Viewing student engineering through the lens of ”engineering moments”: An interpretive case study of 7th grade students with language-based learning disabilities

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Abstract

Though there is a growing consensus that engineering instruction should be incorporated into United States K-12 classrooms,[1,2,3,4] little research has focused on what student engineering looks like in these classroom setting. Topics for investigation include how students understand engineering tasks, which behaviors can be viewed as age-appropriate engineering, and how students may coordinate these behaviors to create a coherent engineering process. In addition, there is a paucity of research focused on the engineering of students with learning disabilities, despite the fact that U.S. classrooms include many students with reading and other learning challenges. In this study, we focus on a small class of students with language-based learning disabilities engaged in a literature-based engineering project. Students with LBLD generally have difficulty with word recognition and fluency, leading to struggles with reading comprehension.[5] Additionally, these students may also face executive function challenges, including issues with memory, attention, organization of information, and generalization of skills to new situations.[6] As these students proceeded through their engineering unit, we looked for evidence of "engineering moments," or moments where students engage in behaviors and thinking that can be viewed as the foundations of productive engineering practice. These engineering moments may include defining problems, planning, designing solutions, and engaging in evidence-based arguments. We argue that the students who successfully engaged in the literature-based engineering challenge exhibited capabilities including the ability to frame problems, use drawings and plans to guide their building, make informed design decisions, and reflect on and evaluate their work. The students who viewed the purpose of the unit as building a working prototype also exhibited the most coherent engineering process. Additional support and structure may be necessary, however, to help all students, including those with LBLD, navigate the complexities of open-ended engineering projects.

Introduction

According to IBM's 2010 survey of over 1500 CEOs, creative thinking will be more important than any other trait for today's students to succeed in an increasing complex world.[7] The American Society of Engineering Education K-12 Center asserts that "engineering is creativity," and that "problem solving and innovation brings out the best ideas from every student."[8] (pp.1) Engaging in engineering practices not only piques students' curiosity, captures their interest, and motivates their study, but also helps them deeply embed knowledge into their personal worldview, empowering them to tackle the major challenges confronting society today and in the future.[1,2,3,4]

The classroom context, however, presents implementation challenges for open-ended engineering activities. These challenges are related in part to a strong focus on highly standardized curricula in current educational institutions in the U.S.,[2] a focus that stands in stark contrast to the flexible, varied, failure-accepting atmosphere necessary for students to engage in open-ended engineering projects.[9] In addition, though there is a general consensus that incorporating engineering instruction into K-12 schools is desirable, researchers and educators must work to deepen our understanding of what engineering design practices look like for younger students and how to support student learning in this context.[10] It is also important to note that students with learning disabilities can be found in every classroom and every school, yet there is a paucity of research on how students engage in open-ended projects or on instructional techniques that might support their engineering process.[11] In order to design and evaluate effective engineering curricula, we must learn more about how all learners engage in engineering projects and what supports may be most useful to particular students.

The engineering design activity presented in this paper is part of a larger NSF- funded project entitled *Novel Engineering* (formerly *Integrating Engineering and Literacy*.) This project has been implemented in over 20 classrooms with students in grades 3 through 7. The engineering design activities are literature-based. Students read high-quality stories or novels, identify problems that characters face and design possible solutions. In a sense, the characters become the students' clients. The setting, character traits, events, and other information in the book provide information about constraints and resources. Previous work on these units has shown that complex problems presented in children's literature can foster the development of engineering thought and practice in the classroom.[10] In addition, analyses of data from this study suggest that students' purposeful use of information from the text in service of designing engineering solutions may support reading comprehension in a traditional classroom setting.[12] It is still unclear, however, how students with learning disabilities engage in open-ended engineering projects and whether text-based projects are beneficial to students with weaker reading skills, including students with documented reading disabilities.

What are Engineering Moments?

The National Research Council's Framework lists eight "engineering practices" students should be expected to engage in, including defining problems, developing and using models, planning, analyzing and interpreting data, using mathematics and computational thinking, designing solutions, engaging in evidence-based arguments, and obtaining, evaluating and communicating information.[3] Among experts, these practices translate to a highly iterative, reflective process involving complex problem framing, thorough research, analysis of tradeoffs, and controlled testing.[13, 14] It is widely acknowledged that student engineering does not generally look like that of professionals, in that students may appear to skip doing research, conduct unsystematic tests or favor immediate building rather than planning in advance.[13,14] Recent work, however, suggests that students can engage in age-appropriate engineering practices.[10,12,15,16] For example, students have been found to discuss the complexities of a problem scope, effectively plan using design drawings, and engage in legitimate testing setups.[12,15,16]

This paper is motivated by the conjecture that students engaged in engineering projects may exhibit productive behaviors that could be a good foundation for developing more sophisticated engineering practices. These specific behaviors may be seen as productive, but may not always be connected, coordinated, or otherwise cohere into what would seem to observers as an organized design process. A productive line of inquiry is to investigate the moments when students engage in activities or behaviors involving skills or practices at the root of engineering. By doing so, we can learn more about the skills and understandings that students bring to their engineering projects and learn more about how to support primary and secondary students' engineering.

A central purpose of this paper, therefore, is to identify and describe "engineering moments," or times during the unit when students exhibit behaviors, practices, or thinking that are associated with productive engineering and that can be considered the beginnings or foundations of a more sophisticated engineering practice. By recognizing engineering moments, we hope to add concrete examples to the conversation about how young students engage in engineering projects. We aim to describe what engineering could mean for these students in order to help educators and researchers identify behaviors that should be recognized, encouraged and supported in the classroom.

