Design Decision Processes of First Grade Students during an Engineering Design-based STEM Unit (Fundamental)

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Introduction

Currently, there is an effort to bring engineering as a part of the curriculum into early elementary classrooms. For this purpose, academic science standards have incorporated engineering design in the pre-college curriculum [1]. According to the NGSS standards for K-2 engineering design, the aim of implementing a STEM curriculum is that children be able to ask questions and define problems that build on their prior experiences and develop models based on evidence. Recent studies demonstrate that elementary students are capable of developing skills associated with engineering design and decision-making processes [2], [3]. However, young students often lack the language and ability to express their ideas and justify their decisions. Therefore, it becomes difficult to grasp their thought processes and identify evidence of such abilities. To this end, we seek to better understand the reasoning behind students' engineering decisions while performing an engineering design challenge. This study addresses the research question: What types of decisions do first grade students make while working in pairs to develop a solution to an engineering design challenge?

Literature

Decision making is essential to engineering design [4]–[6]. Engineers must be able to balance multiple, often competing ideas, issues, and criteria in a design and make decisions about how to balance these tradeoffs. This requires using evidence from a variety of sources in the decisions [5]. Therefore, an essential aspect of engineering education is teaching students to use evidence, tools, and processes to make their decisions. Experienced designers use a variety of tools and processes to help them gather the evidence they need to make their decisions. This necessitates technical scientific and mathematical knowledge, but also other skills and strategies that take time and practice to master. For example, one way that engineers gather evidence to make their decisions is by creating and testing models of potential solutions. To use these models, engineers need to develop the skills to create and analyze them [7].

Studies have shown evidence that young students are able to make complex engineering design decisions, using skills including creativity, negotiation, and data analysis[8], [9]. Students are also able to show some evidence of their decisions[10]. However, elementary students make their decisions for a variety of unique reasons, such as their personal experiences, the authority of their teacher or teammate, or data they have gathered, and with a range of abilities [11], [12]. Therefore, their decisions are often unpredictable [9]. Additionally, students often make decisions that are based on novice ideas about design, such as becoming fixated on an idea early in the process or not recognizing that a decision needs to be delayed until further evidence can be collected [5], [13]. Additionally, it is often a challenge for novice designers to balance multiple, complex, often competing design criteria, at once [1], [5], [14]. Students need to learn to

identify, implement, and evaluate designs based on criteria and to make decisions about their design based on all of the criteria needed, not just the ones that are most apparent [15].

Teachers play a role in how students make decisions about design and convey their ideas about their decisions. For example, students often mirror the actions they have seen they teachers use in small group interactions [16]. Additionally, when teachers ask students to explain and defend their decisions, they are more likely to explain their evidence in the decisions and overall, make better reasoned decisions [11].

In addition to making complex engineering design decisions, students must be able to communicate with others in order to convey ideas and explain their decisions to teammates, teachers, and others. Young students have vastly different abilities to convey their ideas [3]. At the early elementary level, some students are able to clearly articulate their ideas and explain their reasoning, while many others are unable to do so. Therefore, it is often difficult to observe how or why students make the decisions that they do [2]. However, in order to better understand how to support students as they learn how to make engineering design-related decisions, educators need to better understand how students make their decisions.

Framework

As described in our literature review, design decisions are a key component of engineering design thinking and processes. For this study, we were interested in what kinds of decisions early elementary students made and how they were making these decisions. Previous work examining students' evidence and reflective decision making [3], [10], was used as a foundation to guide this work. One of the products from that work was the Reflective Decision-Making Framework developed by [3]. This framework characterized reflective decision-making during engineering design and identified six reflective decision-making elements related to initial planning and redesign. It was developed using the Engineering is Elementary curriculum [17] and was developed with data from upper elementary school age students engaged in an engineering design challenge. The six elements of reflective decision making included: Articulate multiple solutions, evaluate pros and cons, intentionally select solution, retell performance of solution, analyze solution according to specific evidence, and purposefully choose improvements. These decisions were framed by the structure of the curriculum used for that study and therefore elements from that framework such as the notion of identifying decisions points, provided a starting point for this work . However, that work was primarily conducted with older students and a different formal curriculum, therefore, we expanded our framework to include more and different types of decisions that were seen with the different structure of the curriculum and different ages of students within this study.

