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Dimensions of Experienced Responsive Teaching in Engineering

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Introduction

Responsive teaching is an instructional approach in which teachers base their pedagogical moves and objectives on what their students are doing and saying.[1,2] Instead of pre-determining an entire lesson or unit trajectory, teachers *elicit* students' thinking around a topic, *notice* and *interpret* productive aspects of their thinking, and *respond* to support their disciplinary work. Describing this approach in science classrooms, Hammer, Goldberg, and Fargason write:[1]

> "A responsive approach [to teaching]… is to adapt and discover instructional objectives responsively to student thinking. The first part of a lesson elicits students' generative engagement around some provocative task or situation (or, perhaps, by discovering its spontaneous emergence). From there, the teacher's role is to support that engagement and attend to it — watch and listen to the students' thinking, form a sense of what they are doing, and in this way identify productive beginnings of scientific thinking." (p. 55)

There are several proposed benefits to responsive teaching. First, this approach builds from constructivist learning theories in that the resources and experiences students bring to the classroom are the basis for building new knowledge.[3,4] Furthermore, empirical studies in mathematics and science show that this approach can improve students' conceptual understandings.[5,6] Notably, this approach has also been shown to support students' engagement in disciplinary practices in mathematics and science.[7-9]

We argue that responsive teaching can be a particularly useful approach for teaching engineering design; the changing criteria and constraints of open-ended problem solving inherently require teachers to be responsive to students' changing needs. However, while responsive teaching is becoming an increasing focus of mathematics and science teacher professional development,[2,10,11] it has not yet been a focus in engineering education. Furthermore, while there are similarities between engineering and mathematics or science, the different disciplinary goals and practices—as well as teachers' perceptions of these disciplines[12]—warrant further work into what responsive teaching looks like in engineering and how teachers begin to take up this approach.

A prior study from our research group examined one aspect of responsive teaching—what teachers noticed about their students' engineering work—with teachers new to engineering.[13] In individual interviews with researchers, elementary teachers watched videos of students engaged in an engineering task and discussed what they noticed about the students' work. What teachers noticed fell within four themes: social dynamics in student groups, students' engineering solutions, students' thinking, and the teacher's role. Furthermore, the researchers asked these teachers how they would respond to the students in the video. Teachers saw their role in responding as either providing engineering knowledge, empathizing with the student perspective, or directing the students' work.

We believe that these themes represent productive beginnings of responsive teaching in engineering. However, this research did not characterize what more experienced engineering teachers notice about students' designing. Our current study is motivated by the need to describe what a responsive teaching approach looks like in engineering and how teachers might enter into this approach. Our study is also intended to highlight some of the challenges that teachers face in responsive teaching in engineering.

In this research study we analyze interviews with six elementary teachers who had at least two years of experience with Novel Engineering, an approach to teaching engineering design developed at Tufts University that uses narrative texts as the basis for design problems.[14] In these semi-structured interviews we discussed the implementation of Novel Engineering in their classroom and showed them a short video of some of their students working on the project. We asked teachers to reflect on these students' work, drawing on the video and their recall of the activity in class. We analyze these interviews to address two research questions:

> *In what ways did experienced teachers notice and interpret disciplinary aspects of their students' engineering design?*
>
> *What challenges do teachers describe in responding to their students' engineering design work?*

Study Context

This research study is part of a large-scale, six-year project designed to help elementary and middle school teachers integrate engineering into their literacy lessons. In this project, called Novel Engineering, students use classroom literature such as stories, novels, and nonfiction texts as the basis for engineering design challenges.[14] Students take on the characters in the book as clients and design solutions to problems that the characters face. In doing this, they consider the constraints of the characters, asking themselves "What would this character want in a solution?," and the constraints of the classrooms, asking themselves "What can we build using the materials available here?" We have found that this approach benefits students' learning in both engineering and literacy.[15] Students engage in an engineering challenge that has a client and constraints to address, mimicking a real-world engineering problem. And, to be able to address the client and constraints in their engineering solution, they engage in literacy practices to develop a deep understanding of the text.