In order to classify a moment as an "engineering moment," we are informed by existing literature and experience. We draw on engineering practices of experienced designers, current work published on elementary and middle school engineering, and our own experiences as both engineers and educators. Engineering moments for students may include times when students use knowledge about materials, constraints, or their understanding of science to make design decisions, evaluate their product using consistent and relevant criteria, and use a variety of planning methods that support their overall process. The messy, disjointed, or unfocused nature of many students' overall design processes does not necessarily detract from the value of their individual engineering moments. For example, two students in a freshmen design course argue about how much force the gearing system on their robot chassis is going to need to produce, and then abruptly shift to comparing dining halls on campus. We would argue that their shift in focus is a break in their design process, but does not detract from the fact that they were, however briefly, having a design conversation similar to those of professional engineers.[16]

In this study, we carefully analyze specific engineering moments, rather than attempting to quantify and code all engineering moments in the data collected. This method suits both the nature of our data and our core motivation. First, the students participating in the study were not on camera 100% of the time. Despite attempts to capture as much of their in-class engineering experience as possible, students frequently walked out of range of cameras or groups split up to pursue different tasks. Students sometimes moved around to confer with teachers, look at projects developed by other students, examine the material bin, and look up information online. Attempts to quantify engineering moments would not be appropriate given the incomplete data set and the likelihood that we would be missing important engineering moments. Additionally, our goal is to establish the phenomenon of "engineering moments" in student engineering practice and to describe these moments in some depth. Therefore, a qualitative analytic approach is more appropriate than a quantitative approach. Once we have a better-developed sense of what students' engineering moments look like and how students make sense of their engineering activities, it will be appropriate to sample work from a larger number of students, develop coding systems to look at general trends, and design studies to test quantitative hypotheses about the nature of engineering moments and whether they lead to more sophisticated engineering practice over time.

Research Questions

As stated above, for the central purpose of this paper is to identify and analyze engineering moments. Therefore, this paper will address the following research questions:

1. What characterizes *engineering moments* for small working groups of middle school students with LBLD?

2. How are these student groups' *engineering moments* related to each other? Are individual moments disconnected from each other, or are these moments coordinated in some way to create some sort of coherent process?

In this paper, we argue that students exhibit identifiable engineering moments in which they demonstrate skills and approaches to task that can be seen as productive beginnings of more sophisticated engineering practice. These engineering moments can be connected into a more or less coherent design process depending on multiple factors, including whether students in the small group tacitly understand and agree that the purpose of the task is to build a working prototype as opposed to a representative model. As educators and researchers work to develop instructional approaches and curricula to teach engineering to elementary and middle school students, an attention to these first engineering moments may help us better understand what resources students bring with them to their first engineering experiences, how they understand the tasks, and how to best support their learning.

Literature Review

When examining the engineering of middle school students who are relatively inexperienced in engineering design, it is important to consider how their behaviors compare with the engineering practice of expert designers. This comparison helps us to identify productive moments in student engineering and establishes a long-term goal for student learning. Professional engineering design can be characterized as a goal-driven process that requires decision-making and troubleshooting in order to organize the construction of any artifact that transforms the physical world.[17,18,19] Good engineering deliberately combines "precise and vague ideas, systematic and chaotic thinking, and imaginative thought and mechanical calculation." [20] (pp. 4)

Professional engineers encounter ill-structured problems that can often be broken down into smaller, more precisely defined "sub-problems."[18] Expert designers rely greatly on experience to aid them in partitioning problems into a set of meaningful, additive design tasks.[21] As designers solve sub-problems, they work to assemble what they have learned and created in pursuit of their greater, engineering design goal. According to Cross and Cross's account of two expert designers, main features of a successful design process are a "systemic view of the problem" and drawing on personal experience to frame the problem in a challenging way. Approaching a large, complex problem as a system of many different, dynamic components can provide valuable insight into the task.[22]

In the process of evaluating sub-problems, generating multiple solutions, and testing possible facets of their design, professionals still struggle to know which solution is optimal, or even how to judge what "works." To do so, they must rely on experience.[18] Among well-practiced designers, that experience can be supported by scientific modeling or mathematical optimization strategies to predict performance of multiple abstract concepts. In pursuit of a design solution, reflection on and exploration of the relationship between design decisions and solution performance is key.[17]

At first glance, engineering behaviors of elementary and middle school students do not look a great deal like more sophisticated practices exhibited by professionals. Students in middle school generally do not have a mental toolbox of mathematical concepts and mechanistic thinking to aid their design. Nor do they have the experience level Jonassen, Strobel and Lee suggest is crucial for expert designers to succeed in making solid design decisions. Inexperienced designers may design in a more haphazard way, lack meaningful design reflection, and fail to recognize the complexity of their design problem.[14] Rowe found that young students struggle to develop multiple solutions to a complex problem, or when they do, the ideas are often minor variations on the same concept.[23]

These findings suggest both that student engineering may look very different from that of experienced experts and that students may benefit from different approaches to engineering and additional supports. As Welch notes, "students, when left to their own devices, do not design in a way prescribed by textbooks." For example, he notes that rather than sketching out many different solution concepts before moving on to 3D modeling, as suggested by several models, students may benefit from constructing prototypes earlier in their design process.[13] Similarly, during a parachute design and construction activity with high-achieving 6th grade students, MacDonald and Gustavson found drawing to emphasize representation over ideation, especially when design tasks were limited in nature and set in a restrictive manner.[24] Puntambekar and Kolodner's research suggests that, during more open-ended, middle school Learning by Design™ units, student activities must be scaffolded appropriately, including encouraging students to use multiple supports such as design diaries and class presentations.[25]

It is reasonable to assume that student engineering will look different depending on age, experience with engineering, and knowledge of and ability to apply key mathematical and scientific concepts. A growing body of research, however, has found that students are capable of relatively sophisticated engineering. For example, Watkins, Spencer, and Hammer found that students were able to engage in problem scoping when given a sufficiently rich context and an open-ended problem space. Portsmore has found that students can effectively use planning strategies, such as creating design drawings before construction, to create engineering artifacts that are closely tied to their original ideas.[15] During a unit on service learning, Swenson found that students use both conceptual and functional testing to evaluate their engineering design products.[16] Though these studies provide some evidence about the nature of students' engineering and though the body of middle school engineering design research is growing, most studies focus on students gaining science content knowledge through design[25] or involve fairly limited, well-defined problems where students are not expected to, for example, grapple with problem scoping, identification and prioritization of sub-problems, or evaluating a solution within the context of a messy problem space.[24]

In addition, there is also a dearth of research being done on students with disabilities engaging in open-ended projects in general and engineering projects in particular. All students participating in this engineering design unit have been identified as having language-based learning disabilities (LBLD), a category which spans a range of literacy difficulties, including but not limited to decoding, making text-based inferences, word reading, and overall reading comprehension.[26] Students with reading and writing difficulties often struggle with executive function challenges as well, including issues with memory, attention, organization of information, and generalization of skills to new situations.[6]

It is possible that text-based engineering projects may help students with LBLD engage with the text and motivate them to remain engaged in a complex, multi-step project even when the project taxes their reading and executive function skills. Students may benefit from practice working in an open-ended space and working with others to communicate ideas and work toward a common goal. In contrast, it is also possible that this group of students may struggle to access and apply the rich information about characters and setting within the story, simply because of potential difficulties reading and comprehending the text. If these students also have executive function challenges, they may struggle with key elements of an open-ended project, such as organizing information and materials, staying focused on the most important aspects of the project, and redesigning their prototype. In this case, it is important to explore instructional approaches that could support student learning.

