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Responses to different types of inquiry prompts: college students' discourse, performance, and perceptions of group work in an engineering class

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ABSTRACT

Working in small groups to solve problems is an instructional strategy that allows university students in science, technology, engineering, and mathematics disciplines the opportunity to practice interpersonal and professional skills while gaining and applying discipline-specific content knowledge. Previous research indicates that not all group work prompts result in the same experiences for students. In this study we posed two types of prompts (guided and open) to undergraduate engineering students in a statics course as they participated in group work projects. We measured student discourse, student performance, and perceptions of group work. We found that guided prompts were associated with higher-level discourse and higher performance (project scores) than open prompts. Students engaged in guided prompts were more likely to discuss distribution of labour and design/calculation details of their projects than when students responded to open prompts. We posit that guided prompts, which more clearly articulate expectations of students, help students determine how to divide tasks amongst themselves and, subsequently, jump to higher levels of discourse.

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Inquiry-based learning; discourse; problem-solving

After graduation, students majoring in science, technology, engineering, and mathematics (STEM) fields will face competitive work environments that demand fluency in many types of skills. Some of these needed skills have been identified by professional organisations from a variety of disciplines in the United States. For example, the National Academy of Engineering (NAE, 2004) contends that future engineers will need strong analytical skills; practical ingenuity; creativity; an ability to communicate effectively; business and management knowledge; the ability to be a leader; high ethical standards and professionalism; dynamism, agility, resilience and flexibility; and the ability and desire to be lifelong learners. Similarly, the American Association for the Advancement of Science (AAAS) Vision and Change in Undergraduate Biology Education Initiative

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(2011) recommends that biology graduates should exhibit proficiency in core concepts and competencies, including engaging in interdisciplinary collaborations, communicating to different audiences, and understanding how science affects societies. Hence, discipline-based pedagogy experts have concluded that traditional lecture-based classes, without opportunities to develop problem-solving and communication abilities, are insufficient to prepare STEM graduates for the workforce (AAAS, 2011; Mervis, 2013; National Research Council (NRC), 2012). The challenge for university departments and instructors is to identify instructional approaches and develop curricula to cultivate their students' professional skills called for by respective disciplines without sacrificing content knowledge. In doing so, instructors will allow students to gain both content knowledge and disciplinary competencies that facilitate preparation for post-graduate studies or employment.

Because there is considerable overlap in the competencies necessary to be a successful student in either engineering or natural sciences, the findings from studies across these two vastly diverse disciplines can inform one another (Singer, Nielsen, & Schweingruber, 2012). It is noteworthy that, in the United States, discipline-based researchers in engineering and natural sciences ensured that disciplinary practices and competencies were presented alongside each other in the most recent revision of the national science education standards for school-aged students (NGSS Lead States, 2013). While science instruction tends to focus on inquiry, and engineering instruction tends to focus on design, these ways of knowing and discovering are not limited to specific disciplines. Both science and engineering disciplines require that students learn how to: (i) ask questions/define problems, (ii) develop and use models, (iii) plan and conduct investigations, (iv) analyse and interpret data, (v) use mathematical and computational thinking, and (vi) construct explanations and design solutions (NRC, 2012). The NRC (2012) encourages science and engineering instructors to explore and implement instructional strategies to promote these afore-mentioned skills throughout formal schooling.

Collaborative learning has been identified as a high-impact educational practice by the American Association of Colleges and Universities (https://www.aacu.org/leap/hips), and working in groups to solve disciplinary-based problems is one instructional technique that allows STEM students the opportunity to practice interpersonal and professional skills while also gaining and applying discipline-specific content knowledge. In engineering, the problems posed to groups might most appropriately take the form of design challenges, while in a science course a variation of problem-based learning might better reflect the nature of the discipline. In both cases, students engage in inquiry as they ask questions and acquire new knowledge in pursuit of a 'solution.' What is not known, though, is how the learning experience is affected, if at all, when inquiry-based questions are posed differently. As several have acknowledged, it is not clear what attributes define inquiry-based teaching (Buck, Bretz, & Towns, 2008; Lee, 2012; Spronken-Smith, Walker, Batchelor, O'Steen, & Angelo, 2012). One of the challenges in defining inquiry-based teaching is the differences in inquiry across different fields of study (Lee, 2012). In this study we drew on the inquiry continuum framework informed by several researchers (Buck et al., 2008; Fang et al., 2016; Marshall, Smart, & Horton, 2010) to compare how two levels of inquiry prompts affected students' learning experiences in an undergraduate engineering class.

Background

Inquiry continuum

Inquiry describes both the nature of science and the preferred way for students to learn science – through asking and answering questions. Inquiry-based instruction is intended to evoke questioning by students so they can take ownership of their learning, be more reflective of what knowledge they need to solve problems, and engage in discipline-centred discourse with their teacher and peers (Bransford, Brown, & Cocking, 2000). It can be achieved through collaborative group work (Evensen & Hmelo-Silver, 2000; Gallagher, Sher, Stepien, & Workman, 1995; Kittleson & Southerland, 2004). Although inquiry-based instruction promotes learning, curricula and instruction may support different levels of inquiry (Eick & Reed, 2002). Marshall et al. (2010) claimed that merely increasing the quantity of opportunities for students to actively ask and answer questions is insufficient, if the quality of the instructional strategies is not also adapted for the students and course context. Furthermore, Furtak, Seidel, Iverson, and Briggs (2012) argued that inquiry tasks differ in expectations of how students collaborate and teachers facilitate, and therefore, it is often a challenge to compare studies. Bunterm et al. (2014) also asserted that few studies have examined the impact of different levels of inquiry on student learning outcomes and performance.

To categorise different types of inquiry Buck et al. (2008) reviewed existing inquiry literature and identified multiple terms for different types of inquiry: traditional, guided, structured, open, directed, authentic, scientific, partial, and full. These types of inquiry generally described the type of prompt given, but sometimes, the definitions of the terms were contradictory. Thus, the Buck et al. framework is more difficult to apply. A newer, more concise framework proposed by Levy and Petrulis (2012) also described four modes of inquiry-based learning that describe whether students are addressing their own or someone else's questions, and if they are building new knowledge or exploring existing knowledge: authoring, producing, pursuing, and identifying. In authoring, students explore their own questions to build new knowledge in a field. In producing, students explore an open question posed by someone else. In pursuing, students develop their own question to explore an existing body of knowledge. In identifying, students explore an open question given by someone else to explore an existing body of knowledge.