Many teachers do not have a background in engineering as they start their first Novel Engineering project. Therefore, we have developed a professional development model to support teachers in creating and leading activities that give students the opportunity to engage in the disciplinary practices of engineering. There are three components to our model. First, teachers participate in several design challenges, including a Novel Engineering activity, to gain personal experience with engineering. They spend time reflecting on their experiences after each design challenge. Second, teachers watch and discuss videos of students' activities in prior Novel Engineering projects to see what engineering can look like in classrooms and to help them notice disciplinary aspects of students' thinking. Lastly, teachers plan Novel Engineering activities for their classroom, which includes anticipating possible student questions and challenges and considering potential responses. These three components all serve to support a responsive teaching approach by helping teachers think about eliciting, noticing, and responding to their students' engineering.

Methods

The second author and two graduate students conducted semi-structured interviews with six elementary school teachers from two different schools (Table 1). All teachers and students are referred to by pseudonyms in this study.

Table 1. Six elementary teachers from two schools with experience in Novel Engineering (NE) participated in the interviews analyzed in this paper.

	Teacher	Grade	NE Experience (years)	Book Used in NE Activity Discussed in Interview
School A (Rural)	Allison	4	2	*Number the Stars* by Lois Lowry
	Charlotte	3	2	*America's Champion Swimmer: Gertrude Ederle* by David Adler
	June	5	2	*City of Ember* by Jeanne Duprau
	Ross	5	2	*City of Ember* by Jeanne Duprau
School B (Suburban)	Kendra	4	2	*Tuck Everlasting* by Natalie Babbit
	Molly	4	2.5	*The Trumpet of the Swan* by E. B. White

The protocol for the interviews can be seen in Appendix A. At the time of the interviews (June 2013), all teachers had at least two years of experience with Novel Engineering. All of these teachers participated in a weeklong professional development workshop during the summer of 2011. After this initial workshop, members of the research team from Tufts University continued to work with these teachers, meeting monthly during the 2011-2012 and 2012-2013 academic years and visiting the teachers' classrooms to observe their implementation of Novel Engineering activities. During these visits the members of the research team would talk with the teacher about what they were noticing about their student's engineering and literacy work and what might happen with different pedagogical moves.

In the June 2013 interviews, the members of the research team first asked the teachers to reflect in general on a recent Novel Engineering design challenge their students had completed in class. Then, the teachers viewed a short video of some of their students working in class and discussed these students' work with the members of the research team. We selected clips that showed students working on-task and engaging in aspects of engineering design. These clips highlighted student-student interactions were contained to less than five minutes in length.

As an example, the short video shown in Molly's interview featured two students, Jacob and Anthony, choosing a problem to solve from the book *The Trumpet of the Swan* by E. B. White. In this novel, a mute trumpeter swan named Louis learns to use a trumpet to communicate and impress a female swan. Jacob and Anthony had individually brainstormed solutions to multiple problems prior to the video segment, and have now come together to discuss which problem they want to solve as a pair (Figure 1). The video shows Jacob and Anthony bringing up each possible problem, discussing their initial solution designs, negotiating which story and classroom constraints their solution must satisfy, and rejecting possible problems when they cannot think of a feasible solution that meets all the constraints. The following transcript is taken from the first part of the video shown to Molly. The transcript of the entire video shown to Molly can be seen in Appendix B.

Figure 1. Jacob and Anthony discussing problems they wanted to solve together, referring to solutions that they had brainstormed and written on sticky notes.

Jacob: So I have an idea for, um, the raft idea.
Anthony: Let's- let's just narrow it- Let's do this first.
Jacob: I have a- I was thinking we could use a water bottle.
Anthony: Oh and it would float around? Then how would they steer it?
Jacob: Ding ding ding! Paddle.
Anthony: But I don't know if a- the swan can paddle.
Jacob: Oh, true.
Anthony: But that's a good idea. Okay, let's try swimming first. Let's come- What do we have for swimming?
Jacob: We have the- this
Anthony: Bike pedal, and my, thing.
Jacob: And my- and the thing I'm making right now but-
Anthony: I have- like a wall around it maybe with some video cameras and stairs and a bear trap.
Jacob: Well, the thing is, we have to *make* these kind of things.
Anthony: So, like, protect nest, out of the question.
Jacob: I was thinking we could use a dome like, out of like um- You know I don't know what to make it out of but, a dome.
Anthony: Let's not- let's not do protect nest.
Jacob: Yeah okay so that's out.
[Jacob rips sticky note with his idea for a nest protector.]

