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The Impact of Scaffolding Prompts on the Collaborative Problem Solving of Ill-Structured Tasks by Undergraduate Engineering Student Groups

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Introduction

This evidence-based-practice paper explores the impact of including scaffolding prompts in ill-structured tasks for collaborative problem solving in undergraduate engineering courses. Ill-structured tasks are important to engineering courses because they are similar to authentic problems that students will encounter in their future workplaces [1], [2]. Solving ill-structured tasks collaboratively allows students to expand their learning beyond "drill-and-practice"-type problem solving and engage in higher order thinking and co-construction of knowledge [3]. Nevertheless, studies have indicated that it is necessary to scaffold ill-structured tasks because they are complex [4], [5], and students do not naturally implement effective collaborative interactions while solving these tasks [6]. However, it is not clear what type(s) of scaffolding prompts can foster students' participation in effective collaborative problem-solving interactions that include not only attempting to solve but also exploring the task, planning how to solve, and evaluating the completed solution [7]. This study investigates the impact of scaffolding prompts on collaborative problem-solving interactions and quality of groups' final task solutions so that instructors can better understand how to design effective ill-structured collaborative tasks for undergraduate engineering students.

Collaborative Problem-Solving Interactions

Ge and Land's research in collaborative problem solving has stressed the importance of four problem-solving processes necessary for effectively solving an ill-structured task in groups. These processes are: exploring the problem (P1), planning solutions (P2), attempting to solve (P3), and evaluating the solution and considering alternatives (P4) [7]. Researchers argue that these processes are associated with better learning outcomes; thus, it is important for students to engage in all four as they solve this type of task [8], [6].

In previous work [9], we developed a literature-based framework that outlines and defines these four collaborative problem-solving processes as demonstrated through verbal interactions that take place among group members (Table 1). We adapted the framework to fit the context of collaborative problem solving in engineering by relying on characteristics defined in literature, such as visual representation of the problem through construction of a free body diagram (FBD) as an important element of exploring and setting up the problem [10], [11]. Using the adapted framework, we introduced a method for characterizing verbal interactions within each of the problem-solving processes (P1, P2, P3, and P4) in the context of collaborative problem-solving engineering classrooms. Doing so provides insight into the nature of students' engagement with the task, which can inform instructors for refining and improving their task design.

Table 1: Process Coding Scheme	
Code	**Definition**
Process 1 (P1): Exploring the Problem	Interactive turns[1] in which students verbally explore the scope of the task. This can include communicating their understanding of the task (or lack thereof), elaborating on the task, and creating a joint representation of the task.
Process 2 (P2): Planning How to Solve	Interactive turns in which students identify and select a method or plan for solving by discussing choices and reasoning. This can include further representing the problem in multiple ways.
Process 3 (P3): Attempting to Solve	Interactive turns in which students attempt to solve the task, correction to the solution, or alternative solution. This can include discussing their chosen solution method and making arguments or justifications in order to advance along the solution path toward a final answer.
Process 4 (P4): Evaluating the Solution and Considering Alternatives	Interactive turns in which students evaluate their solution and assess alternatives. This can include identifying errors in their solution and suggesting a method for correcting the errors, but does not include attempts to solve the corrections or alternatives.
No Process (NP)	On-task, interactive turns that do not fit one of the four processes.

Scaffolding Ill-Structured Tasks

Task design has been established as important for problem-based learning (PBL) tasks, as PBL focuses on authentic tasks that help students make connections between classroom content and real-life scenarios [12]. According to Hung's chapter from the Wiley PBL handbook, "Problem design is a critical step in a PBL implementation as the quality and the affordance of the problem could affect students' learning in various ways, such as ability to identify learning objectives, or motivation" [12 p. 250]. Affordances, or task properties that clue the participant toward how the task can be approached or solved, include task scaffolding, which serves to guide students correctly through the necessary sequence of realms within the problem space.