Inquiry-based teaching can occur in both lecture and laboratory class contexts. Buck et al. (2008) proposed a method to standardise classification of inquiry teaching in laboratory classes after analysing 22 laboratory manuals and 400 lessons. As a result, they constructed a rubric of five levels of inquiry (Level 0/Confirmation, Level 0.5/Structured, Level 1/Guided, Level 2/Open, and Level 3/Authentic) based on the presence/absence of guidance of the following attributes during a laboratory experiment/task: (i) problem/question, (ii) theory/background, (iii) procedure/design, (iv) results analysis, (v) results communication, and (vi) conclusion. Because supporting inquiry during hands-on laboratory activities during small group work is more common than in lecture, Buck et al. (2008) argued that a separate rubric of inquiry levels was justified. Buck et al.'s (2008) rubric aligns somewhat with Marshall et al.'s (2010) categories, which was developed for more general class activities and not necessarily laboratory experiences. Although there are two existing rubrics, our team selected the Marshall et al. (2010) framework because

Table 1. Characteristics of assessment prompts along the inquiry continuum (based on Marshall et al., 2010).

Directed Inquiry	Guided Inquiry	Open Inquiry
Learner must respond to teacher-posed task	Learner must clarify how to complete task/solve problem	Learner must figure out how to use resources and to solve task/problem
Teacher engages student in how to complete the task/solve the problem	Learner led to evidence that should be used to complete task/solve problems	Learner poses questions to help him/her solve task/problem
Learner provided with evidence that should be used to complete task/solve problem	Learner not given connections to link evidence to problem to be solved	Learner must determine what evidence is needed to solve task/problem
Learner given connections to link evidence to complete task/solve problem	Learner has some flexibility to ask questions to solve problem	Learner independently examines resources to form explanations
Prescriptive organisation and recording	Some prescriptions about response/no prescriptions about how to record or develop response	Non-prescriptive guidelines on how to organise evidence and record final solution/answer.
Learner can anticipate results		Learner has much flexibility to ask questions while solving task/problem

our study was conducted during a lecture class. The framework shown in Table 1 provides the characteristics of directed, guided, and open inquiry adopted by the current study.

In addition to the different descriptions of inquiry, there is mixed evidence regarding the benefits of the different levels (Sadeh & Zion, 2009). For example, Berg, Bergendahl, Lundberg, and Tibell (2010) found that a revised version of their open prompt (which became guided) resulted in higher student learning outcomes and perceptions of chemistry experiments during laboratory work than the directed instruction. Trautmann, MaKinster, and Avery (2004) found that guided inquiry instruction was less frustrating for both teachers and students than open inquiry. Sadeh and Zion (2009) reported that open inquiry was associated with higher procedural understanding than guided inquiry and that there were no differences in students' learning processes or perceptions of the experiences. Levy and Petrulis (2012) found that (1) students had different perceptions of the same inquiry prompt and (2) these perceptions are likely influenced by students' prior experiences with research and inquiry-based education. In one study, students perceived that their inquiry experiences and learning outcomes were higher under knowledge-building and open inquiry prompts; however, in that study, the researchers only assessed students' perceptions and not student learning outcomes (Spronken-Smith et al., 2012). Because of the lack of clarity of what inquiry means and how instruction can support it, some researchers are critical and cautious about touting it at all (Kirschner, Sweller, & Clark, 2006). On the flip side, some experts encourage science instructors to integrate opportunities for inquiry because it models how people learn (Bransford et al., 2000) and how professional scientists and engineers ask and answer questions (NRC, 2012).

Some researchers argue that open and authentic inquiry should be reserved for advanced students, while structured inquiry tasks are more appropriate for lower-achieving or introductory students (Healey & Jenkins, 2009; Hodge, Haynes, LePore, Pasquesi, & Hirsh, 2009). However, other studies challenge this claim (Derting & Ebert-May, 2010; Laredo, 2013; Mehalik, Doppelt, & Schuun, 2008; Spronken-Smith et al., 2012; Yerrick, 2000). Mehalik et al. (2008) found that students learning physical science using an open inquiry process had higher test outcomes than their peers who followed a scripted inquiry investigation. Low-achieving and under-represented students in Mehalik et al.'s (2008) study made the largest gains. Similarly, Yerrick (2000) found that a science class for low-achieving high school students that was structured around open-ended inquiry helped the students develop scientific reasoning and inquiry skills, allowing them to apply scientific reasoning and knowledge to real-world problems. Hence, providing the optimum amount of guidance for inquiry is not as simple as decreasing the amount of guidance as students move through their studies.

Despite the reported benefits of inquiry-based instruction, though, instructors still require information to design inquiry-based curricula to meet their course objectives. Dym, Agogino, Eris, Frey, and Leifer (2005) as well as Levy and Petrulis (2012) reported that faculty members are often unclear on how to meaningfully integrate inquiry-based group tasks in their courses. It is not surprising, therefore, that Harwood, Reiff, and Phillipson (2002) found that there was little clarity among 52 science faculty members interviewed regarding how existing STEM curricula can be modified to be more inquiry-based. Studies, such as ours, aim to address the need for documention of the effect that different levels of inquiry-based tasks have on student outcomes.

Inquiry-based tasks and group work

The engineering education community, in recent years, has integrated collaborative group work into their curricula in efforts to prepare graduates for teamwork experiences common in the engineering profession (ABET, 2012; Froyd, 2005). In fact, some engineering educators give students time for collaborative problem-solving during lecture classes, and not just in their laboratory or practical classes, in keeping with ABET recommendations (ABET, 2012; Atadero, Rambo-Hernandez, & Balgopal, 2015), and for some classes, both theory and practice are combined (Purzer, 2011). In their narrative review of over 100 undergraduate engineering team work studies, Borrego, Karlin, McNair, and Beddoes (2013) found that most studies were concerned with how to design teams, team products, or attitudes of team members. Borrego et al. (2013) identified five constructs that are particularly important across these studies: (a) social loafing (presence of a non-contributing member), (b) interdependence (levels of dependency on others), (c) conflict (often related to task interdependence, goal incompatibility, differentiation of individual orientations of team members, and the perception of limited resources), (d) trust (especially in self-distributed and self-managed groups), and (e) shared mental models (enable groups to approach ill-defined tasks and coordinate their actions by leveraging all team members' abilities). The challenge for instructors, Borrego et al. (2013) concluded, is to design tasks that are 'sufficiently complex [or else] students may lose motivation and disengage, especially if they have experienced conflict, social loafing, or lack of trust in previous team projects' (p. 497). Reiterating Mathieu, Maynard, Rapp, and Gilson (2008), they called for more studies in engineering education that study group dynamics in authentic classroom settings. Inquiry-based collaborative work requires sustained levels of interaction and provides an opportunity to study group dynamics and performance outcomes, especially when faced with the challenge of creating and agreeing upon a shared mental model.