The teachers commented on things that they noticed in the video, but the conversation ranged beyond the short clip that was shown. The teachers discussed aspects of the students' thinking and behavior based on what they recalled from the class. The interviews ranged in length from 27 to 42 minutes.

Data Analysis

The primary source of data used in this analysis was the transcripts of interviews. We also consulted, but did not systematically analyze, a number of secondary data sources to check assumptions about the context of what teachers were saying in interviews. These included the original videos of interviews, field notes from classroom observations of these teachers, video data from classroom observations of student teams, and field notes from the professional development workshops in which teachers participated. As we prepared to analyze transcripts, we reviewed prior literature on responsive teaching, including our research group's prior study of interviews with teachers new to engineering,[13] and literature on how to characterize the disciplinary components of students' work.[16] This gave us a definition of responsive teaching—eliciting, noticing, and responding to the disciplinary substance of student ideas and practices—and prior work upon which to base our analyses.

Our analysis of the interview transcripts followed a systematic, iterative process based on methods of grounded theory and constant comparative analysis to look for themes and patterns in what teachers said about the videos and their teaching.[17] Analysis proceeded in three rounds. In the open coding round, all three authors read all interview transcripts and made note of instances when the teachers noticed an aspect of student ideas or practices and appeared to interpret it in a disciplinary manner—that is, with attention to the ways in which student ideas or practices were engineering-like in nature. We then discussed our notes and combined our initial codes into a list of possible categories of disciplinary noticing. In our second round of analysis, the first author used the constant comparative method to combine categories that referred to the same kinds of noticing. For the third round of analysis, the first author used these categories to analyze the full set of interview transcripts again. Categories were used to code either a single turn-of-talk by a teacher, or an exchange of turns by the teacher and interviewer. The second and third authors reviewed all coded excerpts and approved the applied codes. Finally, we grouped together all excerpts from across different teacher interviews coded within a single category to create a "flight" of data.[18] We reviewed and discussed the flights in order to elaborate on the definition of the category. These categories and their definitions are the themes we present below.

Findings

Teacher Noticing and Interpretation. Four themes emerged from our analysis of teacher interviews. We found evidence of teachers noticing how students 1) framed (or interpreted) the project, 2) engaged in the engineering design process, 3) exhibited informed designer patterns, and 4) communicated with each other in ways that supported their engineering. In this section we step through each of these themes in turn, providing evidence from the interview transcripts.

To provide continuity across all four themes, we focus primarily on the interview with Molly. Molly was the pilot teacher for Novel Engineering, and had the most experience with the program. She also displayed evidence of all four of these themes in her interview. To reinforce that these themes were discussed by multiple teachers, we support each finding with evidence from other teachers' interviews. This also adds depth to the discussion, as teachers often noticed different aspects of student thinking within the same theme.

How Students Framed (or Interpreted) the Project. For many elementary students, Novel Engineering projects are the first time they formally experience engineering design in school. Therefore, in examining student work our research team[20] has emphasized the importance of how students interpret what kind of activity they're engaged in—how they *frame* the engineering tasks[21,22]. For example, we have found that some students can interpret a Novel Engineering challenge as an arts and crafts project, in which they focus on decoration at the expense of functionality, or as an opportunity to provide correct vocabulary for the teacher; or as a collaborative endeavor to design functional solutions for a fictional client.

McCormick characterizes three different framings of a Novel Engineering project, in which students foreground 1) the story and the characters, 2) classroom norms and teacher expectations, and 3) the process of making and testing artifacts.[23] She notes that students' framing is not necessarily stable for the entire activity; they may juggle multiple framings simultaneously and/or they may shift between framings. In her analysis she highlights how students can coordinate their attention to characters, classroom requirements and norms, and functionality to support their engineering.

Our teachers similarly noted when students were foregrounding different aspects of the project. For instance, Molly pointed out how Jacob and Anthony assessed their ideas based on the abilities of the swans:

> Molly: There was one point also where they were doing, like, the raft, and Jacob's like, "So, we could - It would float on water bottles," and Anthony was like really excited about it, and then he goes, "Well but, how would it turn?" He's [Jacob's] like, "Well, maybe oars," and he was, like, all excited that he came up with oars, and then Anthony was like, "Yeah, but they're swans. How are they gonna hold an oar?" And Jacob's like, "Yeah, you're right."

