EXPLORING THE NATURE OF STUDENTS' COLLABORATIVE INTERACTIONS DURING A HANDS-ON ILL-STRUCTURED ENGINEERING DESIGN TASK

BY

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THESIS

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ABSTRACT

Engineering education is experiencing a shift in curriculum format toward more emphasis on collaborative design work. This can be accomplished through means such as collaborative ill-structured tasks, which provide students with experience authentic to industry. However, research on effective ill-structured task design in the context of undergraduate group problem solving is relatively limited. Studies have explored how to design and construct ill-structured tasks that effectively engage students and promote higher learning outcomes and group collaboration, but these tasks have primarily been limited to two-dimensional representations that lack opportunity for students to realize their design implications in the physical world. While some tasks may include three-dimensional representation of task content, little is known about the influence on students' collaborative interaction that can result from the use of physical, hands-on task products in this context. This study seeks to address this gap by characterizing the nature of students' interactions as they worked in small groups on an ill-structured engineering design task for which a physical object was a central component. The study uses mixed methods to analyze the interactions and experiences of twenty undergraduate engineering students in five groups as they worked together to dissect a product, model its components, and make justified design changes to their model. Ethnographic observations were recorded during multiple dissection sessions for each of the five groups. Thematic analysis was used to identify initial trends in the data and to develop a coding scheme, which was then applied to characterize participants' behaviors and collaborative processes at both individual and group levels. Frequencies of codes were compared against task scores to investigate the impact of participation in identified behaviors and processes on group performance. Results indicated positive relationships between 1) participation in dissection and task scores, and 2) participation in collaborative reflection and task scores, both of which are meaningful for future collaborative task design. The study supports the evolution of collaborative engineering problem solving by contributing to our understanding of the impact of hands-on learning in design tasks.

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TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

Engineering education is continually transforming. Indeed, a comprehensive review of 100 years of engineering education by Froyd et al. (2012) identified five major shifts in that time (2012). Ragonese and Starkey (2020), building on work by Issapour and Sheppard (2015) and Huerta-Wong & Schoech (2010), noted that engineering faculty were accustomed to delivering theoretical concepts solely through a lecture-type format until roughly forty years ago. This deviation corresponded with Froyd's (2012) third shift, which saw renewed emphasison design. The fourth shift saw the adoption of problem-based learning, which is defined by Cornell University's Center for Teaching Innovation as "a student-centered approach in which students learn about a subject by working groups to solve an open-ended problem" (Cornell University, 2021). As problem-based learning has become more prevalent in engineering education in recent decades, the adoption of collaborative problem-solving practices has become increasingly common in engineering courses (e.g., Freeman et al., 2014). Modern employers now tend to place more emphasis on students' skillsets and personal traits over academic achievements (Kamp, 2016), making the development of a collaborative problem-solving skillset imperative for new generations of engineers.

Research has established the efficacy of ill-structured tasks for providing students with collaborative design experience that mimics the nature of design problems encountered in industry (e.g., Jonassen et al., 2006). However, research on effective ill-structured task design in the context of undergraduate group problem solving is relatively limited. Studies have explored how to design and construct ill-structured tasks that effectively engage students and promote higher learning outcomes and group collaboration (e.g., Kapur & Kinzer, 2007; Shehab et al., 2017; Tucker, Shehab, & Mercier, 2020 [2]), but these tasks have primarily been limited to two-dimensional (i.e., paper or digital worksheet) representations that lack opportunity for students to realize their design implications in the physical world. As hands-on learning can provide experiential opportunities necessary for synthesizing theoretical concepts (Huerta-Wong & Schoech, 2010), it is a necessary element for a well-rounded engineering education. Some tasks may include three-dimensional representation of task content (i.e., in the form of a model or prop), which can be effective in supporting students' deeper understanding of the content (e.g., Padalkar & Hegarty, 2015); others may require the use of physical measurement tools. However, there is limited research on how engineering students interact with, and collaborate with, each other on a design task for which working with a physical artifact is central to the task.

Context

Importance of Collaborative Problem Solving

Solving real-world problems can help students develop skills such as generating hypotheses, evaluating information, and justifying appropriate design decisions (Schmidt, 1989). Complex real-world tasks require practicing engineers to consult and work with not only colleagues of similar discipline but also experts from various other fields (Jonassen et al., 2006); thus, supporting collaborative problem solving in engineering curricula is important for effectively preparing new generations of engineers for the demands of the workplace. Efforts to increase collaborative learning in engineering courses have been driven by research indicating that this form of pedagogy allows students to deepen their conceptual knowledge and develop better team skills (e.g., Barron & Darling-Hammond, 2008).

Research has also established that quality of interaction is essential for student group work (e.g., Barron, 2003), highlighting the need for task design that effectively engages students in quality interactions. Fostering effective collaboration may be addressed through various methods; many computer-supported collaborative learning studies strive to reach this goal through digital spaces that prompt higher-quality interaction (e.g., Müller-Tomfelde & Fjeld, 2010; Martinez-Maldonado et al., 2013). There is a clear interest in characterizing and manipulating various physical and environmental aspects of collaborative learning; still, these studies do not focus on the influence of task-related objectson the distribution of student collaborations.

Well-Structured versus Ill-Structured Tasks

In recent years, there has been a trend toward redesigning the typical delivery of undergraduate engineering content. Traditionally, material was taught in a way that supported grading, heavily focused on rote methods in which students would "plug and chug;" i.e., plug values into existing formulas and then chug through the equation to solve for the final answer (e.g., Agogino et al., 1992; Jonassen et al., 2006; Douglas et al., 2012). An instructor could easily compare a student's process and solution to an answer guide to identify mistakes. This type of work falls into the category of well-structured problems (Schön, 1990; Jonassen, 1997), which define a clear path to a single correct answer. In his characteristics of well-structured problems, Simon (1973) notes that these problems have "a definite criterion for testing any proposed solution, and a mechanizable process for applying the criterion" (p. 183). While this method supports quick, reliable feedback on the implementation of formulas and mathematical problem solving, it does not necessarily support the growth of students' design skills.

As previously mentioned, the STEM curriculum evolution has brought problem-based learning (PBL) more to the forefront. Task design has been established as important for PBL tasks, as PBL focuses on authentic tasks that help students make connections between classroom content and real-life scenarios (Hung, 2019). As Hung (2019) writes, "Problem design is a critical step in a PBL implementation as the quality and affordance of the problem could affect students' learning in various ways, such as ability to identify learning objectives, or motivation" (p. 12). It naturally followed that ill-structured problems, which more closely resemble authentic work (Jonassen & Hung, 2008), would become more valuable to engineering education. These problems are motivating and require collaboration because they stimulate problem-centered interactional activity (Kapur & Kinzer, 2007). Indeed, Simon (1973) wrote that "the problems presented to problem solvers by the world are best regarded as ill-structured problems" (p. 186). 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 (Hung, 2013). Additionally, the collaboration aspect is significant for engineering students because engineers typically do not work alone, and rely on input from other engineers and experts in various fields to arrive at an informed solution (Jonassen et al., 2006). Thus, the collaboration skills fostered by ill-structured tasks are directly relevant for students' practices in the workplace.

Both well-structured and ill-structured tasks are meaningful to engineering education. Kapur's (2010) study of showed productive failure in mathematical problem solving showed that students in a productive failure-type practice condition tended to outperform their counterparts in a "lecture and practice"-type condition in both well-structured and higher-order application problems. These findings build on Kapur's earlier work (2008), which outlined a cycle in which students who solved ill-structured tasks were found to evolve their strategies for solving well-structured tasks, which in turn supported their ability to set up an ill-structured problem. In other words, the students' exposure to an ill-structured problem type provided the opportunity for them to grow their strategies for approaching design tasks. It follows that it is necessary to expose students to a strategic balance of task types as they grow as designers, and that this balance of task types needs to include both two-dimensional (i.e., paper-based) and three-dimensional (i.e., including a physical element) design tasks.

Research Framework

This study builds on previous work that developed a research framework that outlines four collaborative processes necessary to effectively solve an ill-structured task as they appear in an engineering context (Tucker et al., 2019). The framework, which relies heavily on the work of Ge and Land (2003, 2004), defines these processes as the following:

P1. Exploring and representing the problem

P2. Planning how to solve

P3. Attempting to solve (iterating plans and making justifications)

P4. Evaluating the solution and considering alternatives

Implementation of the framework relied on the interpretation of effective verbal participation in each process, which were outlined for a STEM context primarily using Jonassen et al.'s (2006) study of characteristics of the collaborative engineering workplace. Exploring the problem (P1) can lead to deeper understanding of the problem space and strong joint attention. Planning how to solve (P2) prompts the groups to consider more than one approach, leading them to explicitly define their chosen path and the reasoning behind it. Attempting to solve the task (P3) moves students to collaborate in generating computations, which can support their co-construction of applied knowledge. Evaluating the solution (P4) moves students into a joint reflection space where they can collectively judge how effectively they approached and solved the problem.