Ertmer and Glazewski's chapter of the PBL handbook [13] outlines the need to scaffold problem-based learning. In effect, scaffolds transfer responsibility from the teacher to the student by fostering autonomy. The chapter discusses two overarching purposes of scaffolds: to guide students through the task such that they are able to effectively engage with the problem, and to assist students in identifying and focusing on the most important aspects [14]. Such prompting is significant for fostering agency and deeper engagement in students, who need to prepare for similar situations in their future careers. However, the actual effect of adding scaffolding prompts in ill-structured engineering tasks is not clear; additionally, the impact of scaffolding prompts on collaborative interactions as groups solve these tasks is unknown. Scaffolds should be intentionally designed and implemented and are expected to be used dynamically [13]; however, it is unclear how to properly adapt scaffolds in our context, as students' experiences solving ill-structured tasks has not yet been comprehensively characterized. Knowing that scaffolding is meant to aid students in effective immersion within the problem space, and engagement with the task, it can be hypothesized that proper scaffolding will enhance the quality of students' collaborative interactions. As literature has already established a positive relationship between good-quality collaborations and higher learning outcomes [6], it follows that task scaffolding should lead to further improvement of these outcomes. To address this gap in the literature, this paper examines two different collaborative ill-structured engineering tasks

[1] For this coding scheme, "interactive" refers to either verbal interaction between at least two group members or interaction that takes place through the shared tablet space during narration by one group member.

and contrasts how including scaffolding prompts influenced 1) students' verbal interactions as they worked and 2) the groups' final scores on the task. The study seeks to answer the following questions:

1. How does the presence of scaffolding prompts influence the collaborative problem-solving interactions of groups as they solve ill-structured engineering tasks?
2. How does the presence of scaffolding prompts influence groups' final scores on the task?

Methods

Design

Design-based implementation research is a research approach that "applies design-based perspectives and methods to address and study problems of implementation" [15 p. 137]. This study is part of a multi-year design-based implementation research project, Collaborative Support Tools for Engineering Problem Solving (CSTEPS), that involves the design and implementation of authentic ill-structured tasks in actual undergraduate engineering discussion sections, where students worked in small groups to solve these tasks. This study compares the verbal interactions and quality of final solutions from the same groups on a non-scaffolded and a scaffolded task.

Participants

Participants were 40 undergraduate engineering students (6 females, 34 males) who were registered for a required introductory engineering course at a large, public Midwestern university. The 200-level course, which introduced students to solid mechanics, heavily emphasized the deformation of bodies by internal and external stresses. The course guided students through design principles based on mechanics such as normal and shear stress as well as compressive, tensile, and torsional loading.

Tasks

The non-scaffolded and the scaffolded tasks were both designed using a literature-based framework developed by Shehab and Mercier [16]. The tasks included an introduction that contextualized the problem in a real-life scenario, a description of the task itself, and supplementary material that provided information useful for solving the task. Only the scaffolded task included scaffolding prompts that explicitly directed the students to set up the task, develop plans, draw diagrams, and evaluate solutions. Both tasks were presented to students as digital worksheets.

The non-scaffolded task was comprised of five sections: an introduction that defined beam deflection; a description of the problem (to design a pair of salad tongs that can lift one cherry using the cheapest wood); supplementary material that showed the model, loading direction, and dimensions of the tongs, as well as information about three types of wood; a follow-up prompt that asked students to determine which wood would be the cheapest per unit for manufacturing the tongs and verify that their choice still allowed the tongs to function as specified; and a second follow-up prompt that required students to implement design changes that further lowered the unit cost of the tongs and then prompted them to evaluate the performance of their altered design.

The scaffolded task was comprised of five sections: an introduction that defined loading distribution; a description of the problem (to analyze the tensile stress felt in the cables of a pick-up truck tailgate caused by a load placed on the lowered tailgate); supplementary material that showed sample loading diagrams of the tailgate, weights of six item choices for loading the tailgate, and mechanical properties for three different cable choices; a marked area dedicated to constructing a free body diagram of the tailgate (i.e. an explicit prompt for P1); and a follow-up prompt requiring students to evaluate the performance of a different cable choice in place of the original material with explicit direction to evaluate the factor of safety (i.e. an explicit prompt for P4). The scaffolded task also included a prompt to plan the type of loading used to solve the problem (i.e. an explicit prompt for P2).