In this interaction that Molly recalls, Anthony and Jacob were scoping one possible problem to solve—helping the swans to swim. She notices that they were negotiating the constraints that their solution would have to solve, and they both implicitly agree that the solution must work for their client, Louis the swan. It would certainly be possible for Anthony and Jacob to satisfy only the classroom constraints and build a water-bottle boat with oars; however, they hold themselves to the constraints imposed by the story.

Other teachers noticed when students were considering the constraints of the classroom and discussing what they would be able to physically build and test themselves:

> June: I like how many different ideas they came up with before they actually picked one that they thought they could do with what they have. So it was nice to see them thinking about, "Well, this is what we have available, what can we do with it?"

Finally, Molly noticed a time when her students were simultaneously considering the constraints of the story and the classroom.

Molly: What I've noticed with a lot of the clips of the brainstorm is they always were like, "Well it has to be something that we, like, we can find in nature, we can find…" And I feel like, I feel like I- I don't know, but I don't think I emphasized, like, over-emphasized that.

Interviewer: Yeah.

Molly: And yet that's something that they feel really strongly about, and to me that means they must really be thinking through the book, because they know they can't just be like… Like- We can't just find a magnet and just turn it into electricity. And that's one of those things that they- once they realized that they actually couldn't do that in the classroom maybe they wouldn't be able to do that, you know, in real life. But I like that um, how- I like that they were like, "Well, you might find a cup floating around, but you wouldn't find you know, this, this, or this."

As Molly indicates, students' consideration of both framings reinforced each other and helped students to construct their overall conception of how their solution should function. The students began by considering the story, and then realized that developing a solution that respected the constraints of this particular story would inherently lead to a solution that would function in the classroom. Molly's observations reflect the findings of McCormick, in that she notices how students' coordination of these different framings supports their engineering work.[23]

How Students Engaged in the Design Process. Teachers become familiar with the engineering design process through Novel Engineering professional development, both by engaging in engineering activities themselves and in planning a Novel Engineering activity. While there are multiple conceptualizations of the engineering design process, the main components include defining and scoping problems, designing solutions, and testing and refining these designs. We found that most teachers talked about and valued how their students participated in this process.

In Molly's interview, she recalled that a pair of students in her class had settled on solving the problem of helping the cygnets (young swans) to fly:

Molly: Like who needs to put a brace on a swan's wing? The swan is meant to fly, and yet, they had so much fun, and they had such great experiments, and they had trials.

In this quote, Molly first remarks on a challenge to her students' design, namely that they haven't considered that the swans will learn to fly on their own. However, she identifies that these students are testing and iterating upon physical prototypes of their brace, valuing their engagement in the design process.

June also commented on how students in her class tested their idea for a waterproof candle with a physical prototype.

> June: Um, but I was just asking them, "Well why, you know. What's with the water bottle?" and they, "Well, we're trying to make it so that the candle they have doesn't get wet, so they can move, and…" Um. So they were really excited so we ended up going and finding, um. We got a clay and a candle, like a birthday candle, and stuck it in, and so they were able to actually walk around and test, you know, let the wind get in there, and it didn't. They were very excited about it. I mean they walked around with that thing for like ten minutes.

June describes how these students did not just want to test their idea because it was required for their assignment; they were excited to engage in the engineering design process and see how their physical prototype functioned. June's comments indicate how she valued their engagement in this activity by helping them to find a candle they could use in their test.