Previous Work

Collaborative Support Tools for Engineering Problem Solving (CSTEPS) (Collaborative Learning Lab, 2021) is an ongoing design-based research project (Penuel et al., 2011). CSTEPS has investigated task design and the use of interactive technology in an undergraduate engineering context. Prior to CSTEPS, collaborators had found that overcoming constraints typical of higher-level STEM classrooms requires designing for teacher, team, task, and technology, as well as the interactions among these (Mercier & Higgins, 2012). Subsequent work on the CSTEPS project developed a framework for designing ill-structured engineering tasks (Shehab et al., 2017). My contribution to the study began with exploring how to evaluate the effectiveness of a task's design using data gathered during implementation of that task (Tucker et al., 2019). Findings indicated that students tended to spend the overwhelming majority of their time attempting to solve the task (i.e., P3); in other words, deviating from rote problem solving did not come naturally.

However, 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 (e.g., Roschelle & Teasley, 1995; Barron, 2003). These findings led to the question of how to design the task to prompt students to engage in each of these collaborative processes. We expanded the study to examine groups across three ill-structured tasks and introduced the use of the Gini coefficient, a value that conveys the magnitude of deviation from a preset standard, as a group-level measure (Tucker, Shehab, & Mercier, 2020a). We hypothesized that, instead of placing significant emphasis on attempting to solve the problem (P3), groups should instead distribute weight more evenly among the four processes. Although we did not know the ideal proportions for each process during a problem-solving session, it was clear from previous work that students should experience a shift toward exploring the problem, planning how to solve it, and evaluating the effectiveness of their solution.

Using the Gini coefficient, we tested a scenario in which the ideal distribution would beto spend equal time in each of the four processes. It was found that the task with the lowest Ginicoefficients also had the highest scores for final work, per our pre-developed grading rubric (Tucker, Shehab, & Mercier, 2020a). Additionally, we saw a moderately negative correlation across the three tasks between Gini coefficient and task score, indicating that a tendency toward more equal participation among the four processes correlated to a higher average final score on the task. These results led to an in-depth analysis of two of those three tasks, one of which had explicit scaffolds for each of the four processes and one that did not contain explicit scaffolds. We investigated the impact of scaffolding prompts on 1) students' problem-solving interactions and 2) the quality of groups' final scores and found that the scaffolded task evoked significantlymore collaboration in monitoring and evaluation, and significantly less time spent attempting to solve, than the non-scaffolded task. Additionally, the scaffolded task had significantly higher final scores (Tucker, Shehab, & Mercier, 2020b). These findings were meaningful to task design because they indicated that explicit scaffolds could successfully provide opportunity for students to engage in a more even distribution of the four necessary processes, which in turn led to more effective problem solving as demonstrated by their tendency to perform better on the scaffolded task.

Our most recent work (publication in progress) investigated why these scaffolds were effective. Relying on insight from observing students' behaviors, combined with research on cognitive processes (e.g., Shehab, 2019), we hypothesized that the four processes can be thought of as a problem-solving space with unique characteristics. As students work to solve a task, they have opportunities to enter each space and participate in appropriate cognitive interactions to progress along a solution path. As we have already established that all four processes are necessary for effectively solving this type of task, it follows that the characteristics contained within each space are also necessary elements. Our findings showed that the cognitive interactions that groups implemented withineach process when solving the scaffolded task were different from those they implemented when solving the non-scaffolded task. It seemed that the scaffold prompts guided groups through the complexity of the task by supporting them in following a structure conducive to implementing cognitive interactions effective for participating in each of the four collaborative processes. From these findings, we could suggest why the scaffolds were effective: “...they provide fruitful opportunity for students to enter each space at strategic moments during the task such that they experience corresponding cognitive interactions in the proper space. The scaffolds themselves do not cause groups to problem solve correctly or experience desired cognitive interactions, but they provide opportunity to do so, making these outcomes more likely” (Tucker, Shehab, & Mercier, in press).

Our studies thus far have allowed us to progress in task design and implementation, but these tasks have still been limited to a two-dimensional context, lacking hands-on learning elements or other opportunity for experiential learning. As STEM concepts are embodied in real-world applications, the natural next step in the evolution of ill-structured task design is toinvestigate how to scaffold physical components. This work seeks to advance that goal by characterizing the nature of students’ collaborative interactions in a non-scaffolded engineering design task for which a physical product was the central component.

CHAPTER 2: REVIEW OF RELEVANT LITERATURE

Scaffolding in Ill-Structured Task Design

Historically, engineering design skills have been nebulous and therefore hard to teach effectively to students (Mabogunje et al., 2016). Previous work has suggested methods for teaching design in engineering education (e.g., Crismond & Adams, 2012; Dringenburg & Purzer, 2018; Ragonese & Starkey, 2020). Literature has also repeatedly demonstrated the necessity of scaffolding for proper task work. For example, in an early study of young children, Wood, Bruner, and Ross (1976) found that the tutor needs to support (i.e., scaffold) students' task engagement by enlisting the student's attention, as well as highlighting important features and model solutions. In the context of undergraduate problem solving, the task design itself acts as the "tutor" that guides students through the problem.

Task affordances, or 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. Ge (2001) advocated for the need to scaffold these tasks by arguing that "merely exposing students to ill-structured problems does not necessarily mean that students will effectively engage in problem solving" (p. 4). More recently, in a study of first-year engineering students collaborating in teams on ill-structured tasks, Dringenburg and Purzer (2018) encouraged educators to "consider the ways in which learning experiences in specific disciplinary or educational contexts require students to identify strategies for recognizing and navigating ambiguity" (p. 26). In the context of problem-based learning (PBL), Ertmer and Glazewski's (2019) chapter of the PBL Handbook outlines the need to scaffold problem-based learning. In effect, scaffolds transfer responsibility from the teacherto the student by prompting them into making moves that take ownership of their learning. Such prompting is significant for fostering agency and deeper engagement in students, who need to prepare for similar situations in their future careers. Atman et al.'s study (1999), which tracked student designers from freshmen to seniors, showed that as students adapt to, and become skilled at, solving open-ended design tasks, they grow to produce higher-quality designs and display higher tendency to engage in higher-cognition problem-solving processes such as gathering information (i.e., P1) and considering alternative solutions (i.e., P4). Thus, proper scaffolding during initial stages of the design task learning process can support students in developing strategies for approaching and solving these tasks autonomously.

Scaffolds are also significant to task design because of their role in providing opportunity for students to engage in necessary cognitive interactions at strategic points along the solution path of a task. Research has established the necessity for engineering educators toengage students at cognitive and emotional levels in authentic, meaningful, and immersive learning experiences (Astin & Alexander, 2016); it follows that deeper engagement in higher-cognition problem-solving processes supports students' evolution as designers and problem solvers. Our most recent work (Tucker, Shehab, & Mercier, in press) presented the need for students to engage in important cognitive processes in the proper problem-solving realm, showing that scaffolds serve to create opportunity for students to enter each realm at a strategic point in the task and thus experience meaningful cognitive processes that can lead to higher learning outcomes. Thus, in the context of hands-on ill-structured tasks, scaffolding must be considered as a strategic means for effective design. However, in order to properly scaffold this particular type of ill-structured task, it is necessary to first understand the processes and experiences students go through as they collaboratively problem solve, as well as the role of similar task elements such as three-dimensional visualization of the problem.

Importance of Three-Dimensional Visualization

Before considering the implications of the dissection process as a hands-on learning element in ill-structured tasks, it is important to recognize that the opportunity to visualize design in a three-dimensional space is meaningful; indeed, representing the problem two-dimensionally also has significant implications for task work. Diagrams and models may be considered similar because they are both visual representations; in the context of ill-structured tasks, they are often used to represent some aspect of the problem with the goal of bringing clarity or enhancing the students' understanding of that aspect. Unlike a verbal task description, which may be ambiguous or misunderstood, a properly constructed visual element can explicitly assert the constraints and characteristics of the problem. Tasks may provide diagrams or models for students to use to understand the content; however, according to Ge and Lands' (2003, 2004) framework, simply seeing pre-constructed representations is not enough for effective understanding of the task. Instead, students need to be able to create their own representations. In classroom studies that implemented tasks with prompted diagrams, one apparent theme is the variance in ways in which students inherently construct diagrams and models. Berge discussed the complexities of student learning and notes that when it comes to using diagrams, students do not simply create them to move linearly from point to point within the problem (Berge & Weilenmann, 2014). Similarly, Heckler (2010) presented a discussion of physics students' strategies for using force diagrams to set up mechanics problems. When specifically prompted to construct a diagram, some students tended to construct diagrams that fit into the flow of their work, while others treated the diagram as a separate task (Heckler, 2010). Uesaka et al. (2007) reported that in a study of Japanese versus Australian students solving the same task, the Japanese students' prior assumption that using diagrams is a teacher strategy, as opposed to a method that can be adopted individually by students, meant that they may perceive greater difficulty in using the diagrams. However, this perception did not correlate to the students' actual spontaneous creation of diagrams during problem solving. It is clear that students' individual proclivities and assumptions with regard to visualization methods will influence how receptive they are to using these methods in problem solving. It is important to note that research has also found that students do not naturally use models effectively (Keehner et al., 2008). Indeed, students of a younger age may struggle to effectively use models; in Martin and Schwartz's (2005) study of fourth-grade students using visual representations to solve math problems, the students' manipulation of three-dimensional structures did not correlate to correct understanding of the concept represented by the structure despite seeming to help their understanding.