We used the idea of decision points in a similar way as [3] by describing the decision points as implied questions. However, we expanded the decision points to include all types of

decisions that the students were making, not just those that fell directly within the scope of the curriculum. This included teamwork decisions and decisions that fell across phases of the design process. By including these types of decisions in our framework, we were able to look more holistically at the students' engineering design processes and include more aspects that are important in engineering design decisions [5], [14]. We based these decision points on any direct observations we could make of the students, including what they said or actions that they took, as others have also done to look at decision making in young students [11], [12], [16].

Methods

In this qualitative study, we used a naturalistic inquiry approach [18] to study the decision making of first grade students during the solution generation stage of an engineering design challenge as it allowed for examination of student and student interactions in their natural classroom setting. The use of a naturalistic inquiry approach allowed the researchers to observe, describe and interpret the students in their natural decision making processes with minimal disruption from the observer. This was important because, as emphasized by [18], meaning is largely determined by the context in which it is situated and therefore if we want to understand more about students' decision making while working in pairs during their engagement in a specific task then it is important for the research to be conducted in this setting through largely unobtrusive methods.

Participants and context

This research is part of a larger externally funded project that is focused on examining CT and engineering thinking for K-2 students within in-school and out-of-school STEM and computational thinking (STEM+C) environments. As part of this larger project, the project team wanted to understand the decisions that young students make as they are engaged in engineering design and computational thinking within the context of a formal STEM+C curriculum unit. This study took place at one of the partner schools for this larger project that is a public elementary (K-4) school located in a small city in the Midwest. The student population consisted of 1% Asian, 16 % Black, 38 % Hispanic, 36% White, 7% of students who identified as two or more races and 73% of the students were eligible for free or reduced-price lunch.

As participants in the larger project, all five of the first-grade teachers attended a summer professional development around CT and the STEM+C curriculum observed in this study and were asked to implement the same STEM+C unit in their classrooms. Furthermore, as part of the research design from the larger study, a small group of students in each classroom who had consented to the project, were identified by the teachers as representative focus students. These focus students were included as part of the case study design and therefore data collection efforts for these students was centered around capturing their engagement in both the in-school and out-of-school STEM+C environments. These focus students from the larger project were selected

as the focus for this study because their inclusion in the case study design allowed for the close examination of how first grade students engaged in decision-making across the curriculum unit.

Even though all 5 first-grade teachers participated in the larger project, the goal of this study was to look at first grade students decision making while engaged in a specific engineering design challenge as part of the larger STEM+C curriculum unit and therefore it was important to have students engaged in similar tasks and approaches within the same curriculum. Consequently, this led to a focusing on three of the five teachers and their focus students, due to the extent to which the three selected teachers adhered closely to the curriculum and resulting in more consistency across the classrooms.The three teachers were Miriam in classroom A, Moira in classroom B, and Kristen in Classroom C. The focus students from each the three classrooms included a pair of students who were part of the case study teams and were recorded throughout the implementation. Team A, in Miriam's class, consisted of two girls. For the planning stages of the design challenge, Alice and Annie worked together. However, on the second day of solution generation, Annie was absent so Alice worked with Andrea. Team B, in Moira's class, had a boy and a girl, Bobby and Betsy. Finally, Team C in Kristen's class, had a boy and a girl, Connor and Clara. All names are pseudonyms.