Methods

Population

This case study was conducted in a 7th grade classroom at a private school. Admission to the school is contingent on diagnosis of a specific learning disability in reading or writing, including, but not limited to, dyslexia. Students at this school typically score average to well-above average in cognitive measures but have relative weaknesses on measures of reading and writing. The tuition of approximately half of the students is paid by their local school district, while the other students' families pay without assistance. Most students have college-educated parents.

Setting

This unit was implemented within the "Tech Tools" class, an elective that met twice a week for 45 minutes, totaling 15 sessions over 9 weeks. The classroom teachers, Colin and Todd, led all activities, although members of the research team provided feedback and instructional support throughout the unit. Three researchers attended classes (one researcher was in all classes, two alternated) to collect video data and provide classroom support and materials.

The class read *The Most Dangerous Game* (MDG), by Richard Connell, in their language classes as part of their regular literacy curriculum. MDG is a short story published in 1924 in which the main character, Sergeant Sanger Rainsford, finds himself trapped on an island with an overzealous hunter, General Zaroff.[27] After discovering General Zaroff's hobby of hunting humans, Rainsford faces a number of challenges as he attempts to outwit the General and escape the island.

The students, split between two language classes, had the story read to them by their reading teachers, and took turns reading aloud in class over a span of four weeks. Both classes read the story slowly and carefully once, with teachers actively working to aid comprehension, and then more quickly a second time. Students finished the story by the end of the 5th week of the unit. While they were still reading, the students did some introductory engineering activities in the Tech Tools class, including brainstorming how to improve a snow shovel, and discussing problems faced by the characters in the story *The Three Little Pigs*. The Tech Tools class then moved into a teacher-led brainstorming session about problems Sergeant Rainsford faces in MDG. Teachers and students also discussed possible solutions to some problems. Students were divided into groups of two or three and tasked with creating storyboards of their chosen problems. The remaining class periods were spent planning, building prototypes, and presenting to the class during mid-design and final presentations. Testing of prototypes was encouraged but generally took place spontaneously when students decided they wanted to see how an element of their design would work.

Students had access to a MakerBot Replicator 2 3D printer, as well as a small laser cutter. Students did not have much experience with these tools, however, and relied mostly on found materials such as cardboard, bubble wrap, balloons, tape, plastic cups and wire to construct their prototypes.

Midway through the building process, each team had a “share-out,” which gave students a chance to describe their engineering project to date, articulate any challenges they were encountering and get feedback from peers. In addition, each team gave a final presentation and demonstration to peers and other teachers from the school. Students spent one class period preparing and rehearsing a slideshow presentation, which involved answering teacher-generated questions about their engineering process. The final two class periods was spent entirely on presentations, demonstrations and questions from teachers and other students in the class.

Data Collection

Multiple cameras in the design space recorded videos of student activity during the engineering project. In addition, researchers wrote daily observations, conducted teacher interviews, and collected picture documentation of student work at various stages of the process. This paper will focus primarily on evidence from transcripts of student dialogue.

Researchers acted as participant observers. Students occasionally seemed to be influenced by the presence of video cameras and unfamiliar teacher figures. Researchers generally did not interfere with students’ activities and avoided making specific suggestions, but did ask questions about what students were thinking and doing. Researchers might also suggest a particular material or show a picture or video that they thought might support student thinking.

More than 48 hours of video footage was collected over the span of 9 weeks. Small digital cameras on flexible tripods were placed around the room, each one usually focused on one group of students. When students moved, researchers or instructors picked up cameras and followed the students to other areas of the room. Students sometimes moved quickly or members of a group went in different directions, making it challenging to record all students at every point in the process. Portable microphones were also used to increase audio quality. Students occasionally commented on the cameras or microphones, but largely did not interact with the equipment.

In the following case study, we analyze video clips from three of the four groups in the class. A fourth group was omitted from the analysis because both students had multiple of absences, limiting their participation in the unit. The clips of the other three groups presented in this paper were chosen because they are representative of these students’ discussions and behaviors during this unit and because they provide strong evidence of students’ engineering moments, or lack thereof.

Data Analysis

All video data was transcribed using InqScribe digital media transcription software. Researchers carefully reviewed the data, looking for instances when students engaged in engineering behaviors and demonstrated thinking that was reminiscent of the behaviors and thinking of more experienced engineers. Videos were reviewed by individual researchers and then relevant clips were viewed and analyzed by multiple researchers as well as by the larger research group. In an attempt to add to the growing knowledge base of student engineering, the authors here point out recognizable moments of beginning engineering, aiming to aid researchers and instructors in the difficult task of seeing the engineering in student work.

Evidence of Engineering Moments

Students making knowledge-driven decisions

Elise, Claire and Tom worked on a scene in MDG in which Sergeant Rainsford gets trapped in quicksand. In the following episode, the student group discusses the relationship between product ideas and theories about the problem scenario. Notably, we see a disagreement between Claire and Elise about whether a proposed solution would work in actual quicksand. Claire has proposed a design idea – rain boots with propellers on the bottom to push the quicksand out of the way – while Elise challenges this idea in a non-confrontational way by expressing her understanding about what a person should do when stuck in quicksand.

1 Claire: We could get him a umm like rainboots. But they like, inside them they have like, like a fan, but they're going really fast to get out of this quicksand. Like [the fans could be] on the bottom. [Gestures to demonstrate.]
2 Elise: Wait, but if you're in quicksand, the more you struggle, the harder...the faster you will sink. So what you want to do is you want to stay really calm and slowly move your way over.
3 Claire: Yeah. But...
4 Elise: So you wouldn't want something that moves fast, or else you'll just go farther deep.
5 Claire: Yeah but then how about just like... how about we...
6 Tom: Really? Really I didn't know that. If I were in quicksand I would've died.
7 Elise: So. Now you know. Just stay calm.
8 Claire: Now that I'm thinking.... Maybe we should....
9 Elise: And just lean back...lean back and try and float.