Despite students' mixed responses to diagrams and models, the literature agrees that visualization is important for scientific understanding. In a study of undergraduate students working on a task in organic chemistry, Padalkar & Hegarty (2015) reported that their treatment group did not show significant improvement in performance on the posttest under afeedback intervention alone, but did when prompted to check their answers on the task using models; those students whose work included the models demonstrated significantly better understanding of the material in the posttest than did the control group. It is important to note that no student in the experiment spontaneously used the model during the pretest, which reinforces the notion that problem visualization does not come naturally to many students.

However, with proper scaffolding and instruction, students can be prompted to adapt to, and eventually adopt, problem visualization strategies that will ultimately enhance the qualityof their learning. This learning in turn becomes crucial for skills to be applied in industry. Indeed, as reported by Jonassen et al. (2006), engineers in industry rely on problem representation skills as an integral part of their problem-solving process, and will typically represent the problem in multiple ways, such as creating a two-dimensional sketch and three-dimensional CAD model.

Another theme emerging from the literature is the necessity for students to indiscriminately use varied methods to represent or encourage solving of the problem. Ge and Land (2003, 2004) characterize visualization as an important step for solving ill-structured tasks; however, it is not clear how different types of representation affect collaboration. In his dissertation, Koch (2006) investigated whether three-dimensional visualization through the useof software is more effective than sketching alone in designing a prototype. Keeping in mind that his sample size was limited, his findings indicated that there is not a significant differencein effectiveness between the two methods. It is unclear whether the inclusion of a physical component in an ill-structured design task will enhance engineering students' collaborative learning; however, knowing that these students will later be called upon to work effectively in teams, and also represent problems (as well as to represent their understanding and their proposed solutions) in multiple ways when they are in industry, visualizing how three-dimensional representation shapes group collaboration can be a valuable asset to engineering education.

Role of Dissection in Engineering Education

The dissection process, in which students work on reverse-engineering a product through physical deconstruction, provides experiential opportunity for practicing design (Sheppard, 1992; Lamancusa et al., 1996). Also known as "disassemble, analysis, assemble" (D/A/A), dissection has become a common pedagogy for providing students with practical experience in the classroom (e.g., Calderon, 2010). Literature has established that experiential design opportunities are meaningful for a rich engineering education. Ragonese and Starkey (2020), building on work by Huerta-Wong and Schoech (2010), noted that "listening to lectures on theoretical concepts without the experiential opportunities to put these concepts into application does not benefit a student as well as an experiential, hands-on approach" (p. 1). Indeed, Lamancusa et al. (1996) characterized pre-digital age engineers as "tinkerers" who "developed an instinctual, common sense feeling for engineering" (p. 1). The overview of a new product dissection-type course by Lamancusa et al. (1996) showed that students' exposure to physical products improved their awareness of design by supporting visualization skill development and a more common-sense aptitude for engineering.

It follows that dissection can be an accessible pedagogy to incorporate into ill-structured task design. Beyond meaningful learning outcomes inherent to the dissection process, doing so can also support learners in experiencing multiple levels of cognitive interaction. Pugh's work on the Head-Heart-Hands model (2002), first introduced by Dewey (1910), builds on transformative learning theory by characterizing the transformative experience as the expansion of perception resulting from the active use of a learned concept. The theory asserts that cognitive (head), affective (heart), and psychomotor (hand) processes are connected in transformative learning (Sipos et al., 2008). It follows that effective ill-structured tasks, which already incorporate cognitive and affective processes through problem-solving and social aspects, should also incorporate psychomotor processes. The idea to integrate hands-on learning in applied STEM tasks has manifested in different forms in literature; for example, Gazibara (2013), building on work by Jensen (2005), says that teachers should integrate STEM content, among others, and physical education. Gazibara goes on to suggest several strategies for effective holistic learning, such as the meaningful application of technology in teaching and the use of visualizations and creative problem solving. It is clear that dissection pedagogy can serve a meaningful role in ill-structured problem solving, perhapsacting as a conduit for students to experience hands-on learning. However, while literature exists on individual factors that impact collaborative dissection (e.g., Toh et al., 2013) as well as cognitive load experienced during the dissection process (e.g., Starkey et al., 2018), there is not much content on what student collaboration actually looks like during a dissection task. Studies like Barron's (2003) have established that effective collaboration is crucial for successful group work; in order to effectively incorporate a physical (i.e., psychomotor) element into existing task design, the influence of such an element on collaboration must be understood.

Collaboration in STEM

Some recent studies have investigated aspects of student collaboration in groups in an engineering design context. For example, Guzey and Aranda (2017) studied the verbal interactions of junior high students working on an engineering-type task and found that each group tended to make design decisions according to majority rule. Schmidt (2019) discussed the importance of orienting the classroom such that positive emotions are optimized and integrated into the course in order to foster deeper levels of engagement and learning.

Atman et al.'s (1999) extensive study of expertise in engineering investigated the differences in freshmen and senior engineering students as they worked in groups to design a playground. It was found that freshmen tended to spend the majority of their time attempting to solve the task (P3) by moving forward with a design, which supports our later findings that students do not naturally propagate among the four problem-solving processes (Tucker et al., 2019). By comparison, the seniors tended to request more information early on, or in other words, participated more in P1 and P2. They were also able to make faster and more frequent transitions among design steps, and were more confident in their abilities, leading to more frequent expressions of criticism regarding the design of the task itself (Atman et al., 1999).

In a later study (2007), Atman et al. comparedseniors and freshmen working the playground task to experts from the field. It was found that experts spent significant time in scoping and understanding the nature of the problem (i.e., P1 and P2). They also explored more alternatives, which contradicts literature (e.g., Cross & Clayburn, 1998) that suggests they are more likely to decide on an overarching idea and make modifications to it. Experts were more consistent in time and transitions, with smoother timelines than those of students. However, they did not spend significantly more or less time. Atman et al. (2007) suggests that students would benefit from instruction designed to teach how to scope a design problem before attempting to solve, to gather information for the design process before and during problem solving, and to attend to important elements of project realization while designing. This work supports the need for evaluating the solution (P4) and also connects to Jonassen et al.'s (2006) lessons for engineering educators, which shows that engineers need to spend time exploring the problem (P1) and planning how to solve (P2).

In an intensive study of two students collaborating on a physics task, Roschelle (1992) investigated how the students converged in collaboration, especially while speaking/explaining their understanding in lay terms instead of scientific terms. Findings indicated that context and embodied cognition (i.e. cognitive processes experienced physically, such as through gesture) were both crucial elements for communicating and building a shared understanding of task concepts, as the students tended to pair their explanations, spoken in lay terms, with gestures. This built on the work of a previous study (Roschelle, 1991), in which the researcher found that these same students would only transition from lay terms to scientific terms in explanation after working through several problems of the same topic. As embodied cognition encompasses the notion of hands-on learning, it follows that implementing hands-on learning opportunities in ill-structured tasks could result in similarly positive learning outcomes.

Impact of the Covid-19 Pandemic

Applying hands-on learning in traditional undergraduate curricula became more of a challenge with the onset of the Covid-19 pandemic. Indeed, the pandemic played a disruptive role in education across the board, causing many classes to shift to an online format, postpone, or otherwise reformat. Since that time, research has investigated the pandemic's implications for online learning (e.g., Dhawan, 2020) as well as the role of virtual collaboration in online learning (e.g., Ragonese & Starkey, 2020). Although teamwork looks different in a virtual space, students can still achieve similar collaborative experiences and learning outcomes; for example, qualitative feedback from 64 engineering students who experienced an entire semester-long design course over virtual synchronous and asynchronous platforms indicated that they tended to share enjoyable, meaningful learning experiences with their peers while also developing self-management (Tucker, Wolf, & Liebenberg, in press). In the case of dissection specifically, a study of 141 engineering students subjected to a factorial experiment found that although cognitive load varied between physical and virtual dissection, levels of conceptual understanding did not have identifiable differences (Starkey et al., 2018).

While all dissection during this study took place physically, project outcomes were likely impacted by the pandemic. All teams transitioned to a virtual format following the mid-semester spring break. The disruption in their face-to-face interaction may have had an impacton their ability to work as a team, leading to an impact on the quality of their final work. Due to the limitations of this study, this factor has not been measured.

Proposed Research Questions

It is clear that many facets of collaborative task design have been extensively investigated in previous research studies. This review has explored the importance of scaffolds in ill-structured tasks, the roles of three-dimensional representation and dissection in collaborative task work, the importance of hands-on learning to students' learning outcomes, and the impact of the recent pandemic on collaborative task work. However, it is still unclear what students' collaborative interactions actually look like when influenced by a hands-on component in an ill-structured task. This work seeks to address this gap in the literature by characterizing group collaboration during a non-scaffolded engineering design task centered around a physical product. The proposed research questions for this work are as follows:

1) What are the collaborative processes and behavioral characteristics of students’ interactions during a hands-on ill-structured task?

2) How might differences among groups’ experiences impact their final scores on the task?