All three teachers implemented the PictureSTEM curriculum developed to integrate STEM disciplines with an emphasis on engineering design and literacy. The curriculum for first-grade students was established to provide interdisciplinary experiences to the students, and it aligns with Indiana State Standards for Science, mathematics, English/Language Arts and Computer Science. The curriculum is student-centered and engineering design-based with the objective of engaging students in planning, building, testing, and redesigning a hamster trail. The curriculum has a set of thirteen lessons that state the objectives for each lesson aiming to guide and inform the teacher about the expected outcomes at the end of each class. At the beginning of the unit, the students were given a letter from a fictitious client who needed them to design an exercise trail for a hamster that fit onto an existing cage. The initial lessons focused on problem scoping, while the final lessons concentrated on solution generation. Throughout the problem scoping phase, the students learned about animal needs, their physical characteristics, hamster's basic and specific needs, basic shapes, concepts about basic dimensional shapes, sequence, preposition words, testing, and failure.

For this study we initially focused on all of the lessons during the curriculum unit, however through the initial rounds of analysis, it was determined that those lessons in which the students were working on generating their solution provided more opportunities for observable and explicit decision making from the students. Overall, in the unit, the students were tasked to design an exercise trail for their hamsters to improve the cages that the client already sells at her pet store. In the lessons that we observed, the students planned their design by drawing it on a paper template. This template included the shape of the hamster cage that the client already sells

with the openings of where it should connect to the exercise trail. After finishing their plan, the students filled out the "shape order form" to get the materials that they needed. Then, the students constructed their prototypes, using plastic blocks of various shapes and setting them up on the building mat form (See Figure 1) .
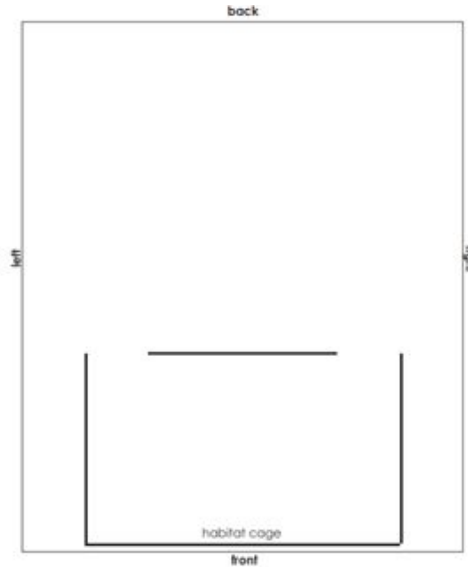

Figure 1. The template that the students used to plan their design and use as a mat for implementation.

They tested their prototype by using a picture of a hamster attached to a toothpick that they could use to simulate the hamster walking through the exercise trail. Finally, the students were able to redesign their prototype by refilling out the "shape order form" and implementing their design. The criteria for the problem were:

(1) The exercise trail must connect to the two openings in the back of the habitat cage Perri [the client] already sells.
(2) The exercise trail should be fun and exciting for the hamster. In order to keep it fun for the hamster, we will use no more than 10 of any one shape.
(3) The exercise trail and habitat cage cannot take up too much space. We do this by limiting the number of shapes to 20.
(4) The exercise trail and habitat cage should keep the hamster happy. We will add structures to the trail like bridges, towers, caps, and dead ends. Bridges are made by one shape on top of two others for climbing up and over. Towers are made by stacking shapes on top of one another. Caps are at the top of towers made by a different shape. Dead ends are trails that do not connect back to the main trail in which a hamster can hide. Each trail needs to include at least one of these structures.

(5) The exercise trail and habitat cage must keep the hamster healthy. So, we must identify where in the cage and trail the hamster will get its food, water, shelter, and space and air. We will mark these with our 2D shapes.

(6) The hamster must not be able to escape, so all shapes must touch

Data Collection and Analysis

As suggested by adopting a naturalistic inquiry approach [18], the data collection was focused on observing and describing the experiences and actions of the participants in their natural classroom setting. In order to capture the experiences, conversations, gestures, and actions related to students decision making during participating in the curriculum, the primary data source for this study were video recordings of the focus group students in each of the three classrooms.. A camera set up close to and focused on the small group recorded the work of a pair of students and provided clear audio and visual information about what the students were doing throughout the curriculum unit. In addition to the recordings for each focus group of students there was one video camera set up in the back of the classroom to capture the whole class setting and provided details on the larger context, such as how each classroom was set up and how the teachers prepared their students to work on their design projects. A third source of descriptive data included field notes that were collected during implementation of curriculum unit.