In this engineering moment, Elise presents a theory about the problem scene (line 2), bringing in her understanding of quicksand in response to Claire's design idea (line 1.), Based on their review of existing literature, Crismond and Adams claim that informed designers make knowledge-driven decisions, using their understandings of how the world works and how things are built to make design decisions. Novice designers, on the other hand, often ignore contextual design constraints in favor of immediate prototype construction.[14] Despite Elise and Claire being novices, here they appear to be taking an approach akin to that of those more experienced, Their approach lacks the scientific knowledge and rigorous logic of an expert approach, but this engineering moment can be seen as the beginnings of a more sophisticated approach. Elise expresses an understanding of how quicksand works that contradicts a design decision proposed by Claire. This initial disagreement prompts a lengthy discussion of how to reconcile Elise's conception of quicksand with Claire's proposed solution. Though the "propeller boots" idea is eventually dropped, this idea of creating footwear to help Rainsford "try and float" on the quicksand remains a strong motivator of their design for the entire unit.

Elise, Claire, and Tom evaluate and redesign their prototype

About two weeks before the end of the unit, Elise, Claire and Tom share their current prototype with their classmates. The purpose of the share-out is to have students articulate their design ideas and have a discussion their peers. At this point in their unit, the group has consistently pursued the idea of creating "floating shoes" to help Rainsford escape the quicksand. They have tested out the floating capabilities of many different materials, including balloons and bubble wrap, in a deep sink of water. Their current design is an oversized shoe that slips on over Tom's regular sneaker. The "floating shoe" is made mostly of bubble wrap and masking tape. The three students explain that have gone outside to test the shoe by walking across in snow and semi-frozen mud to see if Tom "sinks down" or if his feet get wet. Here, it appears that the problem space may have shifted from extracting Rainsford from quicksand to preventing him from sinking into swampy ground.

The presentation begins with Claire giving a detailed description of their problem and solution:

1 Claire: Imagine Rainsford....stuck in a swamp. Can't get out. And he can't move, and he's stuck. Even though he's like...trying to move (turns her hips side to side while keeping her feet in place) he's going, sinking down and down.

2 Claire: We have created.....a shoe for him to stomp across the swamp. That is waterproof.

Claire, Elise, and Tom go on to describe their testing outside, where Tom "stomped straight across" snow, dirt and mud and "didn't sink down at all." They take questions from their teacher, and entertain suggestions from classmates. Their presentation qualifies as an engineering moment because the students are presenting their design as a solution to a particular problem. In addition to describing the problem space and their design decisions, they present testing as an important part of their design process and a way to justify the design decisions made so far.

Shortly after their presentation, the group reflects about previous design choices and design decisions that are currently on the table. An instructor approaches and asks them what they think about the suggestions made by their classmates. Claire mentions liking a proposed idea of adding something "spiky at the bottom [of the shoes], for traction." Elise expresses disagreement:

> Elise: But wouldn't the spike ruin the whole thing? Like...like because the...with the...what the bubbles are for is to help, like, float. And like, spikes are like the complete opposite of bubbles, so... that might not work.

In this engineering moment, Elise maintains a focus on the buoyancy and lightness of the shoes and rejects a potentially appealing idea because it could compromise these key characteristics of the design. According to Schön 's depiction of expert designers, this type of reflection on the scope of the chosen solution is crucial. Engineers learn from reflection as they design, incorporating facets of their earlier process as well as predicting outcomes of possible next steps.[14,28] Designers must recognize what information and aspects of the problem space to prioritize throughout their process.[30] Here, we see Elise refocusing the group on the solution they have been pursuing for the last few weeks. Claire is attracted to the new idea of adding spikes, but Elise expresses that this design change is simply out of their scope.

Claire and Tom test their final prototype

On the last construction day of the unit, Claire and Tom go outside to test the changes they made. The late-winter ground is a mix of soft snow and partially-frozen mud, a surface that they appear to see as the best available analog to the swampy ground portrayed in the story. Since the share-out, they have added wood pieces inside the shoes to increase stability and wrapped them in garbage bags to further waterproof them. In the next episode, we see Claire and Tom conducting a final test, measuring the performance of the shoes against the criteria they have mentioned multiple times during the unit during planning, building, and now testing. The criteria include 1) whether the wearer of the shoes "sinks down" into the ground (here mud or snow), 2) whether Tom's feet get wet through the shoes, and 3) are the shoes "untrackable"? For this group, "untrackable" appears to mean that the shoes leave little or no mark on the soft ground. In previous discussions, Elise, Claire and Tom express that since Rainsford is being hunted as he runs across swampy ground, leaving a mark would make it easier for his hunter to find him.

1 Claire: Tom, I was trying to see you run in mud, but....I don't think we have any mud. So. I want to see how they like... if you can see, like, an imprint in…
2 Tom: Okay. Hold on let's see how it works in snow. [Tom walks slowly on a big area of snow about 1 foot deep] They definitely don't sink down.
3 Claire: Yeah, they're not sinking down, which is good.
4 Tom: I mean they leave pretty big foot marks though (laughs.)
5 Claire: Yeah. Here try it in the mud, cause he's in quicksand and that's the closest thing we can get it to.
6 Claire: Yeah, Tom, walk like...that way [Claire touches the mud with the tip of her shoe.]
7 Tom: Yeah, but how are we (?) supposed to...Oh wow these aren't even close to damp.
8 Claire: Yeah, you can't....like it's not going down at all. And then come over here, like, when there's kinda like....
9 [Tom walks on the pavement after walking in the mud and laughs—he's left giant wet footprints on the walkway.]
10 Tom: I think this would ruin his trail though!!

Claire and Tom here test their final prototype against the same three metrics they mentioned at their very first brainstorming session. Claire is concerned about "leaving an imprint" (line 1) as well as "sinking down" (line 3.) Likewise, Tom makes sure to tell Claire that the shoes do leave a mark in the snow, but also that they do not sink down (line 2) and are waterproof (line 7.) He also tests for the trackability of the shoes, stating that the big wet footprints would "ruin his trail" (line 10). This is the connecting thread through all of their engineering moments.