CHAPTER 3: METHODS

This study uses a mixed-methods structure to qualitatively capture teams' work on the task and then quantitatively measure trends in tabulated data. The QUAL → QUAN format (Creswell et al., 2007) has been implemented in various studies ofengineering students' collaboration and task work; for example, Purzer's (2011) study of first-year undergraduate engineering students used this format to investigate the relationships among verbal interaction, self-efficacy, and student achievement, beginning with discourse analysis and then connecting to correlations among the three variables. Studies have also used qualitative research to observe students working in teams; for example, McCord and Matusovich (2019) developed a literature-based framework to evaluate engineering students' metacognitive processes during authentic problem solving using thematic episodes.

Participants

Participants were 20 undergraduate engineering students (6 female, 14 male) recruited from a one-semester introductory Engineering Graphics & Design course at the University of Illinois. The course, which had 102 enrolled students, was required for select engineering majors. Participants were pre-organized by the instructor into groups of four that worked together throughout the semester. Five different laboratory timeslots, totaling 74 enrolled, were selected for the study based on scheduling limitations. Participant groups were selected based on complete group consent, with one per timeslot chosen by the researcher. In the event of multiple groups from the same timeslot providing complete consent, groups' dissection products were used as secondary criteria—as the course offered a limited selection of product types, the researcher preferred to avoid repeats of the same product to ensure a variety of products in the study. Prior experience, identity, and other participant characteristics were not considered during the selection process. While all enrolled students took part in the class tasks, only participants were observed. Groups were observed throughout multiple 50-minute working sessions during which group members worked together to dissect and model their product. Thegroups were split among three teaching assistant-course assistant pairs. Data collection occurred during Spring 2020 and was completed before the university shut down face-to-face classes due to Covid-19. Post-spring break, the class switched to an online format (e.g., Jonassen, 2007) and all further team communication became virtual, with final presentations delivered to the class via Zoom; there is no way to know how this impacted groups' final scores, but it is highly likely to have been a factor.

Design

Ethnographic observations (Hoey, 2014; Sanday, 2016) and photographs were recorded by typing in word-processing software in a face-to-face classroom environment. The observer did not interact with or otherwise disrupt participants during sessions. A protocol, developed using field notes and memos from previous classroom observations (Table 1), was consulted before observation sessions to guide the observer's focus. All observations were written freeform and the protocol was not present during actual observations. Observations were recorded with corresponding timestamps. A change in notable participant behavior and/or the passing of roughly one minute constituted a new timestamp and corresponding entry. For purposes of analysis, each entry constituted one unit regardless of content. For rapidly changing behavior within one minute's span, multiple observations were recorded under the same timestamp; these were later treated as individual units during analysis.

Table 1

Observation Protocol

Thematic Episodes	Record brief description of the type of *group* work students are doing. For example, this may include reading task material, discussing the object, working individually, or assigning tasks. Mark description with time stamp. Record new description and time stamp when nature of work transitions to different type. If students are working individually, note each role (see below).
Individual Roles and Moves	Using assigned code names, take note of the occurrence of students' individual roles (e.g., emerging leaders, bystanders, organizers, etc.). Were these roles self-assigned? Note changes in roles and include timestamps when possible.
Verbal Interactions	Record nature of interactions including episodes of P1, P2, P3, and P4, as well as off-task talk and any TA interactions. For TA interactions, record the nature of the interaction (e.g., Did students initiate with a question? Did the TA seek out the group toassess progress?). Take note of talk that explicitly includes the object.
Influence of Object	Record nature of students' interaction with object; use timestamps when possible. How is the object being used or manipulated? Is it being passed among multiple students? How many of the group members have touched the object? Do different members use or interact with it in different ways?

Design Project and Group Characteristics

The semester-long design project (Leake & Borgerson, 2008) tasked students with the following: to dissect a commercially-available product, model the individual pieces using Autodesk Inventor™, and devise possible improvements to the product's design. The dissection process, in which students work on reverse-engineering a product through physical deconstruction, provides experiential opportunity for practicing design (Sheppard, 1992; Lamancusa et al., 1996). The final deliverables included an assembled CAD model and animation, a 3D-printed component from the modeling of the product, stress analysis of a central component, an assembled CAD model and animation, simulated stress analysis of a central component, and suggestions for improvements to the design. Students also evaluated their CAD model's accuracy by comparing its projected total weight to the measured total weight of their physical product; teams were required to justify discrepancies.

All students enrolled in the class were exposed to the same bank of commercial products, which had been selected by the instructor. Students had the opportunity to indicate their top three choices for products to use, with the guarantee of receiving one of their choices for the project. The instructor then used the information to divide the class into groups of four. Additionally, groups were designed so that neither gender was placed in a minority setting. Of the five groups that were observed, two had the same commercial product (these have been numbered "I" and "II"). All reported results will reference the groups by the products they dissected, which are as follows: Stirling engine I; Nerf™ gun; calendar puzzle; Stirling engine II; gumball machine (Figure 1).

Figure 1

Products (from left): Nerf™ Gun, Calendar Puzzle, Stirling Engine, and Gumball Machine

Note. All images retrieved from Google Images.

Two of the groups had all-male participants, while the other three had two female and two male participants in each; this breakdown roughly reflects the gender distribution of the class. The gumball machine group was the only group to have two participants who were in the class as part of a study abroad program from the same native country.

Description of Products

All the products were of similar scale and total weight, being that they were easily held with two hands and could roughly fit within 1 cubic foot of space. The Stirling engine had riveted pieces that presented a distinct limitation to the level of dissection students could achieve without destruction. All groups tended to avoid destroying pieces of their products in order to maintain integrity for more accurate modeling; groups deemed their products dissectedwhen pieces could no longer be further separated without destruction. The calendar puzzle, which produced a three-dimensional, clock-like calendar when assembled, came in sheets of pieces with a manual detailing assembly. Although this group did not assemble their product during the working sessions, it is likely that the manual was referenced during the CAD modeling phase. The gumball machine and Nerf™ gun had subassemblies that were only revealed by dissected the outer “shell” of the product; these products also relied on additional components (foam darts and metal coins, respectively) for proper function, which were not required for the CAD model assembly.

Breakdown of Dissection and Presentation Sessions

In-person observations took place midway through the semester, during two consecutiveweeks prior to spring break. During the first observation session, three of the five groups begandissecting their products; two groups did not yet have their products available. During the second observation session, all five groups worked on dissecting their products for the entirety of time allotted. Figures 2-7 depict groups working to dissect and document their products.

Figure 2

Calendar Puzzle

Figure 3

Stirling Engine II

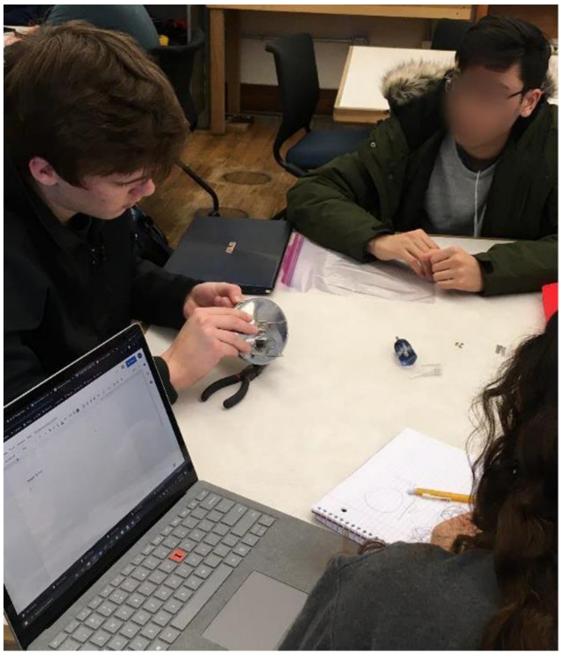


Figure 4

Stirling Engine I

Figure 5

Nerf™ Gun

Figure 6

Group Diagram, Stirling Engine II

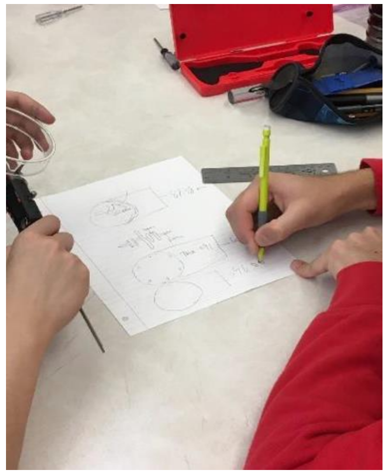


Figure 7

Gumball Machine

The week after their second dissection opportunity, all groups delivered in-person designreview presentations. Graduate teaching assistants (TAs) and undergraduate course assistants (CAs) provided feedback on initial progress and planned next steps; as the university shut down in-person classes post-break, this would be the last face-to-face class meeting during the semester.

Following the spring break, groups delivered multiple virtual design review presentations via Zoom, reporting progress as well as any setbacks they were experiencing as a result of the online format. TAs and CAs again provided feedback. Due to a technological issue,one group was not recorded during this session. During their virtual final presentations, all groups presented their final deliverables and received feedback of the same format.