Although there are many studies that examine the outcomes of inquiry-based collaborative group work and other team-based learning, relatively few of these studies describe student interactions during such classroom activities. There is still much to be learned about how group work discourse supports learning (Shuman, Besterfield-Sacre, & McGourty, 2005), although a couple of studies on group dynamics are informative. Purzer (2011) studied how group work in undergraduate engineering classes supported achievement through students' self-efficacy. Purzer (2011) subsequently claimed that student achievement can be predicted by their discourse styles classified according to individual orientation (task, response, learning, support, challenge, and disruptive). In addition, he concluded that the high-achieving engineering teams collaboratively assigned tasks, discussed and critiqued ideas, and stayed focused. Kittleson and Southerland (2004) also identified similar traits in engineering groups and labelled the discourse associated with high-achieving groups as Concept Negotiation (CN). However, unlike Purzer (2011), they did not describe discourse based on each person's role in a group, and instead focused on the collective discourse of the group.

Some studies have examined and found relationships between discourse and performance, and many more that have found relationships between perceptions and performance. However, what is still not well described is how prompts developed along the 'inquiry continuum' support disciplinary discourse, and how these, in turn, are related to performance and perceptions of group work (Figure 1). In this exploratory study, our primary goal was to describe how students engaged in discourse as they made meaning of problem-based tasks that were designed to enact different levels of inquiry (*guided* and *open*). We describe how students' discourse in small groups during an engineering lecture course that did not have a corresponding laboratory section was correlated with their performance (project scores). We also describe student perceptions of group work (written reflections; Figure 1).

Theoretical framework

Discourse theory

According to sociocultural and interactional sociolinguistic theories, it is through interactions in social settings that people make meaning of the world (Gumperz, 2001). In this regard, language and non-verbal communication help people develop socially constructed knowledge (Gee, 1999). Thus, if we are interested in studying how students

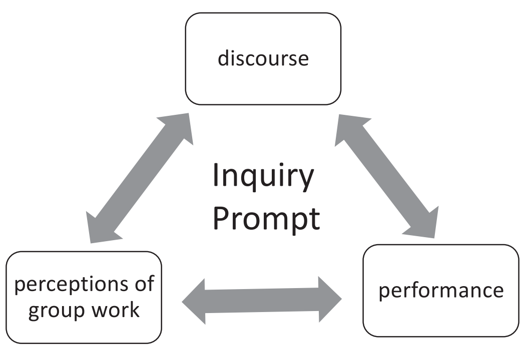

Figure 1. Separate studies have explored the relationship between inquiry-based instruction and one of three constructs: performance, perceptions of group work, and discourse. However, we posit that the relationship of all three in one educational context is important.

learn from collaborative group work, it is important to study the interactions between students when they are engaged with their group as they make conceptual meaning (Kelly & Crawford, 1997). In addition, if individuals interpret instructional prompts differently, they will respond in their own way, making it a challenge for the group to adhere to a shared mental model (Borrego et al., 2013). Small groups engaged in problem-based tasks, therefore, are ideal units for interactional discourse studies.

In response to criticisms that inquiry-based group tasks resulted in discourse around procedural and administrative issues, Kittleson and Southerland (2004) sought to identify how mechanical engineering students generated knowledge about concepts. Drawing on Gee's (1999) discourse theory, they examined small group work in undergraduate engineering classes and subsequently identified different discourse patterns used during collective knowledge generation. Through video-recorded group work and interviews with participants, they determined that discourse fell into four classes (*concept negotiation*, *concept explanation*, *procedural*, and *administrative*), in addition to *off-topic* (OT) discourse. *CN* refers to collective dialogue amongst students who contribute to a developing understanding of a concept, while *concept explanation* (CE) refers to monologues when single individuals convey their personal understanding of a concept to others in the group. CN may be an indicator of students' motivation to apply foundational concepts in required class activities. When the objective of group work is to engage all students in deep learning, discourse classified as CN is the most desirable. It is only through CN discourse that students can collectively construct and adhere to a shared mental model because this type of discourse enables team members to 'form accurate explanations and expectations for the task, and in turn, to coordinate their actions and adapt their behavior to the demands of the task and other team members' (Cannon-Bowers, Salas, & Converse, 1993, p. 228).

Engaging in other types of discourse, such as procedural and administrative, is important for developing the interpersonal skills needed by science and engineering graduates. However, instructors and curricular designers often aim to address several learning objectives at once, and it is important for them to know how their choice of inquiry prompt will impact both student content learning and interpersonal skill development. While students may have the opportunity to engage in numerous group work situations over which they can slowly build interpersonal skills, they may have only one chance to engage with a specific area of content knowledge. For this reason, we have placed greater importance on content knowledge development and CN in this study.

Research questions

Our study was designed to answer the following research questions: (a) which type of inquiry-based task (*guided* or *open)* was associated with increased time and sustained time in CN discourse? (b) which type of inquiry-based task (*guided* or *open*) was associated with increased performance? And (c) what were students' perceptions about inquiry-based group work tasks (*guided* and *open*)?

Methods

Our collaborative research team consists of one civil engineer, two science education researchers, and an educational psychologist. We used discourse theory to frame our conversational analysis and used the literature on inquiry-based learning to inform the development of our instructional interventions.

Context

This study was conducted in one section of the foundational engineering course, Statics, which is a required course for civil, environmental, and mechanical engineering majors. The course content involves the application of Newtonian mechanics to non-moving, static situations. The section was taught by one of the co-authors. Thirty-five of 72 enrolled students consented to participate in video recording. We designed groups so only consenting students were placed together. New groups were configured for each task. There were seven video-recorded groups with an average of five students per group. All students were expected to work in pre-assigned groups three times (the last two of which were studied) during the semester. Most of the students were European-American (72%) and male (87%). Almost all the students were of traditional age for second-year engineering students (with ages ranging from 19 to 21 years old). The discourse dynamics between male and female students are explored in a separate paper.