This student group shows evidence of engaging in both concept testing and mechanical testing. In terms of concept testing, the group uses Tom as a potential user, since the actual user is fictional. Also, as Claire helps Tom to put the device over his shoe prior to testing, she asks about the comfort and perceived stability of the shoe. This type of concept test, sometimes called a mini interview, is commonly used by professional engineers to check for potential shortcomings of a product.[29] The group also focuses on mechanical aspects of testing. They consider multiple options for a reasonable testing situation, with Elise suggesting at one point that they should make quicksand. Claire counters that "mud is the closest thing we have." In both cases, the students are working to create a legitimate testing scenario. As noted above, the students evaluate functionality based on three consistent criteria. After one testing run, they make small changes, like adding wood pieces or covering the shoe in garbage bags, and test again. This iterative testing is similar to what professionals do to test for performance, function, and robustness.[16,29] Other research has found that young students may develop criteria during testing instead of stated explicitly before design began.[16] In these interactions, we see a similar dynamic.

These students exhibited engineering moments that could serve as the foundation of a more sophisticated engineering practice. In addition, these engineering moments were linked into a semi-coherent whole because of the maintenance of their focus on the general problem space and consistent criteria for a successful end product. Because the three students implicitly agreed that the goal was to create something that would really work in the real world and in the world of the story, they were able to coordinate their actions, evaluate their ideas using common metrics, and think of reasonable tests for their design.

Introducing Beth and Anna

The second student group, Beth and Anna, also has identifiable engineering moments and maintains a focus on a specific problem. These two students, though, approach their chosen problem very differently, leading to some confusion on their part and a markedly less coherent design process. Specifically, Beth views the goal of the task as designing something that works in the scope of the project, and could also work in the both the real and fictional worlds. Anna, in contrast, participates in generating the initial design idea, but then focuses primarily on creating a non-functional model that displays what the scene would look like rather than how their chosen mechanism would work. This difference in approach leads to some interesting interactions but also some decisions that seem decidedly odd without an understanding of the students' perspectives.

Beth and Anna focus on a scene from early in the story in which Sergeant Rainsford is locked in a tall tower by his enemy, General Zaroff. Their idea for a solution is to give Rainsford a zip line that he can ride from the tower down to a safe escape off the island. Unlike the first student group, Beth and Anna's verbal interactions are supported by gesture and reference to images or actual objects. They converse, but do not always use content words. For example, much of their conversation consists of utterances such as "well, we could use this…" while holding some material, or "but look at this" while pointing at a drawing they have made.

These mediated communications do lead to some interesting engineering moments, mostly surrounding different drawings Anna and Beth make. They create the drawings as they develop their solution, throughout the process, and also refer back to them frequently throughout the building process, to communicate with each other, teachers, and researchers. This suggests the drawings served multiple purposes, including ideation, representation, and communication, where inexperienced designers usually tend towards only representation.[24]

Beth and Anna plan using information from the text and design drawing

In the following episode, Beth and Anna describe one possible design after they have had about thirty minutes to brainstorm. In this clip, we see Beth and Anna expressing a strong grasp on their client's problem: fleshing out details of what he would want to do in the situation in the book, and what they could make that would help him. Beth and Anna refer to a drawing they have made as they talk to the researcher, and point out features of the drawing to support their explanation.

1 Beth: Okay. So our, um, idea is that Rainsford is stuck in the tower.
2 Beth: And.... one way he could do it is that... there's multiple ways [to solve the problem], but one way he could do it is have like, a three-direction zipline… but they're camouflage.
3 Anna: Yeah so he does this at like, the pitch black of night and he's wearing all black. But the only thing that's uh, that's not black is the zipper foldable raft and the oars.
4 Researcher: Ohhhh!
5 Beth: And then when he's done, the zipper foldable oars will somehow...is there for him.
6 Anna: Yeah so, like, so he can like, pick which direction he goes in.

In this engineering moment, Beth and Anna engage in problem scoping and design drawing. Both of these practices can be seen as foundational engineering behaviors. Beth and Anna have identified a problem, then further develop their understanding of the problem by focusing on particular aspects of the problem such as finding a way to be camouflaged and Rainsford being able to choose the direction in which he wants to escape (lines 3, 6, and 7). Beth and Anna's memory of the literature therefore contributes to their problem scoping, a key engineering practice, as they work to understand the situation and consider a possible solution.[3,31] Anna, in particular, puts herself in her client's place—thinking about when he could use their product (line 3.) As Beth and Anna talk, they unpack more complexities of their character's problem. Rainsford is not only stuck in a tower, he also needs to escape creatively, and must choose a particular direction in which to flee in his boat. Though their ideas are only partially formed, they are thinking creatively about possible solutions to a particular problem. In addition, they are focusing on both a mechanism for escape – a zip line and a collapsible raft – but are also thinking in terms of a system. Specifically, Rainsford will wait until it is dark, dress in black to avoid being seen, go down the zip line, and row away on a raft.

As they talk, Beth and Anna both reference two drawings they have created: one, a storyboard of the problem (requested by the teacher) and another, a design drawing done spontaneously and unrequested on the back of the distributed worksheet. This design drawing is then used to communicate ideas to the researcher. The reliance on their drawings at this point and later in the unit suggests this group engaged in meaningful planning, an engineering behavior that is seen as complex and not consistently observed in novice designers.[14,24]

Beth and Anna evaluate their first prototype

On the third day of building, Beth and Anna share their progress with their classmates. They draw on the whiteboard as they describe what they have done so far.

1 Anna: We did know that you were.. uhh...we just like decided to use the box, because we thought it was, like, a good structure and then, our thing is like a...lighthouse tower (drawing on the white board.) And then Rainsford is right here... And then..uhh... we have this zipline, and I think we're gonna use a different.... I think we're gonna use a wire, because we had string in the beginning, but...
2 Beth: It wasn't working.
3 Anna: Yeah, it wasn't working.
4 Colin: Why wasn't it working?
5 Beth: Because the string is like...(gestures)...floppy, loose.
6 Anna: Yeah.
7 Beth: Or something like that. And then we are thinking of making Rainsford out of wood this time.
8 Anna: Yeah.
9 Beth: Because we used felt, and that did NOT work.
10 Anna: Yeah it was really floppy (gestures her hand back and forth.)