Preliminary Analysis Process: Emergent Themes

This study used thematic analysis, an actively inductive process that consists of identifying recurring ideas inthe data, consolidating those ideas into codes, and using the codes to identify patterns that evolve into themes throughout the process (e.g., Braun & Clarke, 2006), to identify preliminary themes (Table 2) emerging from the observations. These included: type of product, including its characteristics and affordances; individual roles; "divide and conquer" episodes in which students purposefully divided task responsibilities; TA interaction with groups; episodes of collaborative behavior; physical interaction with the product; and physical collaboration through the product. Individual student activities (Table 3), which were self-assigned by groupmembers either subconsciously or purposefully during the dissection process, most notably included the following: documentation, active dissection, active observation, passive observation, leadership, and investigation through tools. Initial themes were developed by the observer. These were then discussed with fellow researchers to reach a consensus. Based on discussion and feedback, themes were revised and finalized. Tables 2 and 3 reflect the finalized themes derived from the thematic analysis process.

Table 2

Emergent Themes from Dissection Section Observations

Theme	Description
Type of Product	Characteristics related to the product itself, such as purpose, target audience, difficulty to dissect, and amount of available information.
Individual Roles	Groups tend to self-assign roles during the dissection process. These roles may include: documentation, active dissection, active observation, passive observation, leadership, and investigation through tools.
Divide and Conquer	Episodes in which group members divide into subgroups, either subconsciously or by choice, to tackle multiple aspects of the dissection process simultaneously.
TA Interaction	Nature of TA's interventions with group during dissection process.
Collaboration	Episodes of collaborative behavior as characterized by P1-P4 processes.
Physical Interaction with Object	Group's physical interaction with the product.
Physical Collaboration through Object	Group's physical collaboration with each other through manipulation of the product.

Table 3

Observed Individual Activities

Role	Description
Documentation	Student documents dissection process by taking notes (e.g., in a google doc), making labels, etc. This includes organization of parts (such as separating into labeled bags for storage).
Active Dissection	Student actively works to dissect product. May include following directions from active observer.
Active Observation	While not actively dissecting the product, student assists in dissection process by retrieving necessary tools, helping to hold parts, making suggestions for what dissector should do, etc. May include following directions from other students.
Passive Observation	Student observes dissection but does not assist, interact with the product, or make suggestions.
Emergent Leadership	Student takes leadership of the group. This can include delegating tasks to others, makingplans on behalf of the group, giving instructions, and making organizational moves.
Investigation through Tools	Student interacts with object/parts through tool use. This can include taking photographs, sketching traces or diagrams, taking measurements, etc.

Data Coding

Themes were used to develop a coding scheme (Table 4) intended to capture behavioral and collaborative trends as recorded in the observations. The coding scheme was developed bythe observer with input from fellow researchers. The observer and a second researcher then iterated the coding scheme to a workable version that was applied to observations from all five groups. For every entry (i.e., each unit), all applicable codes were applied. Inter-rater reliability averaged 92.3% agreement (with the lowest agreement being 82% and the highest being 98.4%); discrepancies were discussed to reach consensus when necessary.

Table 4

Observation Coding Scheme

Code	Definition
TA Interaction	0 = No TA interaction noted
	1 = TA is interacting with at least one group member
TA Whole Class	0 = No TA announcement to class
	1 = TA is making announcement to the entire class
TA intervention (only applicable when TA is interacting with group; only apply once per TA episode)	0 = TA initiated the interaction
	1 = Student(s) initiated the interaction
Subgroups	0 = No division (either all working together or all working separately)
	1 = Presence of subgroups
Collaboration (includes non-verbal signals; multiple codes may be applicable)	0 = N/A (no collaboration observed)
	1 = Students are working together on task. Includes episodes of actively measuring loose pieces (no dissection). (NP)
	2 = Students are exploring the scope of the task (P1). Examples include asking what they need to do or discussing the type of task ("So are we just taking this apart?" "I think we need to take pictures today"). This can also include exploring supporting materials.
	3 = Students exhibit planning behavior, such as verbally planning what to do (P2). ("Someone needs to document while we do this," "We should start by removing this piece.")
	4 = Students discuss the dissection itself, such as commenting on difficulty; students quietly work to dissect the product (P3). ("It's hard to get this piece off," "Can you help me do this?" "I think we now have to look at this.")
	5 = Students evaluate their work. This may include identifying errors or suggesting changes to their method (P4). ("We should've taken this part off last," "Maybe we should label these instead.")

Table 4 (continued)

Task Confusion	0 = No confusion noted
	1 = Students indicate confusion related to dissection process, such as being unsure of how to remove part from product ("I'm not sure how to get this off without breaking it"). Does NOT include confusion related to tools/tool usage (ex. "What does this tool do?")
Off-Task	0 = No off-task talk/activity noted
	1 = At least one student is behaving or talking off task
Verbal Interaction	0 = None specified
	1 = Verbal interaction is occurring among at least two group members (i.e., dialogue or narration, whether as a full group or in subgroups)
	2 = Group is specified as working quietly
Dissection	0 = Dissection is not taking place (i.e., object is being disassembled; parts are being removed, often through the use of tools)
	1 = Dissection is taking place
Physical interaction with object	0 = Students are not physically interacting with product
	1 = Students physically interact with object through touch. Can include inspection, manipulation, & handling, but does not include removal of parts (dissection itself)
Physical collaboration through object	0 = Students are not experiencing physical collaboration through the object
	1 = Students physically collaborate/interact with each other through use of the object. This can include gathering together around the object; multiple students holding or touching the object at the same time; students passing the object around while talking about it; students assisting each other in dissection by working on the object at the same time
Individual Activities	0 = None observed
	1 = Documentation
	2 = Active dissection
	3 = Active observation (apply to both dissection and investigation through tools
	4 = Passive observation
	5 = Emergent leadership
	6 = Investigation through tools

Table 4 (continued)

Tool Talk (does NOT mean tool use)	0 = None noted
	1 = Verbal indication of students' recognition of experience with tools. Can include suggesting to use a specific tool, remarking that a tool doesn't work, expressing confusion over purpose of tool ("Here, try this screwdriver," "I don't know what to do with this tool.")
Tool Use	0 = None noted for purposes other than active dissection
	1 = At least one student is using a tool for purposes other than dissection (this can include using a phone to document process, using a ruler to measure a loose part, using a pencil to trace or sketch a part)
Use of Supporting Materials	0 = No supporting materials sought/in used
	1 = Students are either seeking or using supporting materials, such as product manual, YouTube reference videos, Amazon product page, websites, etc.

To account for limitations associated with capturing ethnographic observations by hand in real time, several assumptions were made in the implementation of this coding scheme; namely, that a group displaying interactive behavior was also interacting verbally unless otherwise specified; that group behaviors persisted until noted as changed in observations (timestamps were devised to capture real-time changes in groups' behaviors); that in episodes of questionable engagement, benefit of the doubt goes to the group interacting/remaining on task; and that events within the group that occurred outside close proximity to the observer (i.e.away from the worktable, out of earshot or vision) were not captured.

Additional Data and Data Analysis

In addition to the data collected during observation sessions, groups' scores on their final CAD model (i.e., the complete assembly of their product with modifications made to the design) were included. Scores were assessed by the teaching team using a rubric provided by the instructor. The head TA for the course ensured consistency of grading by reviewing all final scores of the class. Additionally, group members were required to complete peer evaluations that did not impact the group's CAD model score. To do this, students completed online peer evaluations via the CATME Peer Evaluation tool (Ohland et al., 2012; Loignon et al., 2017) after completion of the design project during the last week of the course. The CATME website (CATME, 2021) is a secure interface for collecting and reporting data on team-member effectiveness. These evaluations were factored into each member's final project score by acting as a multiplier that could raise or lower the final score assessed to the team by the instructor. Thus, while group members each received the same base team score and CAD model score, their individual final grades in the class were impacted by their groupmates' assessments.

All codes were tabulated and grouped into a set of tables that present subsections of the data according to the following descriptions: observation and score quantities (Table 5), behavioral codes (Table 6), collaborative processes (Table 7), student activities (Table 8), and a description of students' peer evaluation scores (which had no impact on the scores in Table 5) (Table 9). Through these groupings, tabulations could be compared to quantify trends that characterized groups' experiences. These were evaluated against groups' scores on the final CAD model to quantify their impact on task performance. Findings were then evaluated qualitatively using vignettes from notable groups. In addition to presenting the raw number of each code, proportions were calculated by tabulating each code across all observation sessions per group and then dividing by each group's total number of time-stamped observations. A low value indicates that the groups engaged in the coded behavior for a lesser duration of the task, whereas a high value indicates that they engaged in the behavior for a larger duration. The raw numbers indicate magnitude of groups' participation in each code; the proportions allow for easier comparison across groups. Table 5 provides the total number of timestamps and score out of 100% for each group. The number of timestamps produced per group varies; group's individual densities of behavior and participation in observation sessions was not controlled. A low value indicates that the groups engaged in the coded behavior for a lesser duration of the task, whereas a high value indicates that they engaged in the behavior for a larger duration. The raw numbers indicate magnitude of groups' participation in each code; the proportions allow for easier comparison across groups. Table 5 provides the total number of timestamps and score out of 100% for each group. The number of timestamps produced per group varies; group's individual densities of behavior and participation in observation sessions was not controlled.