How Students Exhibited Informed Designer Patterns. In addition to outlining what it means to engage in the design process, researchers have examined what both beginning and experienced designers do at different phases in the design process. Summarizing this work, Crismond & Adams' Informed Design Teaching and Learning Matrix outlines differences between how beginning and informed designers typically address each phase of the engineering design process.[16] For example, Crismond and Adams note that when generating ideas, beginning designers typically practice idea scarcity—working with a few ideas on which they can become fixated. On the contrary, informed designers typically practice idea fluency, in which they use brainstorming and divergent thinking to ensure they are working with many ideas. While Crismond and Adams make the claim that children are included in their framework as beginning designers, their classification is primarily supported with research on undergraduate[24,25] and professional engineers[26]. Other research has pushed on the characterization of children as beginning designers, finding evidence that students engaged in open-ended problem solving can demonstrate behaviors that Crismond and Adams classify as informed designer patterns.[19,27] Beyond Crismond and Adams' classification of informed designer behaviors, McCormick and Hynes described children engaging in another informed designer behavior that is not captured in the Informed Design Teaching and Learning Matrix—students relying on and using their own "lived experiences" to navigate an ill-defined problem spaces.[15]

Although the Novel Engineering professional development did not address these designer patterns, we found that the teachers in our interviews noticed similar aspects in their students' work. The teachers did not just notice that students were engaging in a particular phase of the engineering design process (as the previous section discusses); they noticed student behaviors that resembled informed designer patterns within that phase. For example, similar to Crismond and Adam's description of how informed designers "represent ideas," Molly described how Anthony and Jacob deeply inquired about the design and functionality of their solution and its interface with the client. She also commented on the way they communicated and explored these design ideas, pointing out how they spent time writing and drawing ideas on sticky notes and remarking that she liked "how they almost storyboarded or, like, came up with all these ideas."

Other teachers also noticed informed designer patterns in their students. In a quotation presented earlier in this paper, June noticed how students in one group practiced idea fluency (Crismond and Adams' Pattern A: Understand the Challenge):

> June: I like how many different ideas they came up with before they actually picked one that they thought they could do with what they have. So it was nice to see them thinking about, "Well this is what we have available what can we do with it?"

Charlotte noticed how students in one group responded to her feedback and iterated on their solution in a meaningful way (Crismond and Adams' Pattern H: Revise/Iterate):

> Charlotte: They had a finished product at the end of the first day that they could have shown the group. They had the most functional at the end of the first day, like, they had a solid idea, they never really strayed from it. But they made appropriate changes based on what I was saying. Like, they listened, even though they thought they were done. They were still able to, as a group, listen to the questions that I had asked and make adjustments to make it even better.

And lastly, Ross noticed how students in one group used their learned experiences in designing a solution for the open-ended problem presented to them:

> Ross: They must have some kind of background knowledge. They must have seen, you know, boats being loaded into water or something like that. Because the process is somewhat similar to getting boats into the water. So I think one of them could have had a good amount of background knowledge.

How Students Communicated in Ways that Supported the Engineering. In the earlier paper examining interviews with teachers new to engineering, one of the main findings was that teachers often noticed the social dynamics in the student groups, particularly whether or not the students were "working well together."[13] With our more experienced teachers, we also found that they attended to how students were communicating with each other, but their interpretations of these interactions often included aspects of engineering design practice.

In one example, Molly discussed how Anthony and Jacob engaged in productive problem scoping together:

> Molly: I like that they questioned each other, and that they both accepted the question, and they're like, yeah… And that's another thing with parameters is that they didn't just say, “Well, we could just, I mean we could just say, like maybe they could hold it in their beak.”
>
> Interviewer: Exactly.
>
> Molly: They really were like, “Yeah, that's a good question, and you know what - you're right about that. Let's let that one go,” and I really like that they were able to do that.

Molly is not just noticing that Jacob and Anthony are communicating well; she is attending to the *disciplinary aspects of their communication*. She points out how the students questioned each other—and accepted each other’s questions—to hold themselves accountable to design criteria. In other parts of the interview, she notes that Jacob and Anthony first gave each other an opportunity to share their initial solution ideas before questioning whether they will work. She observed that this allowed Jacob and Anthony to build upon each other’s ideas so that they could collectively brainstorm potential solutions that they can solve as a group.

Charlotte also noticed disciplinary aspects of her students’ collaborations**.** In response to the interviewer asking her what kinds of discussions get her excited, Charlotte stated:

> Charlotte: Um, kids who are disagreeing almost, like, I like hearing them politely disagree like, “That might not work but we can try this instead.” You know, piggy backing on each others ideas, um, making everyone feel heard.

Charlotte notices that her students were disagreeing in ways that were productive for her students’ engineering: by listening and respecting each other’s ideas even when they disagreed, and then suggesting further iterations that built upon those ideas. In this, they were able to refine their engineering solution to a problem.