The data analysis process followed a method of constant comparative analysis [19] and was carried out in four subsequent stages that allowed for an iterative process of coding, comparing, and condensing the data as the researchers worked to focus the data and analysis to create rich descriptions and interpretations of the design decisions of the first grade students from each classroom. In the first stage of data analysis the focus was to gain an overall understanding of the context, to identify which of the teachers were implementing the curriculum similar to how it was intended, and to identify which lessons had evidence of student decision making. Two researchers individually observed the video recordings of the entire curriculum in multiple classrooms to understand the dynamics of each classroom better, make initial observations, and choose which teachers' classrooms to focus on. This first round of data analysis revealed that three of the classrooms, noted above, were closely implementing the curriculum as intended and would be the focus for this study. Additionally, although the students made many other decisions throughout the design process, it was difficult to observe evidence of their decisions in other areas of the curriculum and in earlier phases of the design process because they did not vocalize their decisions or their made the decisions individually. This led to a focus on the solution generation lessons within the curriculum.

After the first stage, the next round of analysis included a more fine grain look at the students as it was focused on the description and earlier interpretation of the videos of the students working in pairs throughout the design challenge. In this second stage, the data were

split between the two researchers and both researchers watched the videos of the pairs of students working on the solution generation lessons. Initially, the researchers watched the videos to record detailed observations of the students working. Then, they came together to compare notes around the types of initial themes they found in the data. Following suggestions from the Reflective Decision-Making Framework [3], the researchers decided to focus on the specific points where students had to make a decision, which were called decision points. Each decision point was described using the question that the students needed to answer at that point. Then, the researchers interchanged which videos they focused on, so both researchers had a chance to identify and describe the students' decisions points in all three classrooms. The two researchers met to discuss their findings and reach a consensus about the identification and description of each decision point within each of the three classrooms.

In the third stage of the data analysis process, the researchers coded the decision points using the six elements from Reflective Decision-Making Framework [3], as a starting point for identifying the types of decisions within the data. This allowed for a set of provisional codes from which the researchers could work, but also allowed for the emergence of new codes or patterns as the data was coded and compared. From this stage, the researchers held frequent meetings with a third researcher to analyze the initial findings related to those decision points and the findings from this round of coding were discussed with a third researcher. In the final stage, a fourth researcher reviewed the initial rounds of the data analysis and together the patterns in the data were further analyzed and condensed into the larger themes described in the results section.

Limitations

The goal of the naturalistic inquiry approach that we used for this study is to understand how students make design decisions in their natural setting. Therefore, we worked to limit the disruptions caused by the observer and our data consisted of video recording of the students working without intervention from the researcher. This allowed us to observe the students using their more natural decision making processes. However, because we were not able to ask the students questions or probe for their reasoning, a significant limitation in this study is that we were not able to identify or understand many of the decisions that students made. Therefore, we were not able to quantify the decisions in any way or make definitive conclusions about all of the decisions that students made throughout the process. However, as described in the examples that we gave, we were able to observe many decisions that the students made and focused on those for the purposes of this study. Additionally, a limitation of our study was that we only focused on three teams of students. We worked to reduce this limitation by looking across three different classrooms with different teachers.

Results

In this study, we examine the engineering design decisions of first grade students across three different grade classrooms as they each implemented the same PictureSTEM curriculum. We found that the three teams made multiple decisions during the solution generation stages of the engineering design challenge in order to develop their solutions. Our results are organized around each of the activities that the students performed during our observations; namely, plan, implement, test, and redesign. Additionally, we observed decisions around teamwork across the lessons and those are also described here.

Planning decisions

Decisions related to planning included decisions about how to begin the initial plan, how to balance multiple criteria, especially the limited number of shapes available to them, and how to combine ideas from both partners. The students demonstrated varied ways of approaching these decisions and, although in several examples they became frustrated with the difficulty, they were able to make appropriate decisions to set them up well for the rest of the design challenge.