Table 5

Observation and Score Quantities per Group

Group	Stirling engine I	Nerf™ gun	Calendar puzzle	Stirling engine II	Gumball machine
Total Observation Timestamps	58	60	72	42	80
Score	88.9%	88.9%	85.2%	81.5%	100%

CHAPTER 4: RESULTS

This study focused on the following two research questions:

1) What are the collaborative processes and behavioral characteristics of students' interactions during a hands-on ill-structured task?

2) How might differences among the groups inform their final scores on the task?

To answer these questions, I explored the data through a series of tables and related trends among groups to their final CAD model scores. To narrow the scope of the data for purposes of this study, TA-related codes were not analyzed. Future work can investigate the impact of TA interventions on groups' interactions during the task. Also, tool-related talk was not analyzed separate from verbal interaction. Additionally, the "confusion" code was rarely applied and was not applicable for the majority of groups; this has also been omitted from analysis in this study.

Behavioral Codes

To understand the behaviors groups displayed as they worked on the task, the data were coded for a variety of group-level activities as described in Table 6. These codes reveal trends that provide insight toward groups' experiences during, and engagement with, the task. Notably, groups showed very different approaches to their use (or lack thereof) of supporting materials such as supplementary videos and reference guides related to their product. As the highest- and lowest-scoring groups both used supplemental materials for a majority of the task (with nearly identical numbers of timestamps that included supplemental material use), it seems that these materials did not impact groups' engagement with the task. All groups engaged in "divide and conquer" episodes in which members divided, either subconsciously or by design, into subgroups; for all groups, this behavior was infrequent, indicating that all groups preferred to work together on the task. Groups experienced various amounts of off-task behavior; while the highest-scoring group displayed the lowest amount, the lowest-scoring group displayed the second-lowest amount. This suggests that deviation from on-task behavior impacted each group in different ways. Groups' levels of verbal interaction also seemed to impact each group differently.

Notable Group Based on Behavioral Codes: Calendar Puzzle

The calendar puzzle group experienced the least verbal interaction and participated the least in dissection. This group also had the least physical interaction with their product, which was the only one that did not require substantial dissection. These behaviors suggest that the lack of need to dissect impacted group members' motivation to interact with the product or with one another. Indeed, visual inspection of the data (Figs. 8-9) show a linear relationship between groups' participation in dissection and scores on the task, with the three higher-scoring groups participating more in dissection than the two lower-scoring groups, and the highest-scoring group participating the most.

Figure 8

Task Scores versus Dissection Proportions

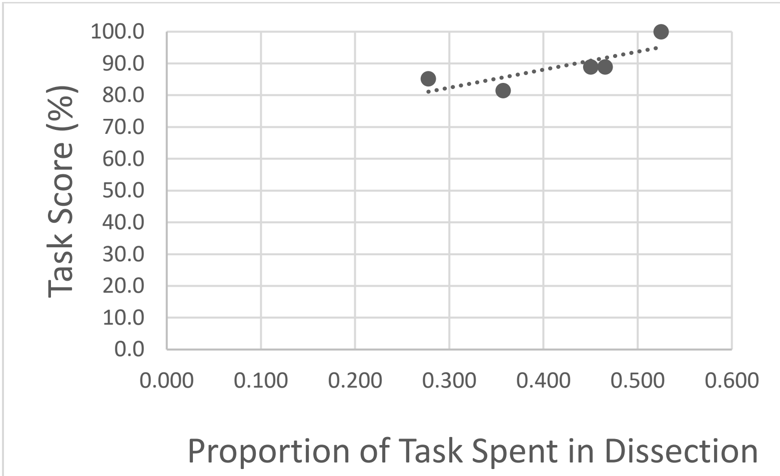
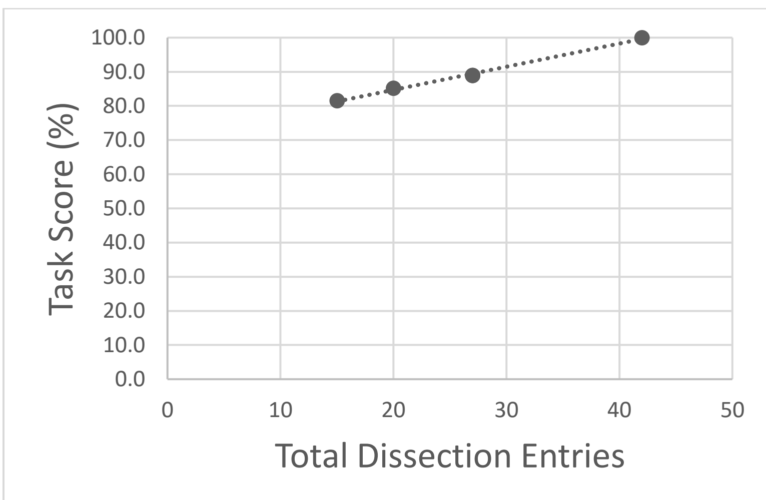


Figure 9

Task Scores versus Total Dissection Amounts



This linearity suggests that groups' participation in dissection directly contributed to their engagement with the task, which in turn impacted their learning outcomes.

Table 6

Proportions of Behavioral Codes out of Total Timestamps per Group

Code	Stirling engine I	Nerf™ gun	Calendar puzzle	Stirling engine II	Gumball machine
Off-task	.155 (9)	.083 (5)	.208 (15)	.071 (3)	.013 (1)
Subgroups	.293 (17)	.117 (7)	.125 (9)	.190 (8)	.088 (7)
Verbal interaction	.672 (39)	.900 (54)	.653 (47)	.762 (32)	.838 (67)
Dissection	.466 (27)	.450 (27)	.278 (20)	.357 (15)	.525 (42)
Physical interaction	.466 (27)	.600 (36)	.208 (15)	.810 (34)	.563 (45)
Physical collaboration	.244 (13)	.117 (7)	.125 (9)	.024 (1)	.088 (7)
Use of supporting materials	.000	.067 (4)	.514 (37)	.952 (40)	.513 (41)

Note. Raw numbers are presented in parentheses.

Collaborative Processes

To understand groups' collaborative interactions during the task, the data were coded for the four collaborative processes adapted from the framework discussed earlier. Table 7 describes each group's participation in these processes. All groups engaged in exploring the task (P1), planning how to solve (P2), and attempting to solve (dissect) (P3); all but one also engaged in reflection (P4). Visual inspection of the data (Figs. 10-11) shows a linear relationship between participation in reflection and task scores.

Figure 10

Task Scores versus Reflection Proportions

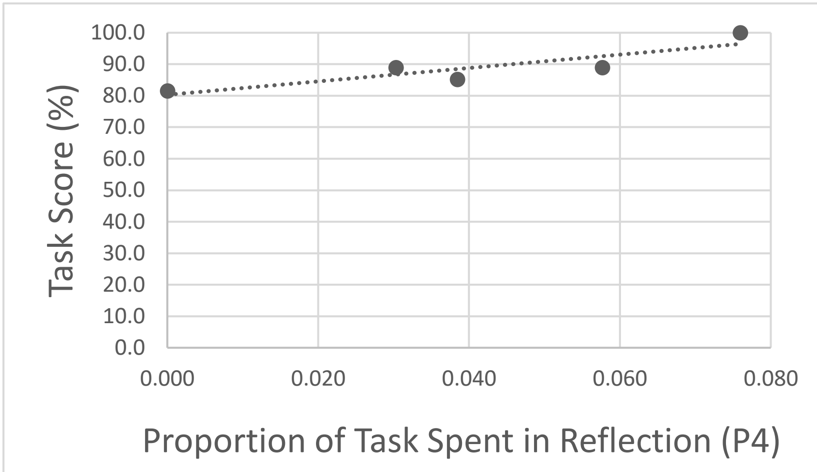
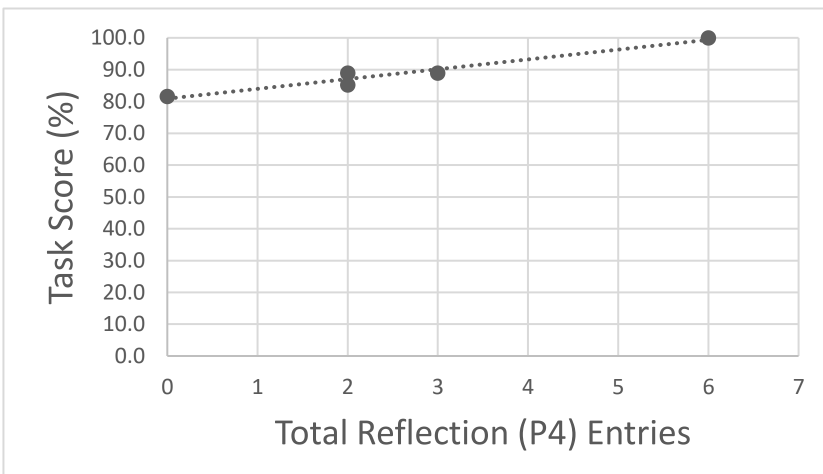


Figure 11

Task Scores versus Total Reflection Amounts



This linearity suggests that participating in reflection supported stronger outcomes on the task.