Challenges in Responding to Students’ Engineering Design. In addition to discussing noticing and interpreting students’ engineering design, many teachers also discussed how they responded to their students’ work and challenges that they faced in determining the best response. One common challenge was how much to push students with their responses. For example, when teachers noticed that students were engaging in part of the engineering design process and neglecting another part, they questioned whether they should do something about this. Molly commented on this tension in her interview, before she noted how students were engaging in the engineering design process (a quotation presented earlier in this paper):

Molly: So that was one of those things where I was like, well, do I want to kind of push them into a different problem that's gonna affect the book more? Or is this something that, I mean it's- It's still gonna give them an opportunity to do some writing about it. They're still gonna get to engineer. So I mean I guess if I wanted to really make a difference in that, I would have to say, not only does it have to be a problem that engineers solve, but it has to affect the book, it has to change something in the book.

Interviewer: That's interesting.

Molly: But I don't really know if that's necessarily something that I value, because I thought that's something I valued, but I feel like some of the ones that were really successful... Like who needs to put a brace on a swan's wing? The swan is meant to fly, and yet, they had so much fun, and they had such great experiments, and they had trials.

Teachers also reflected on times when they had responded in a particular way to students, and questioned whether they made the right decision. Kendra reflected on an interaction she had with a group, whose originally-proposed solution featured a magical component that would hypnotize an intruder:

Kendra: I'm like, "Oh, I wonder if they went with that and researched hypnotism if they could've made something."

Interviewer: Mhm. Like a strobe or something.

Kendra: Yeah. I mean that's something I'd like to do for next year, kind of focus more on the research aspect of it.

[Kendra and the interviewer discuss another group who researched a potential solution.]

Kendra: But looking at this now, I'm like, oh they [the students designing the solution with hypnotism] were really excited about the idea because it was more into the science engineering. I really did kind of shoot them down. I'm like, "Okay well, there's no technology for that, so what can you do?"

After this interaction with Kendra, the students did indeed abandon their hypnotism idea and created another solution for the same problem that was, in Kendra's opinion, an "average" solution. During her interview, Kendra reflects on how much she may have influenced the students' final product:

Kendra: So I would say theirs is kind of an average, kind of middle of the road, you know, project. Where there wasn't as much creativity involved.

Interviewer: Okay.

Kendra: But that could be because their first idea, you know, I cursed [sic] them to kind of think more about it and they couldn't think about how it's connected to science.

These reflections show that crafting a response to aspects of students' engineering design is challenging and can have unintended consequences, even when teachers have experience with engineering programs and are confident that they have the ability to notice and interpret students' engineering design activities.

Discussion

These findings suggest that teachers with no formal background in engineering can notice disciplinary aspects of their students' engineering design. While we focus on what teachers notice in video interviews, we believe these findings show promise for teachers flexibly responding to their students' work to support their engagement in engineering design. Once teachers can notice disciplinary aspects of students' engineering design, they can actively work to promote these in class. This will give elementary students experience with the open-ended problems of the engineering profession and the actual strategies that engineers use to solve these problems. Students gain an appreciation for engineering as rigorous, informed problem solving, rather than simply arts and crafts or the application of mathematics and science. Framing engineering this way may interest more students in engineering as a future career, particularly those who are interested in problem solving but do not believe they are good at mathematics and science. Furthermore, when elementary students are exposed to the disciplinary practices of engineering they can develop technology and engineering literacy, understanding how the technological, human, and natural components of an engineering problem all affect each other.

The findings from our interviews have implications for professional development. Most professional development programs in engineering design focus on increasing teachers' content knowledge and introducing engineering curriculum.[29] Our findings suggest that teachers need to also be prepared to assess and respond in-the-moment to students' engineering design. During Novel Engineering professional development, teachers watched classroom videos and interpreted student thinking in engineering, building on work in mathematics and science.[30-32] By working with other teachers to identify productive aspects of students' work, they practiced noticing students' engineering outside of the chaotic classroom environment. We argue this is a critical component in preparing teachers in engineering design. With this support, all six teachers we interviewed were able to notice and interpret disciplinary aspects of their students' engineering design.

