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EXPLORING THE EFFECT OF THE DESIGN PROMPT ON STUDENTS' DESIGN COGNITION

Christopher B. Williams
Dept. of Engineering Education
Dept. of Mechanical Engineering
Virginia Tech
Blacksburg, VA, 24061

Yoon Lee
Dept. of Industrial Engineering
Virginia Tech
Blacksburg, VA 24061

John Gero
Krasnow Inst. for Adv. Study
George Mason University
Fairfax, VA, 22030 &
University of North Carolina – Charlotte, NC, 28223

Marie C. Paretti
Dept. of Engineering Education
Virginia Tech
Blacksburg, VA 24061

ABSTRACT

Engineering design educators often provide their students a task (or "prompt") to guide their design projects. Similarly, engineering design educational researchers also provide research participants with a design task to guide their activity during experimental sessions. In both contexts, there is a fundamental underlying assumption that the design task has no significant effect on the students'/participants' design cognition. Specifically, the authors test the hypothesis that a design task does affect a student's design experience. Failing to disprove this hypothesis could significantly impact both design education practice and design education experimental research.

To determine the effect of a design task on students' design cognition, experimental sessions were conducted wherein student design teams worked together to solve a speculative design task. The student teams were presented with two nearly identical design tasks; however, one featured an additional design requirement. A task-independent protocol analysis method grounded in the Function-Behavior-Structure design ontology is performed on audio and video recordings of the design sessions to provide a common basis for comparing the two groups. Differences in design cognition are identified by analyzing and comparing the percent occurrences of the design issues and design processes and the Problem-Solution indices.

1 THE ROLE OF THE DESIGN PROMPT

1.1. Design Prompts in Design Education

At the beginning of each course offering, design instructors are faced with the challenge of creating a meaningful, appropriate, and valuable project experience for their students. These project-based learning experiences (PjBL) provide students with an open-ended challenge that is to be solved with the aide of the instructor's guidance and scaffolding (i.e., not via deductive lecturing). PjBL learning approaches have been found to improve the development of critical thinking and problem-solving [1], and to enhance understanding of critical engineering concepts [2].

However, it is noted that the projects themselves must be carefully designed. They must provide students an opportunity to synthesize and apply their knowledge. Following the situated cognition theory of learning, which notes that knowledge is contextual and is a product of the activity and situations in which it is created [3], the projects should be authentic and reflective of professional practice, and should be situated in a context that can motivate the students to learn the content. When well designed, PjBL problems have been shown to motivate students, maintain their interest, and actively engage them in learning [1].

Many different types of design projects have been presented in the engineering design education literature. At a high-level, Sheppard and Jenison offer a two-dimensional framework for classifying design projects: either a team or individual project and either a content or design process focus [4]. Following their survey of engineering design courses for first-year students, Burton and White offer a more detailed classification scheme for engineering design projects that includes: (i) reverse engineering, (ii) create something useful, (iii) full scale project, (iv) small scale project, (v) competitions, (vi) non-profit project, and (vii) redesign of a local project [5].

While several project types have been explored in the engineering design education literature, there is very little research on problem preparation, problem presentation, and on how different design problems affect student learning. Jonassen offers a "typology of problems": (i) logical problems, (ii) algorithmic problems, (iii) story problems, (iv) rule-using problems, (v) decision-making problems, (vi) diagnosis-solution problems, (vii) strategic performance problems, (viii) case analysis problems, (ix) design problems, and (x) dilemmas. While Jonassen does describe differences among the problem types, he does not explore how each problem type affects a student's learning [6].

The only literature found that explores the effect of design project types on student learning is that of Ernst and coauthors. Following an evaluation of the implementation of three hands-on first-year engineering design projects, they concluded that the various projects offered no significant difference in their impact on design process knowledge (as assessed via students' critique of a speculative design process) [7]. While their study explores effects at the level of project type, they do not explore the effects of the problem statement itself.