Notable Group Based on Collaborative Processes: Stirling Engine II

The Stirling engine II group was the only group that did not participate in reflection. This group also scored the lowest and had the second-lowest participation in dissection. However, it is interesting to note that this group had the most exploration of the task (P1) as well as the highest participation in collaboratively measuring the product (i.e., working together to measure size, weight, etc. of the whole product, subassemblies, and individual pieces). These results indicate that the group was trying to interact with their product outside of the dissection process; however, doing so did not seem to support strong task outcomes.

Table 7

Proportions of Collaborative Processes out of Total Timestamps per Group

Code	Stirling engine I	Nerf™ gun	Calendar puzzle	Stirling engine II	Gumball machine
Measurement collaboration	.258 (17)	.192 (10)	.192 (10)	.400 (16)	.266 (21)
P1: Exploring the task	.015 (1)	.077 (4)	.154 (8)	.175 (7)	.038 (3)
P2: Planning how to solve	.106 (7)	.192 (10)	.212 (11)	.100 (4)	.076 (6)
P3: Attempting to solve	.591 (39)	.481 (25)	.404 (21)	.325 (13)	.544 (43)
P4: Evaluating work and considering alternatives	.030 (2)	.038 (3)	.038 (2)	.000	.076 (6)

Note. Raw numbers are presented in parentheses.

Student Activities

In order to understand the individual activities in which students engaged within the group collaboration setting, the data were coded for six different activities that were identified during the thematic analysis process. These activities are described in Table 8. Individuals within the highest-scoring group (gumball machine) had the highest tendency to dissect their product; this finding is in agreement with results from Table 6, which indicated that this group participated the most in the dissection process. In other words, students in this group were highly engaged in dissection at both individual and group levels. Members of this group also participated the most in active observation, meaning that they were the most likely to assist their groupmates with dissection. The lowest-scoring group had the highest participation in investigation through tools; this finding is in agreement with results from Table 7, which indicated that this group experienced the most measurement collaboration.

Notable Group Based on Student Activities: Calendar Puzzle

The calendar puzzle group was the only group that did not display any passive observation; in other words, its members did not watch one another's dissection unless attempting to assist. As previously shown, this group also had the least dissection, verbal interaction, and physical interaction with their product. These findings support the idea that the reduced need to dissect the product decreased group members' motivations for interacting with one another during the task.

Table 8

Proportions of Student Activities out of Total Timestamps per Group

Role	Stirling engine I	Nerf™ gun	Calendar puzzle	Stirling engine II	Gumball machine
Documentation	.534 (31)	.333 (20)	.153 (11)	.429 (18)	.263 (21)
Active dissection	.448 (26)	.367 (22)	.278 (20)	.357 (15)	.538 (43)
Active observation	.466 (27)	.483 (29)	.042 (3)	.286 (12)	.500 (40)
Passive observation	.172 (10)	.300 (18)	.000	.262 (11)	.325 (26)
Emergent leadership	.017 (1)	.067 (4)	.181 (13)	.214 (9)	.125 (10)
Investigation through tools	.552 (32)	.217 (13)	.250 (18)	.738 (31)	.438 (35)

Note. Raw numbers are presented in parentheses.

Peer Evaluations

Additionally, group members were required to complete peer evaluations that didn't impact their CAD model scores. These evaluations were factored into each member's final scoreby acting as a multiplier that could raise or lower the final score assessed to the team by the instructor. Thus, even though all four group members received the same base team score, their individual final scores differed according to their peer evaluation multipliers. I characterize strong peer evaluations as those that produced a multiplier greater than one, resulting in a score higher than the base team score. Conversely, I characterize poor evaluations as those that produced a multiplier less than one, resulting in a score lower than the base team score. Table 9 provides a breakdown of the peer evaluation results by group. Student numbers were arbitrarily assigned for purposes of reporting anonymous results.

Of the 20 participants, 12 received strong peer evaluation scores. At least two students from each group received this type of evaluation. These results indicate that, in general, groups tended to have a favorable perception of their peers' contributions to the project regardless of their individual factors such as participation in dissection, etc. This suggests that factors other than the behavioral and collaborative trends identified in this data set were impactful for students' emotional engagement.

Notable Group Based on Peer Evaluation Scores: Gumball Machine

The gumball machine group was exceptional in that it was the only group to receive a perfect score on their final CAD model. This was also the only group for which all four members received strong peer evaluations. These findings suggest that group members' experiences during the task may have supported more favorable perception of one another's contributions.

Table 9

Peer Evaluation Scores

Group	Student	Peer Evaluation Results
Stirling engine I	1	Higher than team score
	2	Higher than team score
	3	Same as team score
	4	Lower than team score
Nerf™ gun	1	Lower than team score
	2	Higher than team score
	3	Lower than team score
	4	Higher than team score

Table 9 (continued)

Calendar puzzle	1	Lower than team score
	2	Higher than team score
	3	Higher than team score
	4	Lower than team score
Stirling engine II	1	Lower than team score
	2	Higher than team score
	3	Lower than team score
	4	Higher than team score
Gumball machine	1	Higher than team score
	2	Higher than team score
	3	Higher than team score
	4	Higher than team score

CHAPTER 5: DISCUSSION

This study set out to characterize the nature of engineering students' experiences as they collaborated on an ill-structured design task for which a physical product was a central component. Of all the results produced from analyzing the data through the series of tables presented above, two trends were found to be the most meaningful for informing hands-on ill-structured task design. These trends will be discussed below.

1) Relationship between participation in dissection and task scores

Visual inspection showed a linear trend between participation in dissection and task scores, with the three higher-scoring groups participating more in dissection than the lower-scoring groups and the highest-scoring group participating the most (Tables 5 and 6). This suggests that groups' participation in dissection directly contributed to their engagement withthe task, which in turn impacted their learning outcomes. This is meaningful to dissection task design because it reveals that in order to foster stronger task outcomes, the task needs to support engagement with the dissection process; strategic scaffolds can be used to prompt students' participation in dissection. We know from literature that students' hands-on engagement withcontent during a design task can support stronger learning and design outcomes (e.g., Sheppard, 1992; Lamancusa et al., 1996); the trend demonstrated by this data supports these studies.

Furthermore, the calendar puzzle group, whose product came in sheets of pre-cut pieces that would require assembly to create a three-dimensional mechanical calendar, participated the least in dissection. This was the only group whose product essentially came pre-dissected, meaning that this group skipped the majority of dissecting their product and moved directly to documenting and measuring pieces, then attempting to assemble. This group experienced the least physical interaction with their product and the least verbal interaction with one another. They also did not participate in passive observation, meaning that they were not moved to watch one another's work unless some form of collaboration became necessary (i.e., active observation). These findings suggest that the nature of this group's product negatively impacted their engagement with the task by compromising their opportunity to collaboratively reverse-engineer, and thus co-construct knowledge around, their product. This group seemed to have decreased motivations for interacting with, or observing, one another as compared to other groups, supporting the idea that their lowered level of interaction with the product impacted their interactions with one another. This hypothesis is supported by Brereton et al.'s study of engineering students working in teams on a seven-month design project (1996), which concluded that "the content of the evolving design depends heavily upon negotiation strategiesand other more subtle and ubiquitous social processes that shape design work," (p. 339). Brereton's study emphasizes the impact of effective social interaction on design outcomes; thus, the reduced social interaction among members of this group may have the opposite result. This is meaningful to hands-on ill-structured task design because it reveals that characteristics of the products themselves can impact students' social behaviors during the task. Therefore, an effective product for group collaboration needs to inherently motivate the group to work, and struggle, together. This in turn leads to increased interaction among members, which is desirable for group collaboration (Barron, 2003; Tucker et al., 2019; Tucker, Shehab, & Mercier, 2020b).

Findings from the student activities grouping (Table 8) showed that members of the highest-scoring group were most likely to engage in dissection as well as active observation, meaning that if they weren't actually dissecting the product, they were most likely to assist groupmates who were. In other words, not only did the highest-scoring group have the most participation in dissection at the group level, but its members also had the highest participationat the individual level. These findings indicate that the individual members' participation in dissection may have made a positive contribution to the group's overall knowledge of their product, leading to a 100% score on the CAD model deliverable. As research has shown that individualpersonality attributes can influence group members' engagement in dissection (Toh et al., 2013), it follows that uncontrolled individual factors most likely impacted each member's participation in these roles. We cannot control the personalities of students participating in the task, but we can design the task with recognition that participants need to be engaged not only collectively as a group, but also at the individual level. The finding that students who tended to participate more in these roles achieved higher group scores is promising because it suggests that implementing this consideration in task design can lead to stronger learning outcomes.