The important aspect of this engineering moment is that Beth and Anna are discussing the functionality of their project. They appear to be working toward creating an accurate representation of the scenario, not having access to a tall tower or an existing zip line. This episode is reminiscent of Elise, Claire, and Tom's attempt to recreate a reasonably analogous testing environment, in which they identified what seemed to them to be a reasonable approximation of either quicksand or swampy ground. Beth and Anna evaluate their project's structural weaknesses, the benefits of using one material over another for the zip line, and incongruities of their previous model to the real life scene (the zip line in real life cannot be "floppy," and felt's structural properties make is an inappropriate material to represent Rainsford's body.)

Clearly, there are problematic elements of this scene in that Beth and Anna are talking about functionality of a representative model and not moving toward creating a working prototype. Nevertheless, this scene should be considered productive behavior and identified as an engineering moment. Creating realistic representative models is an important part of engineering. The next step is recognizing in what ways your model falls short of reality and using this knowledge to create a functional prototype of all or part of the design. As we will see in the next clips, Beth and Anna do not, as a pair, move beyond the representative model to think about creating a functional prototype. The fact that they do not make this transition has important instructional implications for how best to support Beth and Anna at this stage. It is first important to understand why they do not move on to work on a functional prototype, despite encouragement from researchers and teachers.

Different Understandings about Purpose

On the second day of the unit, Beth and Anna have begun to build a representation of their escape system for Rainsford. They were originally given a plastic box in which to store their project and supplies, but they have begun building within the box, using it as part of their project. In the box, they have constructed a tower out of paper cups wrapped in white felt that measures about 12 inches tall. A string comes from the top of the tower down to the side of the box, a height difference of about 4 inches. Anna has spent the last twenty minutes of the work period carefully coloring the string black with a marker. In the following episode, Beth discusses with a researcher her thoughts on the project.

1 Researcher: "So is this your final zip line design?"
2 Beth: This is probably a little mm….. meant to look like what it would look like…We were… we were seeing how it.. works.
3 Researcher: So this is sort of like a model?
4 Beth: It was going to be our final project, but I don't think it's going to be.
5 Researcher: Okay, so what do you want to change about it?
6 Beth: (quietly) A little longer.
7 Researcher: What?
8 Beth: Like, maybe, like, it's a little short. Cause we just wanted to see how it worked and… we don't' know how Rainsford is going to go up and down it.
9 Anna: I don't really…. Get it… because how can we make it longer?

This clip provides evidence that Beth thinks about functionality, specifically how to make a zip line that will really work. Wanting to make the line longer and thinking about how their client is going to go down the line are both valid concerns. Anna, however, is confused about how the string could be longer, given the physical dimensions of the box. This is the first clear evidence that Anna is constrained by her understanding that the two students should be building a representational model as opposed to a working prototype. Given this perspective, her concern is also understandable; how could the string be longer when it would hang over the edge of the box and have nothing to attach to? The time she spends coloring the zip line black also suggests that her focus is appearance, not functionality.

Later in that work period, Beth wonders aloud about how Rainsford could get down their zip line. A researcher shows Anna and Beth an online picture of a person going down a real zip line. Beth is excited by the picture, in particular by the mechanism that attaches the person to the zip line and the fact that the person's hands are not in contact with the line. Beth attempts to explain to Anna what she is thinking about how zip lines work, but Anna looks concerned and says she does not understand. A researcher who has been watching their work period that day attempts to help.

1 Researcher: I think what Beth is trying to say—Beth, tell me if I'm saying this right—is that the real zip line, that you guys saw in the picture, the people don't just hold the zip line, right?
2 Beth: Yeah! (laughs)
3 Researcher: They were sort of holding a string, that went up to this little box, that was sitting on the wire. Do you remember seeing that?
4 Anna: No. (She shakes her head and looks down at the white felt she is working with.)

The researcher attempts to show Anna the picture again, to point out what Beth is observing. Anna is polite but avoids looking at the picture again. It is unclear what prompts her confusion or lack of interest in the picture. It is possible that she is not focused on the way zip lines actually work, so Beth and the researcher's focus on this issue is bewildering. If her focus is on representing the overall system that Rainsford will use to escape (tower to zip line to boat), this close attention to a particular mechanism may not fit into her current thinking. She may also be intimidated by the complexity of the mechanism or the underlying concepts. Beth moves on to work on the mechanism that allows Rainsford to slide down the zip line without touching it with his hands, but both girls continue to keep the entire project within the box and do not explore ideas about the mechanism in other contexts or when considering other materials.

A week later, when Beth is absent, Anna makes decisions that underscore her dual focus on keeping the project within the confines of the box and making it look right, but not necessarily to work in any logical way. First, she moves the little paper boat she has taped to the top rim of the box to the inside the box. She then bends the wire down toward the boat, but finds that it's too long to fit inside the box, ending up in the boat. She takes scissors and snips the wire, so it extends from where it is attached at the top of the tower, over the interior of the box, and stops, hovering in midair, over the boat. Later in the class period, she makes the boat bigger and subsequently cut the wire again so it sticks out only a few inches from the tower. Although she may have been thinking about the system Rainsford would use to escape, taking the zip line to the boat, her design decisions result in a zip line that would not function and that hovers midair in a way that would defy the laws of gravity on a larger scale.

The Nature of Beth and Anna's Engineering Moments

During the course of the project, Beth and Anna exhibit engineering moments that demonstrate their ability to frame a problem, plan, think systemically and maintain a focus on the needs of their client. They create drawings early in the process that they refer to multiple times over the next few weeks. In addition, there is evidence that Beth is interested in how a real zip line functions and in incorporating that knowledge into the design. The two students, however, have very different ideas about the overall purpose of the project. Anna does not understand Beth and the researcher's interest in a functional design and Beth does not push the issue. When Beth returns from her absence and the students present, their "test" for the design consists of pushing a figure down the wire representing the zip line. Though Beth has attempted to alter the design so that it looks more like a real zip line, the overall focus on appearance and limitations on the size of the project leave them with a design that is nonfunctional and therefore untestable. During their final presentation, Beth attributes the failure of the figure to glide down the wire on its own to "friction," suggesting that she is still thinking how to create a workable design given the constraints imposed by the now representative model.