1.2. Design Tasks in Design Education Research

While some design and design education research is conducted within the context of an engineering design classroom, much of this research is conducted in extracurricular experimental sessions. In these sessions, student research participants are asked to work towards a solution for a speculative design scenario. An example design task is provided in Box 1. Typically, the students' behaviors are then recorded, characterized, and analyzed to note any change as a result of an educational intervention and/or use of a specified design process.

Box 1. Playground Design Task (from [8])

You live in a mid-sized city. A local resident has recently donated a corner lot for a playground. Since you are an engineer who lives in the neighborhood, you haven asked by the city to design a playground.
You estimate that most of the children who will use the playground will range from 1 to 10 years of age. Twelve children should be kept busy at any one time. There should be at least three different types of activities for the children. Any equipment you design must:

- Be safe for the children
- Remain outside all year long
- Not cost too much
- Comply with the Americans with Disabilities Act

The neighborhood does not have the time of money to buy ready-made pieces of equipment. Your design should use materials that are available at any hardware or lumber store. The playground must be ready for use in 2 months.

Characterization and analysis of design behaviors is commonly accomplished via protocol analysis. Protocol analysis is a rigorous methodology for analyzing verbalized thought sequences and is validated method for the acquisition of data on thinking [9]. It has been used extensively in design research to assist in the development of the understanding of the cognitive behavior of designers (e.g., [8,10,11]).

Like literature regarding engineering design teaching practice, there is limited research on the effect of the design prompt/scenario on participants in engineering design educational research. Jiang and coauthors studied the effect of the design task on design cognition [12]. In their work, experimental sessions were conducted wherein design teams composed of industrial design students were given two different tasks: the first task related to a well-understood domain where the expectation was some form of variant design, while the second task was in a domain that no one had prior experience. From this research it was concluded that ID students begin their solution of the two very different tasks similarly, but then adapt adjust their strategies to different design tasks when synthesizing and evaluating design solutions.

However, aside from this one paper, it is often a core assumption of most studies that the design prompts have no effect on the participants' responses. Furthermore, there has yet been any research on how small changes on design tasks (e.g., a single requirement) might affect design cognition.

1.3. Context

In this paper the authors seek to answer the question, *Do small changes in design tasks, such as a single changed requirement, affect how students approach designing a solution?*

Answering this question will better inform both engineering design educators and researchers. If design tasks affect student design cognition, educators could select a design problem to target the development of certain aspects a student's design behavior. Similarly, researchers would no longer be able to treat the design prompt as a controlled variable.

To test the hypothesis that a design prompt does affect a student's design experience, the authors use protocol analysis and an ontology-based coding scheme (described in Section 2) to research the potential effects of a design prompt on students' design cognition. Specifically, protocol analysis is used to compare and analyze the experimental design sessions of two student groups that are presented with slightly different design prompts (Sections 3 and 4).

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.

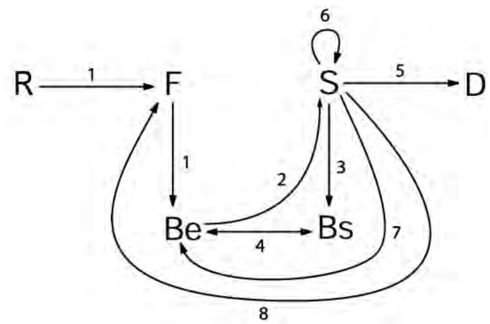

Figure 1. The FBS ontology

The six types of design issues are presented below (and in more detail in the authors' prior work, [13]):

- Requirements (R): designed object are intentions that come from outside the designer
- Function (F): The teleology of the designed object; includes the scope of the design, design functionalities, user characteristics, and value-adding characteristics
- 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.
- Behavior from Structure (Bs): The behavior from structure includes utterances that describe the motions of the structures that form the design
- Structure (S): The structure involves utterances that are associated with an object's property, location, and relationships.
- Description (D): The written or sketched description of the designed object.