Despite teachers' progress, we observed that they still encountered challenges in responding to students. This leads to two recommendations for professional development that supports responsive teaching in engineering. First, professional development should address the full spectrum of responsive teaching—eliciting, noticing, and responding to the disciplinary substance of student ideas and practices. In addition to talking about how to design engineering design tasks, we suggest professional development programs should also present opportunities for teachers to anticipate possible student questions and challenges and how they would respond. Second, our findings suggest that professional development should be continual, rather than a single session. Responsive teaching takes practice; even teachers with two years of Novel Engineering experience had questions about how to respond to their students. Professional development facilitators should follow up with teachers as they begin doing engineering activities. One suggestion is to ask teachers to videotape engineering challenges their classrooms to review students' thinking, to notice the beginnings of engineering design practice, and to consider different possible responses.

Conclusion

In this research study we analyzed clinical interviews with six elementary teachers who had at least two years of experience with an engineering program to show the ways in which they noticed and interpreted disciplinary aspects of their students' engineering design. Specifically, we found evidence of teachers noticing how students 1) framed (or interpreted) the project, 2) engaged in the engineering design process, 3) exhibited informed designer patterns, and 4) communicated with each other in ways that supported their engineering. Teachers also reflected on the challenges of selecting a response, such as wondering how much to push their students or how particular responses they made had affected their students' engineering activities.

In addition to describing these dimensions of teacher noticing, we hope to motivate increased attention to responsive teaching in engineering design and the need for continued research on this approach. While this study focused on teacher interviews, we need to better understand and characterize what responsive teaching in engineering design looks like in classrooms. For instance, in math and science, researchers have developed coding schemes for analyzing responsive teaching[6] and have described particular pedagogical moves that teachers used to advance students' ideas[27]. We are beginning this work by studying in-depth cases from elementary classrooms and from our own teaching.[33,34] Furthermore, while there is research showing the positive benefits responsive teaching has for students' math and science learning,[5-9] we need to examine the effect that responsive teaching has for students as they learn engineering design.

As we develop characterizations of responsive teaching in engineering and study its impact, we also can examine how teachers enter into and progress in a responsive teaching approach. In our work, we are starting to investigate possible trajectories that teachers follow as they become better at responsive teaching in engineering.[35] This research will help inform our understanding about how professional development can support and cultivate teachers' abilities to notice disciplinary aspects of their students' engineering design.

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Appendix A: Questions for Video-Based Interviews with Novel Engineering Teachers

Part 1. Your Novel Engineering Approach

The first thing we'd like to talk about is your general Novel Engineering approach.

1) When you're walking around the classroom while students are working on Novel Engineering projects, or looking over their work, what would you say you're hoping to see?

2) How would you say you generally interact with students while they are working on Novel Engineering projects?

   a) How about when you DON'T see what you're hoping to see?

   b) How about when you DO see what you're hoping to see?

3) How do you assess or evaluate Novel Engineering student work, if at all?

Part 2. Noticing the Students

The next thing we'd like to talk about is ***what you notice about the students*** in this clip - both what you noticed at the time of teaching, and what you notice looking back at it now.

4) Do you remember whether you noticed anything about the students' work at the time of the activity?

5) Looking at the clip now, after it happened, what really stands out to you about these students or their work?

6) What, if anything, was or is confusing or surprising to you about what the students were doing or saying?

7) What do you notice in this clip about the ways that literacy and engineering are being integrated (or *not* integrated) by the students?

Probing questions as needed

   a. What did the students says?
   b. What did the students say about _____ ?
   c. What did the students understand?
   d. What did the students understand about ___ ?

e. What was the students' approach to ___ ?
f. Why did students focus on ____ ?

Reference: Sherin, M.G., Han, S. Y. (2004). Teacher learning in the context of a video club. Teaching and Teacher Education, 20, 163-183.

Part 3. Reflecting on teacher moves

The third thing we'd like to talk about is ***the moves you made as teacher*** related this clip - the ways you might have responded to or thought about the students' ideas, to what they were doing and saying.

[If not yet clarified]

8) Did you interact with the students in relation to this clip?

[If teacher interacted with students around clip]

9) Let's go back to what you mentioned as being confusing, interesting, or surprising. How did you eventually end up responding to the students, and why?