Beth and Anna choose a reasonable problem: get Rainsford out of the tower. They also have a legitimate, feasible solution: make a zip line from the top of the tower. However, there was no consensus on what their project goals were or how they would know whether they had met those goals. They identified an important problem and thought of a creative solution, but differences in their understanding of the task led to a very different result from the "floating shoe" trio. Anna focused on aesthetics, making such their end product looked right. Beth, meanwhile, tried to reconcile the functional inconsistencies between what they were making and a real zip line.

Unlike the "floating shoe" students, there is little sense of a coherent design plan running through Beth and Anna's project. There is evidence of isolated engineering moments, but the girls' unspoken disagreement about the purpose of the project seems to prevent them from building on engineering moments to create a coherent process and working prototype. It is important to note that in any population and any classroom there will be a wide variety of engineering moments and students' ability to knit these moments together into a clear process. Among students with marked learning difficulties and potential difficulties thinking abstractly, differences in students' skills and approaches to the task will likely be at least as varied as in a typical classroom. As teachers work to develop students' engineering skills and their ability to think about solutions, plan, create working prototypes and develop logical tests for their designs, they will likely need to be responsive to students' different approaches to the task.

Dylan and Sam struggle to engineer

The third group, Dylan and Sam, struggled greatly with the engineering challenge. They had few, if any, observable engineering moments. This caused the teacher, Colin, to focus much of his attention on this group, transforming the essence of the unit so it was no longer open-ended design. Below is a brief clip from their first brainstorming period, during which they decide to build a submarine that Rainsford can use to escape the island. Though a submarine may be a feasible solution that could result in some sort of working prototype, the students' initial conversations interactions with their teachers lead them to unrealistic and even magical thinking. (This phenomenon has been observed in multiple classrooms with students of different ages and skill levels). Here, Colin attempts to refocus their energies on a more feasible solution:

1 Colin: Here's my question. Remember, you're going to be building this solution.
2 Dylan: Yeah. We can build a submarine!
3 Colin: But submarines already exist. What makes this submarine specifically useful for Rainsford?
4 Sam: Because it's invisible.
5 Colin: You can't make it invisible.
6 Dylan: When it touches water, it turns to color, but when it goes in the air, it's invisible.
7 Colin: How are you going to make that? How is that possible?
8 Dylan: It's right here, it's invisible!
9 Colin: No, it doesn't work like that.

Colin has a number of similarly unproductive exchanges with Dylan and Sam, eventually leading him to encourage the students to build a "floating car" from a kit. The resulting project becomes closer to a wooden puzzle than a true engineering design.

Before Colin intervenes, there are hints that Dylan could have gotten to some engineering moments. At one point, he expresses a design plan for a "floating car" to help Rainsford escape off the island. His orientation to this possible solution is not stable, however, and Colin's attempts to support his thinking may in fact move Dylan away from his original idea.

1 Colin: Are you re-doing the base (of the car)?
2 Dylan: Yeah, this is the base.

3 Colin: What are you working on?
4 Dylan: Making it float.
5 Colin: Can I show you guys something? (gets out a wooden car that he has built)
6 Dylan: Yeah we were going to add wheels like that once this is done.

Dylan seems to have a construction plan for a few moments. He is creating a floating platform, and then plans to attach wooden wheels onto the base. While this may seem more like tinkering or play than engineering, it shows that Dylan was on task, focused on the project, and thinking about how to make his design idea work using available materials.

Since the seeds of interest were evident, it leads to speculation about why their project never reached its full potential. Once Colin took a more active role in the project, Dylan and Sam appeared to cede all autonomy and only responded to requests from Colin. The pair's difficulty could have stemmed from a combination of misunderstanding, difficulty managing the multiple facets of the task, and the lack of a space to tinker and rethink their design, in other words, to try and fail. This case suggests that this particular group may have needed different kinds of support than were offered to them. The teacher was supportive, positive and worked hard to help the students create a successful project. It is indeed possible that it was important that these students have a sense that their first engineering project led to a successful outcome. It is also possible that letting them spend more time on their submarine idea, encouraging them to try out ideas and respond positively to failure, and letting them get feedback from peers may have allowed them to experience true engineering moments. We do not wish to underestimate the potential difficulty of this balance for teachers—discovering how to provide adequate support for students while still leaving them with sufficient autonomy, autonomy that is crucial for all students engaged in open-ended, creative design activities.[9]

Discussion

Addressing Research Question 1: What characterizes *engineering moments* for small working groups of middle school students with LBLD?

This paper has identified and described in detail multiple engineering moments among this group of students with language-based learning disabilities during their first engineering project. Many of these student designers with very little engineering design experience demonstrate capabilities to engage in productive engineering moments. These engineering moments were characterized by a clear attention to the client's needs and the constraints of the setting. Both the "swamp shoe" and "zip line" groups developed useful problem scenarios based on events in the story The Most Dangerous Game. In addition, there is evidence that most of the students in these two groups interpreted the purpose of the task as the creation of a device that would be helpful to Rainsford in the story and that would work in the real world. Though Elise, Claire and Tom were the most consistent and successful and working in this direction, Beth also attempted to think about how zip lines work in the real world and incorporate this information into her project. Finally, both of these groups exhibited key engineering behaviors without specific prompting from the teachers. For example, Beth and Anna (zip line group) used multiple methods of planning, like drawings and discussion, to develop ideas and communicate their problem and solution ideas to each other and the researcher. Elise, Claire and Tom (swamp shoe group) engaged in meaningful testing and evaluation throughout the unit.

This study has provided evidence that when given the opportunity, many students with LBLD utilize the story context to meaningfully drive an engineering design activity with minimal direct support from instructors. It is even possible that these students may benefit from open-ended engineering units even more than students without learning disabilities, since these projects provide a unique opportunity for students to practice difficult skills in a supportive setting, while engaging in a motivating project. As one of the teachers noted:

> *"For our kids, getting past the decoding can be a big challenge and discussion of the text is often impacted by these obstacles. By taking part in the engineering project, many gained a much deeper understanding of everything from character motivation to the author's use of visual imagery because they found themselves in the position of designing and redesigning for the characters. By requiring the students to identify with the protagonist and the antagonist, the process immersed them in the details and moods of the story in a way that was previously unreachable for most."*

If text-based engineering projects can function as both a support for reading comprehension and a support for the design process among students with reading difficulties, it is possible that these projects would support the development of these skills among a diverse general classroom population.