These six 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 (labeled by number in Figure 1) include:

- Formulation: The transformation of functions into a set of expected behaviors (process 1, Figure 1)
- Synthesis: Where a structure is proposed to fulfill the expected behaviors (process 2)
- Analysis: Wherein the structure is analyzed to determine the behavior it produces (process 3)
- Evaluation: Wherein the behavior from the structure is compared to the expected behavior to determine if the designed product's behavior matches what is desired (process 4)
- Documentation: Wherein the design description is produced (process 5)
- Reformulation I : The reformulation of structure (process 6)
- Reformulation II: The reformulation of expected behavior (process 7)
- Reformulation III: The 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 six design issues, which claim to be the fundamental processes for designing.

2.2 FBS Coding Scheme

In this project we use a principled, design-based coding scheme based on the FBS ontology that translates the ontology into six design issues that map onto the ontological variables. Each design issue is coded using the FBS ontology. The six codes for the six cognitive design issues, which are used to label segments in protocol analysis, can be combined to produce eight design processes, as seen in Table 1, where ">" indicates unidirectional transformation and "<>" indicates comparison. The numbers listed next to each design issue corresponds with the labels presented in Figure 1.

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. Their participation in this study was compensated via a gift card to an online retailer. The participants had all completed a sophomore-level design class in the semester prior to their involvement. The 3-credit course is focused in exposing students to engineering design and design methodologies at the beginning of their entry into the major through active-learning opportunities (e.g., product dissections and designing products for various speculative scenarios).

The control group consisted of 12 students (6 teams of two). The experimental group consisted of 12 students (6 teams of two), as well. It should be noted that the groups had different instructors and took the design course at different times (e.g., the control group was taken from the 2010 class; the experimental group was taken from the 2011 class). It is assumed that the use of different students for the control and experimental sessions is not a variable; this assumption is corroborated by existing design education research.

Furthermore, both cohorts of participants are identified to be a representative sample of their peer group, as determined by a series of spatial reasoning ability tests, as described in [14]. However, 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 & Tasks

In the experiments, pairs of students worked together at a whiteboard to solve a speculative design task. The common design task asked students to design a device to help stroke patients, who are unable to perform bilateral tasks, with opening doors. This task is adapted from [15], as it has been well-established in prior design education research.

The specific wordings of the design tasks used in this research study are presented in Box 2. The only difference between the prompts presented to the control and experimental groups is that the word "portable" (shown in parentheses in Box 2) is added to the prompt for the experimental group. This added word adds a single requirement (a constraint) to the design task.

Box 2. Control (Experimental) Group Design Task

Your design team has been hired by the Metropolitan Rehabilitation Institute, the leading rehabilitation hospital in the country, to ***design a new (portable) 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.

Student pairs worked together on the assigned design tasks for 45 minutes. Working in pairs provided for natural verbalization that could be recorded, transcribed, and analyzed. Two digital camcorders, one recording the whiteboard and the other recording the students, were used to video record the session. In addition, each student was provided a remote lapel microphone to ensure the recorded quality of their conversation was high.

3.3 Protocol Analysis

The basic methodology of the protocol analysis consists of the following sequence of tasks.

- *Videoing 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 carries out the transcription manually. The result is a time-stamped, digital version of the verbalizations in a session in the form of entries in a spreadsheet.
- *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 of design issues as described in Section 2.2. Each segment can contain only one design issue [16]. This harmonizes all segmentation when using this coding scheme since there is now an isomorphism between segments and design issues. 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%. The result is the final, arbitrated protocol. This final protocol is the first data set available for analysis. The final protocol for a 45 minute design session typically generates between 200 and 800 segments. This provides a rich and statistically significant data set.