10) How did that play out? Would you say the students responded as you expected? Why or why not?

[Even if teacher did not interact with students around the clip]

11) What are some possible ways for a teacher to respond to or interact with these students?

12) If you could step in and ask these students some questions, what might you ask them?

13) How do you think these students might react?

14) How does this compare to other students' Novel Engineering work?

Probing questions as needed:

a. What did you say?
b. What did you say about?
c. What did you say in response to ___ ?
d. How did you set up ___ ?
e. How did you facilitate ___ ?

Appendix B: Transcript of Video Shown to Molly

Jacob: So I have an idea for, um, the raft idea.

Anthony: Let's- let's just narrow it- Let's do this first.

Jacob: I have a- I was thinking we could use a water bottle.

Anthony: Oh and it would float around? Then how would they steer it?

Jacob: Ding ding ding! Paddle.

Anthony: But I don't know if a- the swan can paddle.

Jacob: Oh, true.

Anthony: But that's a good idea. Okay, let's try swimming first. Let's come- What do we have for swimming?

Jacob: We have the- this

Anthony: Bike pedal, and my, thing.

Jacob: And my- and the thing I'm making right now but-

Anthony: I have- like a wall around it maybe with some video cameras and stairs and a bear trap.

Jacob: Well, the thing is, we have to *make* these kind of things.

Anthony: So, like, protect nest, out of the question.

Jacob: I was thinking we could use a dome like, out of like um- You know I don't know what to make it out of but, a dome.

Anthony: Let's not- let's not do protect nest.

Jacob: Yeah okay so that's out.

[Jacob rips sticky note with his idea for a nest protector.]

Anthony: Swimming.

Jacob: Um. Swimming, I- We already did swimming.

Anthony: I like that.

Jacob: And I have this one that um, I was thinking they could find like a stick and then they could find like this you know like, how there are just cups floating around randomly, so I think they could, like, just like use these. Use that and like...

Anthony: Oh

Jacob: A lever. So a swan would push it...

Anthony: I came up with this. Like we could maybe use a vacuum cleaner. It's like- so it filters the rocks on the bottom, and it gets water so the wa- the rocks won't go through. And just put water in a little bowl. Once you switch the lever, and this- You know the little toy cranes kids have?

Jacob: The toy what?

Anthony: Toy cranes that little kids have.

Jacob: Yeah.

Anthony: That aren't controlled by electricity. They pull the levers. One makes it raise one makes it snap.

Jacob: Yeah.
Anthony: We could use one of those to pick up weeds from the bottom- bottom.
Jacob: So, um. Do you- I think, um, swimming is the best one right now I think.
Anthony: Yeah.
Jacob: Do you want to not do food and water? How about have food and water be our backup? So like if this completely fails, this will be our backup.
Anthony: This is done for. Yeah!
[Anthony rips up another sticky note with a different potential solution.]
Jacob: Okay now...
Anthony: Hold on… I ripped that one already.
Jacob: Okay now. So I'm gonna try- I'm gonna do one more idea for the swimming. The water- I'm doing the water bottle.
Anthony: Oh, oh oh.
[The interviewer fast forwarded through the portion of the video in which Anthony and Jacob spend a minute drawing new potential solutions and Jacob begins to describes his solution to Anthony.]
Anthony: But how do they steer again?
Jacob: Um, so well you know like how one turns right- like you're driving a car, like the steering wheel. It would be like that.
Anthony: Alright that- that could work.
Jacob: What about yours?
Anthony: I came up with a- swivel-mounted egg-beater on a plank.
Jacob: For... swimming?
Anthony: It's a little boat. So when you- you know an egg-beater, when you spin it, when you turn it? A couple of egg beaters, and you turn them- They push a plank around with a couple cygnets on them.
Jacob: Mhm. Ohh.
Anthony: Um, you do that, and then it's swivel-mounted it so it can turn.
Jacob: So which idea is better? So wait, um.
Anthony: I think we should keep both of them. So we- so we have more materials.
Jacob: Alright. I definitely can- I'm gonna ask Ms. Jackson if we can like bring things in from home 'cause um, I can easily get a water bottle.
Anthony: I'll get egg beaters, or try.
Jacob: Okay.