We developed two inquiry-based assignments: a moderately structured assignment, with opportunities for deviation (*guided task*) and an ill-defined assignment that required student innovation (*open task*) informed by Marshall et al.'s, 2010 taxonomy of tasks. The assignments could be classified along different parts of the inquiry continuum based on the amount of explicit directions provided (Marshall et al., 2010). Two authors determined how to ensure that the tasks fell along the inquiry continuum. One author (the instructor) constructed the prompts, a second author evaluated these while referencing Marshall et al. (2010) and made suggested edits; finally, the entire team reviewed the final prompts until, as a team, we accepted them.

Students participated in a group-based task at the beginning of the course before we started collecting data. This task (designing a Rube Goldberg, an over-engineered machine to complete a simple task) allowed students the chance experience group work within the course. It also allowed us to pilot data collection by asking students to set up video-cameras in each of their small groups. In doing so, we discovered that we needed to provide more directions on how to operate the cameras for the subsequent tasks, which were designed for data collection. The *guided task* required students to design and build a bridge that met specific parameters using materials provided and test its load-bearing strength during class (Table 2). The *open task* required them to select a real-life situation for which friction is exploited for a task and creatively present a demonstration of the concept, along with an explanation of what would occur in a frictionless or near-frictionless environment. Both tasks included a written component involving calculations that demonstrated depth of concept knowledge and self-reflections written by each student. Both tasks asked students to take concepts they had first explored in Physics (equilibrium for the bridge project, and friction for the friction project) and apply their knowledge to an engineering task.

All the assignments were presented to the class as part of a summative performance-based assessment. Performance-based assessments (Slavin, 2003) are opportunities for students to demonstrate what they can do (in our case, they demonstrated how their apparatus or presentation worked), but their summative assessment score was primarily

Table 2. Examples of prompts designed along the inquiry continuum.

Level of Inquiry	Characteristics	Example
Guided	Teacher provides a clear prompt that may explicitly or implicitly state what the expected outcomes are; however, the mechanisms to reach the outcomes are not provided.	Design and build a bridge using materials provided by the instructor. Test this bridge to failure in class.
Open	Teacher provides a loose prompt without an intended outcome and little guidance is provided to students as to how the outcome should be accomplished.	Select a real-life situation in which friction is beneficial or harmful and can creatively illustrate the concept. Develop an explanation of what would happen in a frictionless environment as well.

based on their justification of their design and explanation of the performance results presented in the written report.

Data collection

Discourse

Student groups were provided small video-cameras and a small tripod. The groups spread out either in the lecture hall or just outside the hall in a study space. Either sitting at desks or on the floor, students set up the camera using written directions. They were asked to identify themselves by group number and first name and to not keep the camera in one place during the conversation. In this manner, we observed all group members. By asking students to video record their first group tasks, they could practice using flip cams, ensuring that all voices and faces were included in the recording.

Performance

Students' assignments were marked by the instructor using rubrics, which the research team could review before use. The elements on the guided inquiry task rubric were divided into: (a) performance (stability, adherence to provided materials); (b) design drawings (indication of loading point, professional, accurate); (c) design steps (conceptual planning, analysis of forces, analysis assumptions, failure prediction, adjustments to design); (d) failure analysis (failure description, rationale for failure, professional), and (e) self-reflection of group work. The elements on the open inquiry task rubric included: (a) performance (process of friction demonstrated, explanation of friction, clear engagement of all group members); (b) design drawings (description of how friction is essential, calculations with frictions, calculations without friction, professional); and (c) self-reflection of group work.

Perceptions of group work

For each assignment students were asked to submit an individual written reflection about what they learned from the project and what, if anything, they would do differently if assigned this project again. Reflections were submitted with the final project analysis. The same prompt was given for each of the design tasks. Although students were not asked to explicitly evaluate the individual contributions of each group member, some students included this information.

Data analysis

Discourse

We analysed the videos using a 'nature of talk' (NoT) coding heuristic informed by Kittleson & Southerland (2004); the NoT was classified into one of five categories: *administrative*, *procedural*, *conceptual negotiation (CN), conceptual explanation (CE)*, or *OT*. We calculated the total percentage of time each group engaged in each of these categories. We did not collect data on the amount of time students spent working outside of class, nor on the subsequent in-class discussions students held. As students were assigned to different groups for each task, group number could not be used to compare individual groups or students between the two projects. To establish trustworthiness of our findings, a guideline for inter-rater coding was concurrently developed. Another researcher also coded 21% of the video recordings to establish inter-rater coding reliability. Before discussion over half of the codes overlapped between the two coders using the Kittleson and Southerland (2004) protocol. The two researchers subsequently discussed the discrepant results, and after clarification of coding criteria, completed the coding process with a 95% coding agreement. One primary coder completed analysing NoT discourse for the 184 minutes of video recordings. The mean amount of time each group spent in each type of conversation was calculated for each assignment. Finally, after coding the video data, the time that each group spent in the five types of conversations were compared. Specifically, the percent of time groups spent in each conversation type for each of the two types of prompts, guided and open, was compared using two sample *t*-tests.

Performance

The instructor marked each group project without knowledge of the discourse data, which were coded only after the course was completed. Simple linear regression models were calculated to obtain the strength of the relationship between the percent of time a group spent in CN and their final scores for the assignment for each type of prompt, guided and open.

Perceptions of group work

Using thematic content coding (Braun & Clarke, 2006) one of the authors analysed student reflections and discussed these with the entire research team. Initial themes reflected in student reflections included 12 categories (Table 3). These were collapsed into seven codes, and eventually, in the final round of collapsing codes, three salient themes were identified: (1) content, (2) logistics, and (3) discourse dynamics (Table 3). Most reflections were 1/2 to 1-page long and described students' perceptions of the task as well as of their group interactions. All the reflections were blind coded (i.e. without reference with which student group the student worked) and then were reanalysed by student group. This was conducted to ensure that biases about groups (and their project performance) were reduced. To ensure reliability of coding, the coder recoded all the reflections after a long duration (one year) using the thematic coding protocol developed initially. Finally, student reflections from groups that were engaged in the longest and shortest relative CN discourse times were examined for patterns in perceptions of group work.

Table 3. The coding scheme for the written reflections involved identifying and collapsing themes in three rounds.

