounded in cognitive science.

Though all coding schemes previously described attempt to capture the cognitive processes of K-12 students during ill-defined engineering design challenges, each employs a coding scheme that is uniquely different from inception in representing those mental activities. However, if the purpose of design cognition research is to examine students' cognitive processes, it is critical that researchers choose the most applicable coding scheme. Moreover, of significance for the research presented in this paper is that with respect to published research assessing student engineering cognition, minimal discussion describing the rationale for choosing any given scheme is provided in the research methods. This presents a major challenge for others who possess minimal understanding of what each coding scheme actually examines to conduct similar research.

Codes Employed

Number and Nature of Codes. Comparing the actual codes that were used further aides in distinguishing between differences in coding schemes and establishing consensus. Overall, analysis of previous studies indicates the mean number of codes used is 12, ranging from as few as 5 to as many as 24 codes. Though existing literature does not identify a recommended number of codes, suggestions have been made on the challenge of too few codes being able to fully capture an individuals' cognitive process and too many codes being difficult for coders and too complex (Purcell, Gero, Edwards, & McNeill, 1996). In addition to the number of codes, Table 2 illustrates there are differences in the nature of codes attempting to illustrate students cognitive activity. Whereas one coding scheme applies codes to describe students reasoning around the three domains of function, structure, and behavior (Wells et al., 2014), other coding schemes (Welch & Lim, 2000; Wilson et al., 2013) use codes illustrating more of a linear model of designing (e.g. such as identify a need or a problem, research a need or problem, and model a possible solution). Such coding suggests universal problem solving steps, which directly challenges current beliefs that design thinking is a distinct form of problem solving. Additional categories used to describe students design cognition, identified as cognitive processes, include communication (Mentzer, 2012; Kelley, 2008; Wilson et al., 2013) and skill sets such as computing, measuring, and prototyping (Kelley, 2008; Welch & Lim, 2000). To that end, as Table 2 demonstrates, the codes employed capture considerably different processes students might bring to bear during engineering design. If seeking to describe specific reasoning processes, independent of task and domain, only the Gero (2004) coding scheme used by Wells et al. (2014), captures such processes.

Table 2

Codes Used to Describe Cognitive Processes

Wells et al. (2014)	**Welch & Lim (2000)**	**Wilson et al. (2013)**	**Kelley (2008)**	**Mentzer (2012)**
Requirement	Understanding the problem	Identify a need or problem	Analyzing	Problem Definition
Function	Generating possible solutions	Research a need or problem	Communicating	Gather Information
Expected Behavior	Modeling a possible solution	Develop possible solutions	Computing	Generating Ideas
Behavior from Structure	Building a prototype	Select the Best Possible Solution	Creating	Modeling
Structure	Evaluation	Communicate Solution	Defining Problems	Feasibility Analysis
Description			Designing	Evaluation
			Experimenting	Decision
Mapped Processes			Interpreting Data	Communication
1. Formulation			Managing	Other
2. Analysis			Measuring	
3. Synthesis			Modeling	
4. Evaluation			Models/Prototypes	
5. Documentation			Observing	
6. Reformulation I			Predicting	
7. Reformulation II			Questioning & Hypothesis	
8. Reformulation III			Testing	
			Visualizing	

Granularity. The level and degree of specificity of a coding scheme can also be examined to determine how adequate it is at empirically describing students' cognition during engineering design. Only one coding scheme (Welch & Lim, 2000) breaks down broad codes into more specific categories to further describe students' mental activity. However, the existing categories of that scheme covers modeling and construction, while not as much on the higher order cognitive processes such as analyze and synthesize. In comparison, two coding schemes have been developed that specifically address (a) levels of higher-order thinking and (b) the problem identification stage (Purcell, Gero, Edwards, & McNeill, 1996), both often found to be a challenge and/or barrier to novice designers.

Concerns

Consequently, as the purpose of this investigation was to build consensus for future research centered on K-12 students' higher-level cognition during ill-defined engineering design tasks, analysis and comparison of existing coding schemes raised multiple concerns. First, though each coding scheme attempts to describe students' cognitive processes, minimal discussion focuses on operationally defining a cognitive process for the purpose of their research. Operational definitions are critical for accurate and consistent coding among coders. In addition, not provided is literature on and/or examples of what cognitive mechanisms are captured by each process. Such discussion should dictate how a coding scheme is derived and how it will be implemented for each study. Doing so will better equip researchers and educators with transferring research and findings to practice.

Second, since the type of task affects the cognitive processes demanded (Menary, 2007), the design challenge presented to students, such as design only, or design-to-make, ultimately results in differences in specific processes identified. As Table 3 illustrates, the design challenge presented to students varied across research studies. Kelley (2008) and Welch and Lim (2000) use cognitive processes that extend beyond reasoning skills and include building, modeling, measuring. Using the same coding scheme as Kelley (2008), Strimel's (2014) examination of students in interaction with an engineering problem extended through the designing of a solution to the making and evaluation of final solutions to include processes of experimentation and testing. Yet, when a verbal protocol analysis is employed for analyzing a design task without a making component, the coding scheme will prove inadequate. Conversely, Gero's (2004) FBS model was intentionally developed to be domain and task independent, and therefore describes students' cognitive activity during engineering design. Furthermore, the FBS model specifically addresses higher order thinking skills (e.g. analysis, synthesis, and evaluation) which constitute the very competencies educators are most interested in assessing.