As observed in Dylan and Sam's project, however, it remains unclear whether this kind of project would provide a similarly productive experience for all students. Dylan and Sam, for example, may have been overwhelmed by the multiple dimensions of both the story and the design process. Though their initial idea, a submarine, had promise, they did not focus on a particular solution and relied on one of their teachers to provide them with direction at each step of the process. It is possible that Dylan and Sam struggled to fully understand the literature or did not fully understand the purpose of the engineering, which made this an especially difficult task for these two students. In this case, ensuring reading comprehension, giving discrete design steps with built in supports, and adding instructor help when the group got stuck could have been important. However, it is also possible Dylan and Sam surrendered their autonomy because of what in most cases could be considered helpful support by a caring instructor. Perhaps Dylan and Sam would have benefited from messing about with the materials, getting input from peers, and navigating the project in their own way. This approach, however, would have risked frustrating these students or leaving them with a sense of failure if their design did not function. This raises an important question for future study: how does the type of teacher support impact student design? What is an appropriate balance between student autonomy and adequate support?

Addressing Research Question 2: How are these student groups' *engineering moments* related to each other? Are individual moments disconnected from each other, or are these moments coordinated in some way to create some sort of coherent process?

Evidence suggests that Elise, Claire, and Tom's engineering moments were connected through a focus on the specifics of the problem space and on consistent evaluation criteria. These criteria, which the group generated during their first brainstorming session, were not directly requested by the instructors, but were self-initiated by these three students. The group refers back to their three performance goals -- floating in the swamp, waterproofing, and not leaving a trail --

throughout the project, and all agree on a desired outcome. This suggests they reached an implicit consensus on the purposes and goals of their project, as well on the importance of determining a reasonable test. The consensus that their goal was to make something that would help Rainsford but that could be made and tested in the real world appears to have knit their engineering moments into a somewhat coherent engineering process that forms a nice experiential foundation for future engineering work.

In Anna and Beth's case, there is evidence of multiple, productive engineering moments, but they these engineering moments were not coordinated into a coherent engineering process, nor did they produce a testable or even logical model. While Beth seemed to be pushing for a working prototype, Anna was more concerned with creating a reasonable representation of the problem and solution scene. She constrained their project to the size of a particular plastic box and in the end sacrifices technical legitimacy for appearance and for fitting all elements neatly in the box. Because of the lack of consensus about the purpose of the task, these students' engineering moments do not ultimately cohere into something resembling an engineering process. Despite some promising engineering moments at the beginning and Beth's interest in the mechanism of real zip lines, the two girls ultimately focus on producing a representational model and do not move beyond that to build a working prototype of any element of their escape narrative.

Future Work

More research needs to focus on young students engaging in engineering design, including those with and without learning disabilities. It is unclear, for example, whether the limitations of student projects were due to their inexperience, missed instructional opportunities, or both. The final design prototypes produced by both groups were not what adults would consider sophisticated. Elise, Claire and Tom's creation looked like what it was, a great deal of bubble wrap formed into the shape of a giant shoe and covered with tape and plastic bags. In addition, they did not research a way to make a good analogue quicksand with which to test their "floating shoes." Beth and Anna did not build a workable zip line either in the model or to scale.

Future study should include evaluation of different types of instructor intervention at points when the design seems stalled or off course. For example, in the case of Elise, Claire, and Tom, an instructor could have discussed with the students how to create similar conditions to quicksand to see if the shoes really would support a person in the environment portrayed in the book. Instructors could have worked with Anna to understand the distinctions between what something looks like and how it works. Perhaps at some point an instructor could have declared their model "finished" and asked them to create a zip line that was closer actual size in order to explore different mechanisms. Dylan and Sam may have needed a different kind of support from the instructor. Rather than steering the pair to a more feasible and workable solution, an instructor could have asked questions about their thinking, helped them with mundane tasks like cutting cardboard and tape, and emphasized that the goal was to make something that would work in the classroom. Videos or pictures of submarines or amphibious vehicles may have helped, as may have questions about which materials would stay together in the water. That said, showing Anna a picture did not help her process, perhaps because it did not fit with her goals and her understanding of the purpose of the project at that moment.

This group of students benefited from having an extremely small class size of 9 students (when no one was absent) and generally three to four instructors and researchers in the room to provide support and help find materials. This scenario allowed the instructors to take on advisor roles, consistently following the progress of each group. Ample time for feedback from adults and peers may have been helpful in prompting the students to think about their design problems more deeply, though in some cases it may have allowed students to cede their autonomy and rely too heavily on a teacher. In classrooms where this type of ratio is not possible, it may be possible to create a similarly supportive environment using a combination of teacher and peer advisors, parent volunteers, and multiple group sharing opportunities. In addition, other ways to encourage students to reflect on their engineering work should be considered. Technological supports like tablets may allow students to monitor and reflect upon their process as they document and annotate their process using photos, videos, and captions. Only by looking carefully at the journey students take in pursuit of a design solution and supporting this journey using human and technological supports can we realize students' power to engineer.

This paper has only begun to explore the concept of engineering moments. Further research must be conducted to understanding how to identify and describe these moments and to understand the conditions under which these moments cohere into a clear design process. Additional case studies conducted with groups of students with and without learning disabilities would be helpful in understanding the nature and variety of engineering moments as well as the way students' understandings of the task affect their activities. Future work should include studies with larger sample sizes and the implementation of a coding system to categorize engineering moments to learn more about how and when students coordinate engineering moments into coherent design processes. However, rich description of individual student experiences is important for both researchers and instructors. As evidenced by the three cases cited in this paper, even a small group of students can exhibit a wide range of engineering moments and distinct interpretations of the task. Detailed descriptions of these experiences will be beneficial to teachers and researchers by helping them understand the nuances of student learning and the variety of student experiences.

Continued research in this area could lead to more responsive teaching of students engaged in K-12 engineering, including the recognition that each student is working to make sense of the task and is attempting to apply their skills and knowledge to the project. Building on students' motivation, understandings and fledgling engineering moments may be a more productive approach to teaching engineering than assigning general tasks and using general assessments. In other words, attempting to meet students where they are, recognizing engineering moments, and helping them to link engineering moments into coherent processes may be the best way to help them act like real engineers.

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