At the beginning of the challenge, the students were tasked to plan and sketch their trails individually. Consequently, the students needed to decide how to draw or represent their ideas on the paper template. When deciding how to draw their plan, some of the students were unsure how to begin. For example, in Team A,

Alice: [started to draw her plan first]
Annie: [watching her draw and then started to draw her own plan]

In this example, Annie may have been unsure how to start and used the evidence of how her partner was approaching the plan to start her own. In this case, Annie and Alice's plan drawings ended up being very similar to each other.

To draw their plans, some students decided to first focus on the big picture, starting with an overall outline, and others decided to work from shape by shape to draw it. For example, Alice started her plan with "So it's like a tube [draw a tube-like shape connecting the two openings, then, started to fill in the outline with the individual shapes that she had available to her]." On the other hand, Clara started by saying out loud that she liked the idea of having towers in her design and then proceeded to draw towers on either side of her exercise trail before filling in the rest of the path around them. Although both of these examples demonstrate the students making decisions about how to start their initial plan, they went about it in different ways, both of which turned out to be successful.

The students also made planning decisions while they were choosing the shapes that they needed and recording them on the shapes order form. These decisions were mainly around how

many and which shapes they would need to build the exercise trail. For instance, Team A had the following conversation when trying to decide how many shapes to order:

Teacher: [To the whole class] Your partner is sitting across from you. So, [student name] and [student name] are going to talk and fill out this sheet together. [Student name] does not get a whole set of shapes, ok. Now you're going to team work and your exercise trail is going to be made with two engineers putting their ideas together. [While teacher is talking, Alice is counting on her fingers and recording on her plan].

Alice: I have 20 [holds up plan to show her partner]. Oh wait.

Teacher: [Places shape order form on table between students] This is your order for the shapes store.

Alice: Ok, I have 20 of these [points to plan]. Do you want to use a rectangular prism?

Annie: Uh...Yeah.

Alice: I do too. I want 7 of them. How many do you want?

Annie: 7.

Alice: So, 7 plus 7. 7, 8, 9, 10, 11, 12, 13, 14 [counting on fingers]. That equals to 14 [records 14 on shape order form]. Do you want to use a cube?

Annie: Um...no.

Alice: Ok, I do. Wait, do I? [looks at plan]. So, I do. I want 10 [records on shape order form]. A cylinder? Yes?

Annie: No.

Alice: Ok. Um…[looks at plan] I don't. A sphere?

In this example, the students made decisions about which shapes they needed and how many of each shape they needed. Although they are making decisions about the shapes, they do not give descriptive evidence to the observer about why they made these decisions. They continued this process for each of the shapes on the shapes order form. However, the process results in them having too many shapes total because they have each chosen the number of shapes they want instead of working together. Therefore, when the teacher comes to check on them, the conversation continues with:

Teacher: Alright, this says 14 and 10.

Alice: Yeah.

Teacher: 14 plus 10 makes?

Alice: 20?

Teacher: 24, k. You can't have 24 shapes. The most you can get is 20. [The teacher walks away and Alice hits herself in the forehead several times].

Alice: I don't know what to do [in tears].

Annie: [Bounces around in her seat while Alice calms herself down].

Alice: I have 20 things on this paper [referring to her plan], I don't know how many you have.

Annie: I have 20.

Alice: So, 20 plus 20 equals 40.

Annie: 40! No way, girl!

Alice: 2 plus 2 equals 4 and 20 plus 20 equals 40.

Annie: Oh my god, you can't do anything.

Alice: I don't know if we're going to get 40 shapes. We can only have a...wait. You can have 10 and I can have 10

Annie: Ok.

In this example, they wanted to include all the shapes for both of their individual designs, which would total 40 shapes rather than the 20 shapes they were limited to, so they decided that each member would choose 10 shapes. They then proceeded to help each other change their plans to only include 10 shapes on each. In these examples, they came up with several ways to compromise, first for them each to choose the shapes they needed and, when that did not work, to each pick half. They also needed to balance multiple criteria in their decisions, balancing the limited number of shapes along with matching their plan closely enough to connect both openings.