Primary codes	Secondary codes	Final codes
Real-world connections	Application of concepts	Content
Theory-to-practice		
Visualisation of concepts		
Not enough time overall	Time management	Logistics
Needed to manage time		
Change of project aesthetics	Design	
The prompt was too limited	Expectations of task	
Different materials needed	Planning	
More calculations needed		
Needed better design		
Group worked well	Positive group dynamics	Discourse dynamics
Unequal work distribution in group	Negative group dynamics	

Findings

Discourse

Students spent a significantly greater amount of time in CN for the *guided task* than when engaged in the *open task* ($t(8.7) = 4.03$; $p = .003$ (Table 4, Figure 2), and were engaged in significantly more procedural discourse ($t(9.3) = -2.65$; $p = .026$) for the *open* task than the *guided task*. Furthermore, the maximum length of time spent in CN was also different between the two types of discourse ($t(8.5) = 3.46$; $p = .008$; Table 4, Figure 3). There was no statistically significant difference observed between the amount of time spent in CE, administrative, or OT conversations between open and guided tasks (Table 4).

Different inquiry prompts yielded differences in the amount of time that students engaged in CN. CN involves rich exchanges between most or all group members, whereas CE involves a single individual explaining concepts to group members. The following two excerpts from video recordings of the same group illustrate how CN discourse is characterised by active interactions between at least two group members (if not more, often), during which members acknowledge one another's ideas. There is no one in charge, and all ideas are valued and explored. In the following exchange, students were discussing how to build a bridge with limited resources. Student 2 (S2) asked the group mates about materials in response to S1 suggesting how they could physically structure the bridge. It appears that all group members recognisde the limitations of the original suggestion but work together to explore a possible design solution.

Table 4. Descriptive statistics and *t*-tests for the percent of time groups spent in the different types of task by type of prompt.

	Guided ($n = 7$)		Open ($n = 7$)		Comparison		
	M	*SD*	*M*	*SD*	*t*	df*	*p*
CN	51.9	20.4	17.2	10.1	4.03	8.7	.003
Longest continuous CN	178	85.1	56	39.9	3.46	8.5	.008
CE	8.7	4.9	10.6	13.1	−0.36	7.7	.726
Procedural	24.3	10.5	46.4	19.3	−2.65	9.3	.026
Administrative	8.1	6.4	18.8	21	−1.3	7.1	.235
Off Topic	6.9	13.9	6.9	6.8	−0.01	8.7	.996

*Equal variances were not assumed.

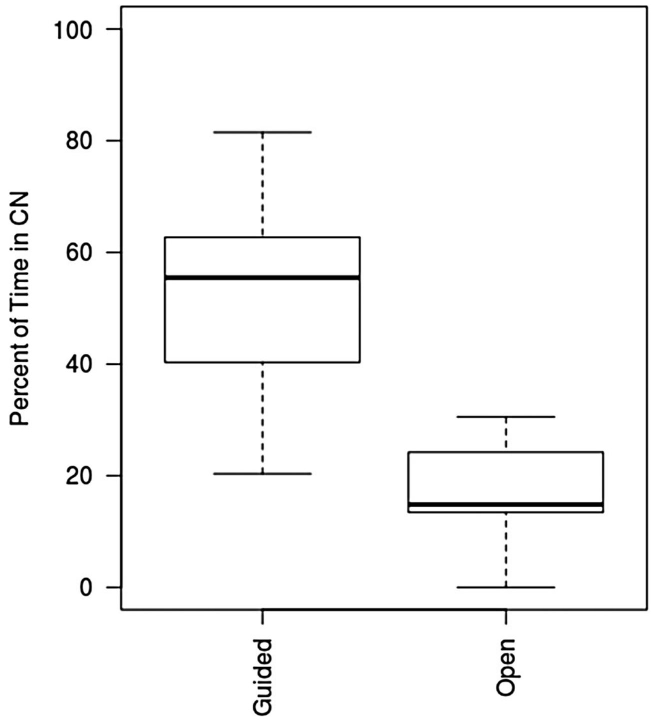

Figure 2. Total percent of time in CN per group by inquiry prompt.

Student 1 (S1): So, we have pieces going like this [demonstrating with pieces of balsa wood].

Student 2 (S2): And then maybe, and then these [demonstrating with pieces of balsa wood] will be structured by the triangles, like, halfway down we will have, and each side will be like that [manipulating materials].

S1: So, it looks like it will be about two to three feet, so we can have …

S3: And, if you see at the base there, I'll blow it up [picture of the golden gate bridge], the base is a bunch of a whole lot of tiny triangles. So, you have the base structure, a rigid base, plus it's suspended by the cables.

S2: If we could actually do that, it would be intense. Should we make those triangles within the actual bridge, should we make it rope or wood?

S1: We should probably make it rope, only because, well, we can play around with it. But, that's a lot of wood.

S2: I would also think we should do more string because if we try to do it with wood, we would have to do a lot of notching and a lot of hoping it would stay together, whereas, the string we could actually tie it

S1: Because we're not allowed to use adhesive

S2: Right.

CE discourse, on the other hand, is characterised by a single individual providing clarity to other group members about a concept. Although there may be interactions between

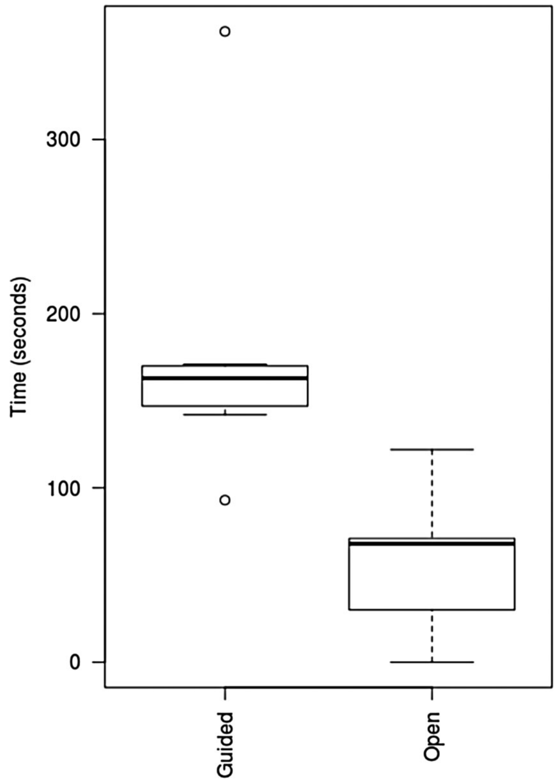

Figure 3. Maximum length of time in CN (in seconds) for each group by project type. Circles indicate outliers.

group members, these are defined by one person providing information, while others respond.