Data Collection

Data collection took place during one semester in four 50-minute discussion sections that were held in a laboratory classroom; each section was taught by three teaching assistants. Each week, groups solved the same ill-structured tasks in all sections. Only one task was solved during each week's section. The tasks were installed as digital worksheets on 11-inch tablets. Tablets of students in the same group were synchronized to allow for the creation of joint representations. Using individual cameras that were installed in the ceiling of the laboratory classroom, video and audio data were collected from groups as they solved the tasks.

Data Analysis

This study analyzed the video recordings from 11 groups with consistent members as they solved the non-scaffolded task during one discussion section and the scaffolded task during another discussion section. First, the 22 video recordings were transcribed using a playscript format. Next, to identify the problem-solving processes that characterized the verbal interactions of the groups as they solved the task, we defined each of the four processes within the context of each task and developed a coding scheme to identify the turns associated with each of these processes in each video (Table 2). To evaluate inter-rater reliability, two researchers coded three videos for each task. Cohen's kappa was .82 for the non-scaffolded task and .87 for the scaffolded task. After coding the interactions per each video, the proportion of each of the four processes was calculated by dividing the number of turns associated with each process by the total number of turns that were associated with any of the four processes. A repeated measures analysis of variance was conducted to compare the four processes that characterized the verbal interactions of the same groups as the solved the non-scaffolded task and the scaffolded task.

Table 2: Samples of Verbal Interactions by Code for the Non-Scaffolded Task		
Code	**Adapted Definition**	**Example**
Process 1 (P1): Exploring the Problem	Interactive turns in which students verbally explore the scope of the task. This can include communicating their understanding of the task (or lack thereof), elaborating on the task, and creating a joint FBD.	*Student 1: "I assume we don't have to take into account the weight of the wood or anything."* *Student 2: "No, we don't."*
Process 2 (P2): Planning How to Solve	Interactive turns in which students select a method or plan for solving by discussing choices and reasoning. This can include exploring multiple design configurations.	*Student 1: "We should find the moment equation."* *Student 2: "Yeah, that makes sense because we need the moments to do the deflection."*
Process 3 (P3): Attempting to Solve	Interactive turns in which students attempt to solve the task, correction to the solution, or alternative solution. This can include discussing their chosen solution method and making arguments or justifications in order to advance along the solution path to reach a final answer.	*Student 1: "Oh, this one should be plus C, and then this turns into PX plus C."* *Student 2: "Yeah, but those should be zero 'cause of the boundary conditions, right?"* *Student 1: "No, C was equal to something."* *Student 2: "But this has to equal zero because Y prime of zero is always zero."*
Process 4 (P4): Evaluating the Solution and Considering Alternatives	Interactive turns in which students evaluate their solution and assess alternatives. This can include discussing factor of safety and producing written documentation of their results, as well as identifying errors and suggesting a method for correction. This does not include attempts to solve the corrections or alternatives.	*Student 1: "There are way too many variables in our answer."* *Student 2: "We can change P over H to 100."*
No Process (NP)	On-task, interactive turns that do not fit one of the four processes.	*Student 1: "It should be 6 Y prime…so then we will need to change this."* *Student 2: "That's a big equation."*

To evaluate the quality of the groups' final solutions to the task, a grading rubric was developed (Table 3). The rubric identified components of the task that could later be correlated with each of the four processes. Each component was scored on a three-point Likert-type scale for "Not present," "Attempted but inaccurate" (which could mean incomplete), and "Complete and correct." "Not present" received a value of 0, "Attempted but inaccurate" received a value of 0.5, and "Complete and correct" received a value of 1. Scores for all components of each process (P1-P4) were tabulated. Each group received a final total score out of a possible 5 for the tongs (non-scaffolded) task or 6 for the tailgate (scaffolded) task; the tailgate task scores were adjusted for a 5-point scale. Per our framework, the rubric categories relate to the four processes as follows: P1–visual representation (FBD); P2–configurations; P3–all calculation categories; P4–factor of safety and written evaluation of the results. For inter-rater reliability, two researchers graded the final solutions of 6 of the 20 groups' solutions; percent agreement was 88%. A repeated measures analysis of variance was conducted to compare the scores of the groups on the non-scaffolded and scaffolded tasks.