3.4 Statistical Analysis

JMP 10.0, a statistical software package, was utilized to identify any statistical differences in the percent occurrences of cognitive effort related to individual design issues between the two cohorts. Statistically significant differences were assumed at a significance level (α) of 0.05. The normality assumption was tested for each design issue and process using the Shapiro-Wilk W test. A two-sample t-test was conducted for those that were from normal distribution, whereas the Wilcoxon rank sum test was used for those that were not from normal distribution.

4 RESULTS AND ANALYSIS

To explore the effects of the design task on design practice, we first compare the experimental and control group's design behaviors. To examine design behaviors, we analyze and compare the percent occurrences of the design issues and syntactic design processes. We also report the Problem-Solution (P-S) issue index, via a sliding window technique, to examine the degree to which students' cognitive effort was focused on problem or solution for either design prompt.

4.1 Syntactic Design Processes

The percent occurrences of design issues for both the control and the experimental groups are shown in Figure 2. It is observed that, for both groups, the large majority of design effort is spent on determining the structure and evaluating its behavior (> 30% on both topics for both groups). Noticeable differences are observed between the groups on the issues of function (2.67% difference), expected behavior (6.47% difference), structure behavior (3.17% difference) and description (7.77% difference).

Results from a statistical analysis of the differences between the two groups are provided in Table 2. It is found that the only statistically significant differences are found in the frequency of design issues of expected behavior and description issues.

This result suggests that the added requirement in the design prompt has affected the design behavior of the experimental group. This result follows what is expected when a requirement is added. A requirement should impact only the framing of the design problem, and thus one should see significant changes only in frequency of discussion of requirement, function, and expected behavior issues.

This result is also corroborated by anecdotal observation of the participants during the experiment: those in the control group spent less time in exploring the functionality of the solution. Without the "portable" requirement, most teams in the control group went straight to solutions in which the door itself was augmented for the stroke patients (e.g., via a motion detector). However, with the "portable" requirement, teams within the experimental group spent significantly more time posing and evaluating solutions that were centered in creating a secondary device to assist a stroke patient with opening a door.

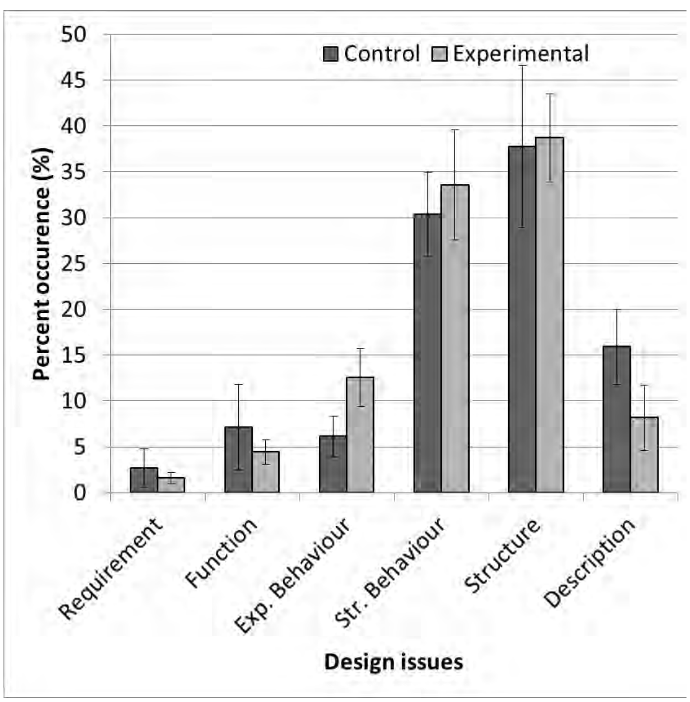

Figure 2. Percent Occurrences of Design Issues for Control and Experimental groups

Table 2. Statistical Analysis for Design Issues Between Experimental and Control Groups

Design issues	*t (z)-statistics*	*p-value*	*Decision*
Requirement	-0.444	0.296	Not different
Function	-1.042	0.297	Not different
Expected behavior	4.104	0.002*	Different
Behavior from structure	1.026	0.330	Not different
Structure	0.235	0.819	Not different
Description	-3.509	0.005*	Different

*$p < 0.05$

4.2 Syntactic Design Processes

The percent occurrences of the two group's syntactic processes are presented in Figure 3. Syntactic design processes are design processes obtained by assuming that any segment is cognitively related to its immediately preceding segment and as a consequence there is a design process that transforms one into the other, Figure 1. The majority of the time spent by both groups is in the processes of Analysis and Reformulation 1. This is a common design behavior for novice designers; the majority of their time is spent in iterating through solutions.