Student 1 (S1): So, what we can do is, and these have been pretty easy calculations, and that's nice. And so, what we can do, we've been doing simple calculations based on this is what we've been doing in homework. So, this would be pretty easy to do quick calculations on, come back on it, and figure out from there our sketch based on the minimum values.

Student 2 (S2): You're saying, what's in these calculations?

S1: Because we can assume, because what we're using, the suspension bridge is going to be massless, we can just assume that there's going to be certain forces that are going to be going on it. So, because of what we have, the calculations we've done have been mainly truss forces. We can do the design we want, we can do and figure out a very simple, at least minimal calculation, and then we'll have to increase it from there, because minimal will never work.

S2: Yeah.

Performance

Simple linear regressions were calculated to determine the relationship between amount of time spent in CN discourse and project scores. The percent of time in CN ($\beta = -0.72$, $p = .07$) was not a statistically significant predictor of grades for the open task. The percent of time in CN ($\beta = 0.79$, $p = .03$) was a statistically significant positive predictor of grades for the guided task.

Perceptions about group work tasks

Student responses fell into three themes: content, logistics, and discourse dynamics. Content comments were exclusively about students' perceptions of how to apply theory through the projects as well as how to make the design (e.g. conducting calculations). Logistics comments were primarily about time management. Although most student comments were classified as content or logistics (Figure 4), the discourse dynamics theme was the most relevant for this study and will therefore be described in more depth. We argue that perceptions of discourse dynamics were indications of students' abilities to arrive at shared mental models.

Content and logistics

Almost every student reflecting on the *guided task* (62/64), and most students (61/68) reflecting on the *open task*, wrote about the value of applying theoretical concepts to design tasks. Content and logistics were often discussed at the same time (Figure 4). Ninety-five percent (61/64) of the students wrote about the importance of the design and calculations discourse during the *guided task* compared to only 72% (49/68) of the students who wrote about such discourse during the *open tasks*. Students reflected on the importance of planning and carefully reviewing calculations as a group. Students wrote often about the need to find time, use time wisely, or not procrastinate. The

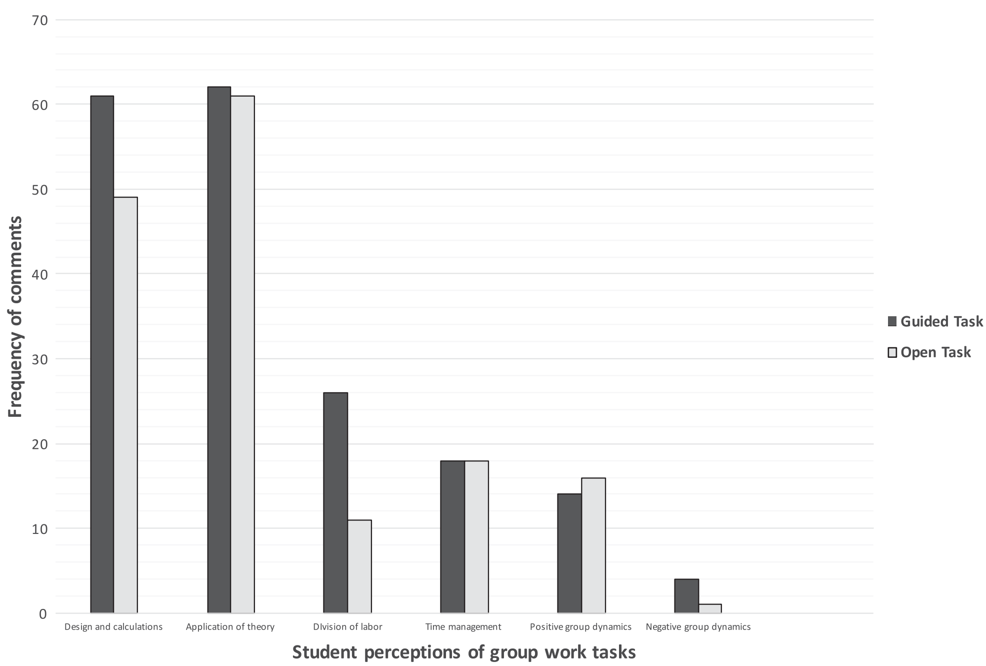

Figure 4. Student perceptions of group work tasks for both the guided task ($n = 64$ students submitted comments) and open task ($n = 68$ students submitted comments).

concern of time management was similar for both prompts; students recognised the constraints of time – either their own lack of time management or feeling overwhelmed with having multiple assessments due at one time. As a result, some students described a trade-off between time and innovation.

Discourse dynamics

Three distinct sub-themes relating to group discourse were identified: (a) positive group dynamics (including the opportunity to learn from others), (b) negative group dynamics, and (c) division of labour.

Positive group dynamics

Many groups were complimentary of how their peers worked with one another, as Alan shared that 'the group worked well together, we weren't able always to meet together, but we did a good job of communicating despite that.'

For the *guided task*, Joey explained that he learned not only about how to construct a truss bridge, but how to work with peers:

> Not only did I learn about statics related ideas, but the group project helped build my patience when working with others and strengthen my group participation. I tend to want to do all the work, but this helps me listen to others.

Negative group dynamics

Not all perceptions about groups were positive. Some students explained that their group needed to work on communication skills. For example, Aidan explained, 'I took most of this project on; this was because of trust issues. I've been burned on many group projects by lazy people, so I feel I did more work than my group members.' Nina wrote that although she enjoyed the group work, she felt that 'the group members were not equally invested in the project.' Although there was frustration with some group members, none of the students identified specific classmates in their reflections.

Division of labour

Division of labour was described by 26 of 64 (41%) students when describing how their group worked on the *guided task*. Of these 26 comments, five were critical of how their group distributed labour. The comments were overwhelmingly positive. Some comments were broad but explained that all group members contributed to the design tasks. For example, Toby stated that his 'group split up the labor well and we each contributed a lot to the project;' Maya concurred: 'Putting many different minds to a single problem yields far greater solutions, especially when solving the problem from scratch. Being able to divide the work required for the report among four people as opposed to one is another advantage.' Other comments explicitly described what each person contributed, such as in Peter's reflection: '… I was not the only one working on this. [student 1] created an Excel program to find the optimum angles for stress management, while [student 2] and [student 3] helped with knot theory and general critical thinking.'