Table 3: Grading Rubric				
Element		**0 points**	**.5 point**	**1 point**
Free body diagram (drawing that represents the given problem and visualizes relevant forces) (N/A for tongs)		Not present	Attempted but incorrect	Complete and correct diagram
Calculations/ Unique elements	Stress calculations (tailgate)	Not present	Attempted but incorrect	Complete and correct
	P force (tongs)	Not present	Attempted but incorrect	Complete and correct
	Force in the cable (tailgate)	Not present	Attempted but incorrect	Complete and correct
	Deflection equations (tongs)	Not present	One or both attempted but incorrect	Both complete and correct
	Factor of safety (tailgate, tongs)	No calculations	Attempted but incorrect	Complete and correct
Number of configurations		No configurations attempted	One configuration attempted/solved, or multiple configurations attempted without solutions	At least two configurations solved
Written documentation stating whether each configuration fails or succeeds		Not present	Present for one configuration	Present for all configurations
Adjusted Grand Total		/5		

Results

The Impact of Scaffolding Prompts on Collaborative Problem-Solving Interactions

Figure 1 shows the mean proportions of the different types of collaborative problem-solving interactions in the non-scaffolded and scaffolded tasks. A repeated measure analysis of variance indicated a main effect of task on the proportion of P3, $F(1,10) = 18.12$, $p = .002$, $\eta 2 = .644$, and the proportion of P4, $F(1,10) = 10.67$, $p = .008$, $\eta 2 = .516$. The mean proportion of P3 is significantly higher for the non-scaffolded task than the scaffolded task, whereas the mean proportion of P4 is significantly lower for the non-scaffolded task than the scaffolded task. These results indicate that groups implemented less “attempting to solve” interactions (P3) and more “evaluating the solutions and considering alternatives” interactions (P4) in the scaffolded task than in the non-scaffolded task.

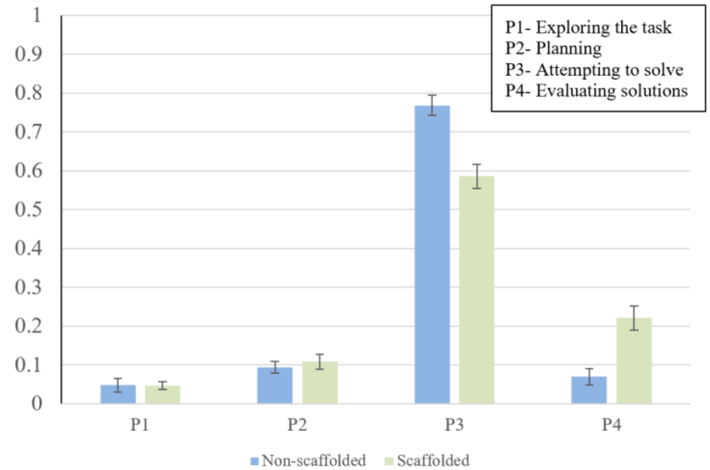

Figure 1: Mean proportions of the four processes by task

The Impact of Scaffolding Prompts on the Quality of the Groups' Final Solutions

Figure 2 shows the groups' final solution scores for the non-scaffolded and scaffolded tasks. A repeated measure analysis of variance indicated a main effect of task on the groups' scores, $F(1,10) = 4.36$, $p = .044$, $\eta 2 = .713$. These results indicate that the quality of groups' final solutions for the scaffolded task was significantly higher on average than the quality of the groups' final solutions for the non-scaffolded task.