In contrast, while the lowest-scoring group (Stirling engine II) also interacted with theirproduct, they tended to do so through measurements and investigative tool usage more than through dissection itself. In comparison with other groups, this group had the highest tendency to collaborate on taking measurements and photos of their product and its components. It follows that individual members from this group had the highest tendency to investigate their product through tools (e.g., scales, calipers, phone cameras). However, this sort of interaction did not seem to equate to strong task outcomes, suggesting that for purposes of design, knowledge of a product's characteristics and affordances is not as valuable without complementary knowledge of its assembly. This builds on previous research that has established the impact of affordances on users' engagement. Gibson (1979) first introduced the concept of object affordances as properties that determine the actions a person can do with or to the object. It follows that the affordances of each dissection product impact how group members approach both investigation and dissection. Indeed, research has shown that affordances play a key role in affecting users' gestural responses to the object (Masson-Carro et al., 2015). However, the notion that affordances alone do not serve user understanding as well as when combined with systemic knowledge of the object is novel. Furthermore, the Stirling engine II group's outcomes resemble those of the calendar puzzle group, who had the second-lowest score. The calendar group had the least participation in dissection, meaning that its members experienced the least opportunity to build knowledge regarding the product's assembly. These findings advocate for designing ill-structured dissection-type tasks such that the affordances of the dissection product itself and the scaffolds implemented in the task supportstudents' engagement with the dissection process at both the individual and group levels.

2) Relationship between reflection process and task scores

Previous work has identified four collaborative processes necessary for effectively solving an ill-structured task: exploring the problem (P1), planning how to solve (P2), attempting to solve (P3), and evaluating the solution and considering alternatives (P4) (Tucker et al., 2019). All groups engaged in P1, P2, and P3; all but one engaged in P4. All groups experienced more P3-type than any other collaborative process, reflecting the same trend demonstrated in historical data of engineering students solving non-scaffolded ill-structured design tasks (Tucker et al., 2019). Indeed, the group with the highest P3 also had the most physical interaction with the product, suggesting that the other three problem-solving processes were not as inherent to hands-on learning. This supports the need for strategic scaffolds in these tasks sothat students can realize opportunities to enter each process.

In general, reflection can be thought of as making one's knowledge explicit to one's self. Research has shown the efficacy of self-reflection for productive design behavior at the individual level (e.g., Crismond & Adams, 2012). Group-level reflection has not received as much attention in research as individual self-reflection, and its benefits are not yet as strongly understood. A study of gender-controlled teams in a strategic management classroom found that teams who engaged in team-level reflection tended to experience higher team effectivenessand project scores than teams who only engaged in individual-level reflection (Domke-Damonte & Keels, 2015). This finding is promising for the role of group-level reflection, but it is not consistent across literature. In a study of 48 adults, all of whom held managerial positions, in different experimental reflection conditions found that those participating in either individual reflection or reflection guided by a coach had significantly higher learning outcomes than did the control group, which did not participate in reflection (Daudelin, 1996). In this study, participants in the small group peer reflection condition did not have significantly higher learning outcomes, possibly because the lack of structure surrounding the group reflection process caused participants to tend to briefly discuss a broad number of topics without any deep probing. As previous work has established that collaborative reflection (i.e., evaluating the solution and considering alternatives) is a meaningful and necessary step for effectively solving an ill-structured task (e.g., Ge & Land, 2003, 2004; Tucker et al., 2019; Tucker, Shehab, & Mercier, 2020b), it is likely that a more scaffolded reflection setting for the peer group would have supported stronger learning outcomes. Furthermore, findings from this study suggest that reflection at the group level is not only necessary for effective collaborative problem solving in this context, but can also be impactful on groups' scores, as the highest-scoring group had the highest participation in reflection. This outcome is also supported by historical data, which found a significantly positive correlation between participation in P4 and final scores on the task (Tucker, Shehab, & Mercier, 2020b). The two groups who participated most frequently in evaluating their work (P4) also had comparable amounts of investigating the product using tools and much lower amounts of this sort of investigation than did other groups. This suggests that the increased participation in reflection may have decreased these groups' motivation or perceived need to continue investigating their product through tools, which illustrates the rich experience that can be gained from collaborative reflection. Accordingly, the lowest-scoring group did not participate in reflection. It is interesting to note that this group had the most individual investigation through tools as well as participation in collaboratively measuring the product (i.e., working together to measure size, weight, etc. of the whole product, subassemblies, and individual pieces). Essentially, this group displays the opposite pattern of the highest-scoring groups, who spent more time in collaborative reflection and less time individually investigating the product or collaboratively measuring. The lowest-scoring group had a comparatively low amount of dissection, yet they were still interacting with their product in other ways. However, the nature of their interaction with the product did not seem to support strong outcomes on thetask. In light of the importance of group-level reflection, it seems that participation in the dissection process, combined with collaboratively reflecting on outcomes from dissection, is more conducive to deeper engagement with the task than either dissection without reflection or non-dissection interaction with the product such as tool investigation. Thus, in order to supportstrong task outcomes, hands-on task design should not only allow for rich engagement with theproduct, but also scaffold opportunities for groups to participate in reflection.

Implications

These findings are meaningful for multiple populations. For educators, task design needs to support group participation in experiential learning opportunities. Doing so includes considering the affordances of the product or hands-on element being used (recall that the calendar puzzle was not conducive to dissection in the same manner as the other products). For researchers, future work can investigate how to actually scaffold collaborative processes during this type of task—for example, how to prompt groups into reflection. For design students, participating in reflection with one's group can be meaningful to one's learning outcomes; thus, there is intrinsic motivation to engage with peers in this manner.

CHAPTER 6: CONCLUSION

Five groups (Stirling engine I, Nerf™ gun, calendar puzzle, Stirling engine II, gumball machine) were observed working on reverse-engineering a product through physical dissection a one-semester ill-structured engineering design task. Findings showed two takeaways meaningful to task design, the first of which was the relationship between groups' participationin dissection and their task scores. Visual inspection indicated a linear trend between groups' participation in dissection and scores on the task, with the highest-scoring group participating the most in dissection and the two lowest-scoring groups participating the least. Furthermore, one of the lowest-scoring groups had a puzzle product that required minimal disassembly and provided little insight toward the assembly process. These findings advocate the need to select task products whose characteristics are conducive to the dissection process; doing so may support stronger learning outcomes.

The second meaningful takeaway was the relationship between groups' participation in reflection and their task scores. The lowest-scoring group was the only group that did notparticipate in reflection, while the highest-scoring group participated the most. It is necessary to scaffold this type of task to provide opportunities for groups to enter the reflection process, which can support higher learning outcomes.

Due to the limited sample size of this study, parametric statistics were not used. For the purposes of narrowing the scope of this thesis, selected data were not analyzed. Future work can use students' individual written reflections to further investigate their perceptions of, and experiences during, the task. As research has since found that more balanced participation among the four collaborative processes can improve students' learning outcomes by increasing opportunities for them to engage in more complex cognitive processes, future work should also investigate the implementation of scaffolds that provide an opportunity for students to enter each process during a dissection task.

The university-wide shift to an online curriculum format mid-semester due to the pandemic impacted the study. Although groups had already completed their dissection processes, the disruption and subsequent challenges may have impacted their final work quality. This thesis has laid the foundation for understanding what students experience when collaborating on a design task for which hands-on learning plays a central role. Findings from this study and ongoing work can help support more effective task design.

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APPENDIX A: IRB APPROVAL LETTER

February 7, 2020

Notice of Exempt Determination

Principal Investigator	Molly Goldstein
CC	Taylor Tucker; Emma Mercier
Protocol Title	*Exploring the Nature of Students' Collaborative Interactions in Engineering Design*
Protocol Number	20575
Funding Source	Unfunded
Review Category	Exempt 1
Determination Date	February 7, 2020
Closure Date	February 6, 2025

This letter authorizes the use of human subjects in the above protocol. The University of Illinoisat Urbana- Champaign Office for the Protection of Research Subjects (OPRS) has reviewed your application and determined the criteria for exemption have been met.

The Principal Investigator of this study is responsible for:

- Conducting research in a manner consistent with the requirements of the University and federal regulations found at 45 CFR 46.
- Requesting approval from the IRB prior to implementing major modifications.
- Notifying OPRS of any problems involving human subjects, including unanticipated events, participant complaints, or protocol deviations.
- Notifying OPRS of the completion of the study.

Changes to an **exempt** protocol are only required if substantive modifications are requestedand/or the changes requested may affect the exempt status.

APPENDIX B: IRB AMENDMENT APPROVAL LETTER

April 3, 2020

Notice of Exempt Determination

Principal Investigator	Molly Goldstein
CC	Taylor Tucker; Emma Mercier
Protocol Title	*Exploring the Nature of Students' Collaborative Interactions in Engineering Design*
Protocol Number	20575
Funding Source	Unfunded
Review Category	Exempt 1
Amendment Requested	• Updating research procedures to record Zoom sessions
Amendment Determination Date	April 3, 2020
Closure Date	February 6, 2025

This letter authorizes the use of human subjects in the above protocol. The University of Illinoisat Urbana- Champaign Office for the Protection of Research Subjects (OPRS) has reviewed your application and determined the criteria for exemption have been met.

The Principal Investigator of this study is responsible for:

- Conducting research in a manner consistent with the requirements of the University and federal regulations found at 45 CFR 46.
- Requesting approval from the IRB prior to implementing major modifications.

- Notifying OPRS of any problems involving human subjects, including unanticipated events, participant complaints, or protocol deviations.
- Notifying OPRS of the completion of the study.

Changes to an **exempt** protocol are only required if substantive modifications are requestedand/or the changes requested may affect the exempt status.