Although not many, there were a few critical comments about division of labour during the *guided task*. For example, Anton wrote that 'I would have assigned the group to do more work as I seem to get stuck with doing all of the components myself.'

Division of labour was described by 11 of the 68 (16%) students when describing how their group worked on the *open task*. Of these 11 comments, seven were critical of how their group distributed labour. Some found it a challenge to spread out responsibilities for a loosely written open-ended prompt. Tanya explained that ' … it would be a good idea to figure out a better way to divide up the work,' and Martin wrote that 'the division of labor within the team could have been more prudently decided, which would have enabled a more in-depth discussion checked by varying opinions.' However, others, while acknowledging the open-endedness of the *open task* prompt, found that their group worked well together: 'All of us got along, and agreed on aspects of the project. We all have specific parts to do and specific ideas to convey.' (Joel).

Some students found value in the wording of the prompt, and as Jason explained, 'I enjoyed the open-ended part of being able to think of any real-world application of friction.' Micah found that an open prompt required that his group think outside of the box and consider other mental models, 'I feel like this project was helpful in opening our minds to the more creative aspects of engineering design. It took us some time to think of examples of situations where it would be useful to have friction.' Therefore, some groups could overcome the potential frustration of a too-open ended prompt, if they could work together to construct a shared mental model.

In summary, students perceived that both prompts allowed them to practice making calculations, consider different designs to meet the task objectives, and make real-world applications to course objectives. However, more students reflected on design and calculations (substantive issues) during the *guided task*. Students for both tasks wrote about the importance of time management to accomplish their tasks. Students differed, though, in their perceptions of distribution of labour. Similar numbers of students wrote about positive group dynamics (14 for *guided task* and 16 for *open task*) and negative group dynamics (4 for *guided task* and 1 for *open task*), but many more students wrote about distribution of labour for the *guided task* (41%) than for the *open task* (16%). These differences are notable as they are considered precursors for teams to arrive at shared mental models.

Discussion

Although educational reformers tout the importance of incorporating inquiry-based instructional strategies in undergraduate STEM courses, there is room for significant variation in how inquiry-based instruction is defined, designed, and implemented (Buck et al., 2008; Lee, 2012; Spronken-Smith et al., 2012). Furthermore, it is not always clear what the effects of tasks designed along the inquiry curriculum are on student discourse and ensuing performance. Different types of inquiry prompts might evoke different student perceptions about the task (Spronken-Smith et al., 2012) and working in teams that likely impact group discourse. In our exploratory study of undergraduate engineering students who participated in group projects designed along two points along the inquiry continuum, we identified four noteworthy findings: (a) students spent significantly more time in CN discourse in response to the *guided task* prompt than in response to the *open task* prompt; (b) student performance was positively predicted by time spent in CN for the *guided task*; (c) students were more critical of the *open task* and preferred the *guided task* and (d) students recognised the need for improved communication skills (including clear distribution of labour), allowing the group to work towards a shared mental model of the design task.

Discourse

One of the major hurdles of using non-didactic teaching techniques in undergraduate STEM classes is to ensure that students gain sufficient knowledge comprehension, preparing them to engage in problem-solving. In our study, the fact that students engaged in significantly more CN discourse for the *guided task* prompt suggests that they may benefit from some baseline direction from the instructor that was not provided in the *open task* prompt. If students invest significant time in trying to interpret the prompt (which was evidenced by more time spent in procedural conversation in the *open* compared to the *guided* task), they have less time remaining to engage in higher-order CN discourse.

Airey and Linder (2009) argued that students need the opportunity to engage in disciplinary discourse, if they are to master disciplinary content and ways of knowing. Mehalik et al. (2008) and Yerrick (2000) both found that inquiry-based science classes helped low-achieving students close their achievement gap with their peers and develop disciplinary ways of knowing, suggesting this strategy may disproportionately help some students more than others. Disciplinary ways of knowing include acquiring skills to use tools and discursive fluency needed to consume and generate disciplinary knowledge. Kittleson and Southerland (2004) described CN discourse as an indicator of students developing disciplinary ways of knowing. Encouraging students to engage in CN discourse during group work is one of the goals of group work, since it involves students collectively constructing knowledge and collaborating. Kittleson and Southerland (2004) acknowledged that in student group work, CN is often rare and difficult to solicit, as is telling students to find a shared mental model. If instructors, though, intentionally and thoughtfully design prompts, they can encourage students to engage in substantive discourse that allows them to arrive at a shared mental model, leverage all group members' skills and knowledge, and solve problems.

Airey and Linder (2009) were cautious and recognised that disciplinary discursive fluency alone is insufficient to demonstrate disciplinary ways of knowing. In response, they suggested that students should make meaning on their own through opportunities, such that inquiry-based group work affords, to use disciplinary discourse. Because the discursive activity of CN is consistent with constructivist learning opportunities that STEM education researchers support, (NRC, 2012), any research on instructional strategies that can improve meaning making and problem-solving skills can help guide curriculum reform. Instructors should strive to identify the 'optimal' amount of guidance. Optimal prompts allow students to struggle conceptually, encourage them to engage in CN discourse with their peers, provide clear intended outcomes, but prevent students from getting too frustrated and allow them to use the time they have in groups more effectively or efficiently with respect to learning. While some researchers have suggested that inquiry prompts should start with more guidance early in an undergraduate education and progress to more open inquiry at upper levels (Healey & Jenkins, 2009; Hodge et al., 2009), the optimum level of inquiry is more complex, as demonstrated by the successes of open inquiry in middle (Mehalik et al., 2008) and high school classes (Yerrick, 2000).

Therefore, continued research on inquiry will help refine how inquiry is defined as well as determine optimum levels of inquiry for specific disciplinary and educational contexts.

Performance

In this study, we demonstrated that there was a relationship between discourse and performance. For the guided task, students who engaged in more CN discourse demonstrated higher project marks, which is not surprising, if one assumes that through sustained discourse about shared mental models, student work is of higher quality (or that better students are more prepared to engage in CN). Inquiry-based instruction has been demonstrated, across studies, to increase students' conceptual understanding compared to passive instructional strategies (Minner, Levy, & Century, 2010).A meta-analysis of small group work in undergraduate STEM classes studied between 1980 and the late 1990s found that small group work increased student achievement, persistence, and attitudes (Springer, Stanne, & Donovan, 1999). However, the precise mechanisms by which these benefits are accrued by students can be hard to determine because each classroom and assignment is unique, and it can be difficult to collect enough data from small sample sizes to tease out individual effects. Video recordings of students engaging in group-based activities that varied along the inquiry continuum allowed us to gain insight into the relationship between CN and student performance. We posit that instructors can help student groups by giving them the time, space, and some initial guidance, so they can jump to deeper levels of engagement with their tasks.