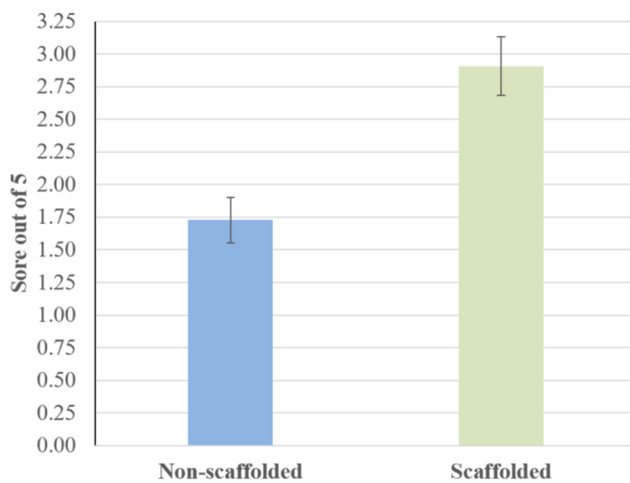

Figure 2: Mean task scores

Discussion

This study investigated the impact of scaffolding prompts on 1) collaborative problem-solving interactions and 2) the quality of groups' final task solutions in an undergraduate engineering classroom setting. Eleven groups solved a non-scaffolded task and a scaffolded task during separate 50-minute discussion sections. The types of collaborative problem-solving interactions and the quality of final task solutions of the groups were compared in the two conditions.

Our previous work [9] revealed that students' unprompted interactions during ill-structured task problem solving in this context tend to fall heavily within the realm of attempting to solve the task (P3). The results of this study indicate that the presence of explicit scaffolding prompts effectively moved students to participate less in verbal interaction focused on attempting to solve the task and more in verbal interaction focused on evaluating their solution and considering alternatives (P4). The shift in proportions of these two types of turns seems necessary for more effective task solving; Ge and Land's work [7] has established that such a shift can indicate effective collaborative problem solving, which in turn can lead to better learning outcomes [8], [6]. Based on Jonassen et al.'s comprehensive work regarding the characteristics of problem solving in the engineering workplace [10], we argue that verbal interactions that are more spread out across the four processes, instead of clustered in the "attempting to solve" realm, more realistically resemble authentic collaborative problem solving in engineering.

Our results also indicate that groups had significantly higher final solution scores on the scaffolded task than they did on the non-scaffolded task. This means that for the scaffolded task, groups achieved, on average, more complete and accurate work on necessary elements such as devising configurations of the design and assessing the level of success of those configurations. As the discussion sections are intended to allow students opportunity to, in collaboration with their peers, synthesize the knowledge content they learned in lecture in collaboration, improved performance on the task indicates a more effective command of the topic. To further investigate this claim, students' understanding of the course material should be assessed through pre- and posttests.

The groups in our study remained consistent throughout the two discussions and solved the non-scaffolded and scaffolded tasks in the same environment. Knowing that the task scores were significantly different between the non-scaffolded and scaffolded tasks and that the task scores on average were higher for the scaffolded task, we argue that characteristics of the task design directly influenced the change in scores. Furthermore, our results indicate that students' collaborative interactions shifted to become better spread across the four processes in the scaffolded task, breaking from the more homogeneous P3-type profile of similar interactions from previous work [9]. This suggests that the shift in students' interactions may have positively influenced the quality of their work on the task as a group. More research is needed to justify this claim.

Conclusions and Implications

Our study promotes the evolution of collaborative problem solving by expanding on ill-structured task design. Scaffolding ill-structured engineering tasks by including explicit prompts for exploring the problem (P1), planning how to solve (P2), and evaluating the solution (P4) enables students to engage beyond the realm of attempting to solve (P3) and participate in a more diverse and realistic distribution of turns, which then leads to more effective collaborative interactions. The shift in interaction seems to produce higher-quality final work, which is especially relevant for engineering educators. Future work should further investigate the potential relationship between task scaffolding and quality of work, seeking to establish the impact of the types of collaborative interactions (as prompted through scaffolds) on the quality of groups' final solutions. Good-quality interactions and higher scores in this study could have been influenced or caused by other variables beyond our control; more controlled studies are needed to validate these findings.

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