Similar to design issues, it is hypothesized that the added requirement will cause differences only in processes related to framing the design problem (e.g., Formulation, Synthesis and Reformulation 2). The largest differences observed in Figure 3 are in the processes of Evaluation (6.82% difference) and Reformulation 1 (5.33% difference).

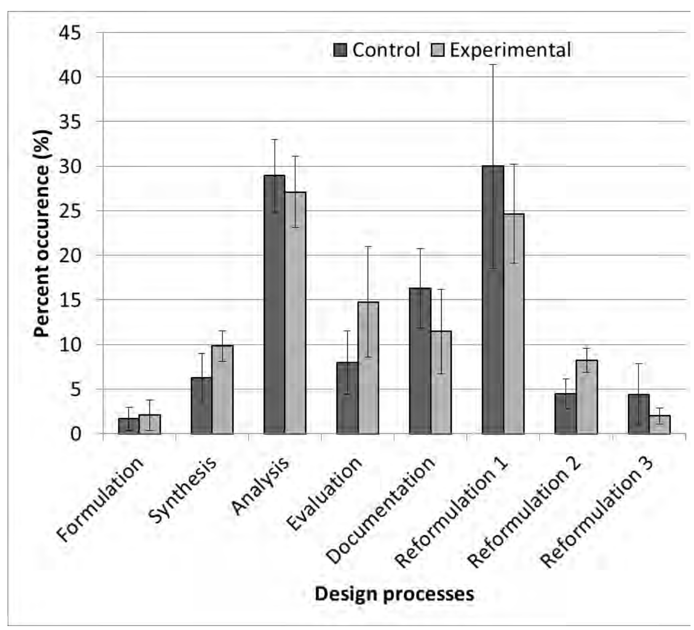

Figure 3. Percent Occurrences of Design Processes for Control and Experimental Groups

Table 3. Statistical Analysis for Design Processes Between Experimental and Control Groups

Design processes	*t (z)-statistics*	*p-value*	*Decision*
Formulation	0.455	0.659	Not different
Synthesis	2.692	0.025*	Different
Analysis	-0.800	0.442	Not different
Evaluation	2.325	0.048*	Different
Documentation	-1.824	0.098	Not different
Reformulation 1	-1.027	0.337	Not different
Reformulation 2	4.255	0.001*	Different
Reformulation 3	-1.122	0.261	Not different

*$p < 0.05$

Statistical analysis of the differences in design process discussion is shown in Table 3. As can be seen, there are statistically significant differences between the groups' use of Synthesis, Evaluation, and Reformulation 2 processes. This result again suggests that the design task has altered the students' design behavior. The presence of the added requirement has translated in longer time being spent on design processes related to framing the design problem.

4.2 Problem-Solution Issue Index

One method to measure meta-level design behavior is to divide all cognitive effort into that which is focused on the problem by that which is focused on the solution. The ratio of cognitive effort on the problem to cognitive effort on the solution is called the problem-solution index. When the cognitive effort relates to design issues it is called the problem-solution issues index (Figure 4).

$$\textit{P-S Issue Index} = \frac{\textit{SUM (Requirement, Function, Expected Behavior)}}{\textit{SUM (Structure, Behavior from Structure)}}$$