Because the engineering professional community is calling on universities to design curricula that prepare students to have the competencies to transfer concepts and engage in inquiry, identifying instructional and curricular approaches that increase 'inquiry abilities' as well as perceptions about science inquiry, are important. Fang et al. (2016), in their comparison of student outcomes after participating in two levels of inquiry, structured (like Marshall et al.'s directed) and guided, found that performance for the structured prompts relied on students' prior content knowledge but that performance for the guided prompts relied on students' prior 'inquiry abilities.' In a separate study of high school students in Thailand, Bunterm et al. (2014) found that student knowledge and science process skills were greater for the cohort of students engaged in guided inquiry compared to those who participated in more structured, or directed, inquiry, as well as their attitudes about science. Results reported by Bunterm et al. (2014) and Fang et al. (2016) indicated that continued studies on the outcomes of tasks designed along the inquiry continuum are warranted and informative. They also raised questions about how discourse abilities are related to inquiry abilities. As we found in our study, students' competencies in inquiry tasks did not necessarily predict their discourse competencies; yet, being able to engage in discourse may affect a group's ability to engage in inquiry.

Perceptions of group work

Students need to work well in teams and have the trust in each other to engage in CN (Borrego et al., 2013). In our study, Aidan, spoke specifically about the importance of trust in student groups. Student reflections illustrate that they recognised the need for strong communication within class groups. Research in self-regulated learning explains that when students engage in socially shared regulation of learning, they work towards constructing a shared mental model and product (Hadwin & Oshige, 2011). Hadwin and Oshige (2011) in their review of self-regulation studies proposed that there are two types of shared regulation of learning: 'a) individual regulation for the social good and b) regulating as a collective entity' (p. 259). They highlighted the need for more research examining instructional tools that foster shared regulation of learning using both discourse and network analyses.

We predict that when students share a mental model, they are likely regulating their group discourse as a collective entity and able to spend time on substantive issues, such as design and calculation tasks. During the *guided task*, students appeared to have been able to distribute the labour and expectations more often than when they were given an *open task*. Interestingly, the *guided task* preceded the *open task*, so if students had discovered that this was an important characteristic of their group work, one might suspect that they would carry this over to the next task. However, we found that this was not the case, suggesting that the nature of the prompt affects group dynamics.

Constructing mental models is a sign of successful team work (Hadwin & Oshige, 2011), and efficiently using time by drawing on all group members' expertise may play a role in helping groups get to the stage of sharing mental models in group work. Instructors can help students construct shared mental models by giving them the opportunity to either learn more about interpersonal communication in a formal way or by assigning tasks that help groups to regulate their discourse in collective ways. Collaboration is affected by participants' feelings of mutual trust, sense of community and cohesion, and team orientation (Fransen, Kirschner, & Erkens, 2011; Fransen, Weinberger, & Kirschner, 2013). Although group work does not always result in positive outcomes, we believe from our study and informed by the literature that with scaffolding through prompts, groups can develop a sense of shared meaning. Through cohesiveness, which may begin with distributed roles and labour, it appears that students may learn from one another and expand their perspectives on how to solve a problem (Borrego et al., 2013; Wickman & Ostman, 2002). Student reflections, which were solicited through open-ended prompts, indicated that students engaged in *guided* prompts were better able to work efficiently on the task by distributing the labour among individuals compared to their group dynamics during the *open task*.

Although the sample size is limited due, in part, to the fact that we analysed discourse and performance in groups (of 4–5 students each), we conclude that discourse, performance, and perceptions of group work are inter-related (Kittleson & Southerland, 2004; Purzer, 2011). We argue that the *guided* task, by providing a few more expectations and guidelines to students, enabled students to use their time in different ways that resulted in deeper levels of discourse and higher performance. Students described successful division of labour, which likely helped them determine as a group how to meet the expectations. Kirschner et al. (2006) were critical of instructional strategies that are too open-ended because they frustrate students, who then require augmented instructor guidance to meet learning objectives. The *open* task prompt may have provided too little guidance, which then required students to spend time on procedural discourse. Such discourse may not have allowed the group members to arrive at a shared mental model, which was indirectly evident in their performance scores.

Despite prompting students to discuss their perceptions of group work, we did not ask them to evaluate each group member. Tools such as CATME (Ohland et al., 2012) have been found to be important in peer evaluation. Such tools can also benefit instructors, who can use information from peer evaluations and from perception and leadership style survey responses to purposefully construct groups to maximise learning outcomes and productivity. Future studies that go beyond shared mental models and focus on students' perceptions of individuals within their group would benefit from using existing tools.

Limitations

We recognise that while our results provide insight into the effect of inquiry-based group work on engineering student discourse, performance, and perceptions of group work, students' preconceptions about their professor may have affected student engagement during group projects, as well as motivation to participate in course activities. We also recognise that the exact definition of inquiry tasks differs across studies, and our definitions may not align exactly with other researchers' use of terms. Because this study was conducted in a single course and the class activities occurred in sequence, it was not feasible to study the impact of *guided* and *open* prompts on student learning of the same concept. The fact that students were discussing bridges in one assignment and friction in another may have impacted the amount of time students spent in different types of discourse. In addition, while we did not record student discourse during their group work sessions that occurred outside of class time, the high percentages of CN measured during the *guided task* during class indicates that specific assignment details and type may affect the type of discourse in which students engage while working on an assignment. In other words, we posit that the task prompt did have an effect. Finally, the data regarding students' perception of group work were collected through open-response writing prompts. Interviews would have been preferred, but interviewing 72 students twice during the semester was impractical.

Implications

The NRC (2012) and NAE (2004) implore science and engineering educators to adopt research-based instructional practices to improve undergraduate learning outcomes. In response, our study examines how engineering students learned how to apply foundational physics concepts and interact with one another during group-based design tasks. Because our research focuses on the impact that curricular design and instructional strategies can have on content knowledge and student perceptions of group work, our findings will be of interest to undergraduate educators in many STEM disciplines. Moreover, our interdisciplinary research team illustrates the importance of endeavours that bring together experts in engineering, science education, and educational psychology in efforts to improve undergraduate STEM education.

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