Table 3
Overview of Study

Authors	**Number of Participants**	**Design Time**	**Challenge Type**	**Research Design**
Mentzer (2012)	17 (2-4)	2 hours	Design: 2 Briefs*	Descriptive & Comparative
Kelley (2008)	7	30 min.	Design: Different Context	Comparative
Strimel (2014)	8	1.5 – 2 hours	Design, Make, & Evaluate	Descriptive & Comparative
Wells et al. (2014)	40 (2)	45 Min.	Design: Prescribed	Comparative
Wilson et al. (2013)	17	3-4.5 hours	Design: Emergent	Descriptive Multiple Case Study
Welch & Lim (2000)	18 (2)	1- 2 hours	Design & Make: Prescribed	Comparative

Note. Parenthesis in participant's column indicates team size. The asterisk* indicates two different design challenges were employed during the study to compare differences between design tasks.

Conclusions

Improved understanding of the mechanisms that promote higher-order thinking skills can assist in developing instructional strategies that aim to improve a student's overall performance and positively impact their achievement and motivation toward learning (Brookhart, 2010). In light of this, design cognition is increasingly perceived as a viable approach for promoting student higher order thinking (Razzouk & Shute, 2012). Therefore, if the primary outcome for employing engineering design pedagogical approaches at the K-12 level is to develop students' higher-order cognition, needed still is research establishing suitable coding schemes for assessing that outcome. And although one such coding scheme (Purcell, Gero, Edward, & McNeil, 1996) has been identified as appropriate for examining students underlying cognitive processes during engineering design, a stronger alignment within the cognitive science literature must also be established. A suitable coding scheme for assessing impact on higher-order thinking coupled with broad support from cognitive science will provide the common platform for future investigations of engineering design cognition at the K-12 level.

Recommendations

As revealed through this examination of the foci and styles of coding currently used to describe students' cognitive processes, the first recommendation is to operationally define cognitive processes and provide some degree of consistency among future researchers of design cognition. Accomplishing this is quite challenging given there is minimal agreement among those in the cognitive science community for an acceptable definition of cognitive processes (Menary, 2007). And though some might suggest that a cognitive process can be described at the task level, the cognitive processes used for tasks such as brushing ones teeth or conversing with a friend might not qualify as the type of higher order thinking that occurs during an engineering design task. Likewise, whereas observing, measuring, managing, or computing might indicate a cognitive process, such processes might not qualify as a form of higher-level cognition required for ill-defined tasks such as engineering design. These considerations challenge existing coding schemes that describe students' cognitive processes in terms of modeling, building, or communicating, as being aligned with cognitive science views.

The second recommendation for achieving alignment with cognitive science would be conducting design cognition research that focuses specifically on the effect attention, memory; metacognition, self-regulation, transfer, and long-term retention have on students' cognitive processes. This is congruent with recent concerns addressing the cognitive limitations associated with decision making during design thinking. For example, Spendlove (2013) suggested such cognitive flaws as anchoring, confirmation bias, affect heuristic, and focusing illusion can affect a student's ability to make appropriate decisions during design thinking tasks. Addressing these cognitive flaws would necessitate the adaptation of current coding schemes, or the development of new coding schemes, in order to account for such cognitive flaws during engineering design tasks and more accurately describe a student's cognitive activity. Moreover, although research has been conducted at the expert level, minimal research has examined the effect such factors have on a student's ability to process information during engineering design tasks, any of which can inhibit their ability to integrate information or construct new knowledge. For example, Bilda and Gero (2007) examined the impact of working memory limitations on the design process during the conceptualization stage of design. Results from their research revealed that when higher cognitive demands were placed upon participants there was an overall negative effect on their cognitive activity performance during an engineering design task. Though such research has been influential in describing the cognitive processes of experts during design, there currently exists minimal research investigating such cognitive processes with students at the K-12 level, none of which has been documented in existing coding schemes. The cumulative evidence presented through published research clearly demonstrates there is still a need to establish a coding scheme that has greater sensitivity for distilling out cognitive processes than does the current coarse schemes such as the FBS ontological framework.

Lastly, upon examination of the cognitive processes K-12 students' employ during designing, few coding schemes actually are informed by educational philosophies, learning theory, and STEM educational reform. Nor, do they indicate how students can be better equipped to learn and develop their cognition while designing. As researchers and educators move forward, examining decision making strategies as well as normative models may provide additional relevance to Design Cognition in terms of how students are performing in relation to educational philosophies, learning theory, and STEM Educational reform.

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