Figure 3. P-S Issue Index Equation

The index is calculated over moving averages using a sliding window method to provide a description of the dynamic behaviors across a design session. The number of data points that will be produced from each sliding window needs to be the same for each protocol to allow for direct comparisons. In this study, 150 data points were computed from each protocol. Since a 45 minutes design session produced between 200 and 800 segments, each corresponding window size was calculated for each protocol. For example, in order to produce 150 data points for a protocol that has 400 segments, the window size needs to be 250. A window size of 250 commences at the beginning of the design protocol (segment #1) and moves a single segment at a time until it reaches the end of the protocol (segment #400). Throughout the window movement, an independent calculation of the P-S Issue index is carried out at each window position by using the averages of the design issues/processes in that window. By putting the calculated results together, a dynamic model is produced, which shows the changing values of the P-S indices in the course of a design session.

Figure 4 shows the Problem-Solution issue index moving averages for the two participant groups. The *x*-axis represents 150 segments from the design protocol and the *y*-axis indicates the P-I Issue index. Both groups show a similar negative P-S Index slope throughout the session, which suggests that both balanced problem framing and problem solving in similar ways. One qualitative difference can be observed: from the consistently larger P-S Issue score, it can be concluded that the experimental group spent more time framing the problem throughout their design session. It is likely that the experimental groups' added focus on framing the problem was due from the added requirement in the design prompt.

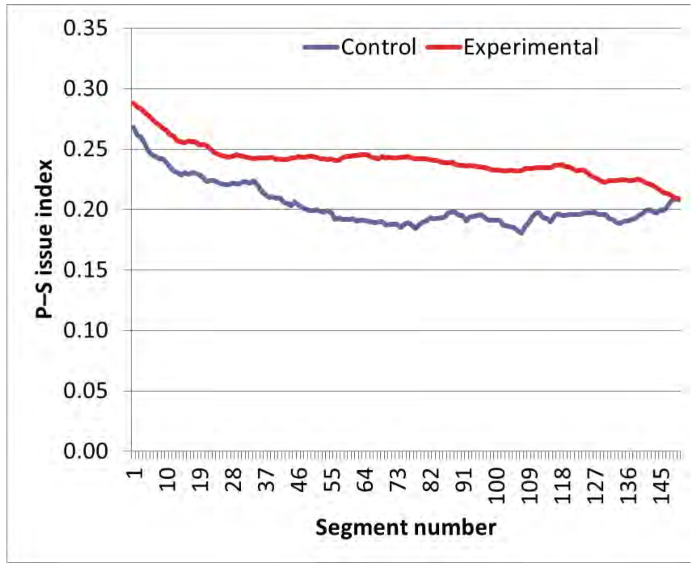

Figure 4. P-S Issue Index for Control and Experimental Groups

5 CLOSURE

In this paper, the authors use protocol analysis to characterize the effect of the design prompt on the design cognition of student designers. Specifically, similar design tasks were presented to two similar student groups: the task provided to the experimental student group included one additional requirement with respect to the control student group.

Following protocol analysis of the verbalized design sessions, the authors can conclude that the added requirement (e.g., the single word, "portable") had an impact on the design behaviors of the students. Specifically, due to the added requirement, the experimental group spent more time on issues related to framing the design problem (as seen in measurements of occurrences of design issues, design processes, and in the P-S Issue index).

This result has significant impact on both engineering design education practice and research. Given that the design prompt can alter a student's design behavior, it might be possible to carefully design design prompts in order to target student activity in areas in the design process in which they need improvement.

With respect to design education research, this result suggests that one cannot assume that the design prompt itself is a controlled variable. Care must be taken when designing the experimental design prompt since, as shown here, the prompt can impact a student's design behavior (e.g., the presence of added requirements causes the students to spend more time in stages relating to framing the problem).

The authors intend to build on this work in the future. Specifically, to build additional confidence in the statistical outcomes of this work, the authors look to study additional student teams. In addition, it would be interesting to study more complex, realistic design tasks that feature a variety of task differences.

6 ACKNOWLEDGMENTS

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