The students also had to make decisions around which criteria to focus on when working on their plans. Each classroom had the six criteria written on a poster, and the teacher also reminded the students of the criteria before they sketched their trails. Nevertheless, the students often appeared to forget or prioritize a certain criterion over the others. For example, Betsy quietly drew her design by connecting the two opening of the cage. She represented the overall shape of the trail like a tube. Although, she did not explicitly say her purpose, it appeared that she was focusing on the criteria about connecting both openings of the cage. On the other hand, Connor and Clara focused on the number of shapes as the next excerpt shows:

Clara: You have to draw the tube baby [pointing out the Connor's sheet].

Connor: What if I don't want...

Clara: But you have to.

Connor: Fine, fine [he starts drawing a column of rectangles in each door].

Classmate: That's the tower.

Connor: I know [keeps drawing two towers, one for each door].

The classmate keeps talking, while Connor continues sketching his trail:

Connor: How will I do this!

Classmate: I'll help.

Connor: I think I can't do this [touching his head], oh damn, [he rewrites the towers using smaller rectangles and adds two horizontal rectangles from one tower].

Clara: You [Connor] had to use 20 shapes, [looks at her plan], one, two, three…
              [counts moving her pencil over her trail's sketch].

Connor: Do we have to use all of them?

Clara: four, five, six… [does not answer and keeps counting].

Connor: [draws three more rectangles next to the two horizontal ones and starts
              counting], one, two, three, …

Clara: [Continues counting and looking at Connor].

Connor: … fourteen, fifteen, sixteen [stops counting]. I cannot finish this.

Clara: There we go, seventeen, eighteen, nineteen, twenty [counting the number of
              pieces that are missed in the Connor's sketch].

Connor: [continues drawing rectangles in the towers and in the horizontal row], one,
              two, three…, [counts again the number of pieces that he will use].

Later, the teacher starts explaining the next activity and Connor stops verifying the number of shapes. In contrast to Team B, Connor and Clara were focusing on the criterion about using less than 20 shapes. Moreover, we did not see evidence that Connor aimed to connect the initial two drawn towers; instead, he ended up connecting the two towers, and by doing that the two doors as a result of the row of rectangles that he drew between them. Thus, he made the decision to prioritize the criterion of having less than 20 shapes over the criterion of connecting the two openings.

Overall, throughout the planning process, students made decisions about which shapes they would need, how they would compromise to deal with having two plans from each student, and which criteria to focus on.

Implementation decisions

Most of the implementation decisions focused on how the students should start implementing their designs, and, as in the planning decisions, on what criteria the students should focus. Since each team used a different strategy to make those decisions, we describe each team's approach separately.

Team A made the decision to stick closely to their planned prototype and decided to first focus on the criterion that the trail should connect both openings of the cage, as demonstrated in the following example. Prior to this example, Alice and Annie had made the initial plan, but Annie was not present in class to implement it. Instead, Alice worked with Andrea to build Alice's design:

Alice: [places cube at the first opening] So it going to go over this, Ok? And then when
              it comes back in, it's going to jump again [places a different cube over the other
              cage opening]. And then it's going to try to jump over this. [places rectangular
              prism next to, but not touching, the first cube]. Phuw [makes jumping motion
              with her finger]. Ok [clear off all shapes]. I'm just going to, I'm just going to...

In this example, Alice explained to her partner how she first decided to place cubes at the openings of the cage to meet the criteria that the hamster would not escape. Alice and Andrea continued to build their shapes using similar dialogue and eventually ended up with a series of rectangular prisms aligned in the general path they first discussed, but the shapes did not touch each other. This caused them to have to make additional decisions to meet the criteria. Therefore, at one point they had the following exchange:

Alice: Bounce, bounce, bounce [using her finger to trace how the hamster will bounce between the shapes to move through the trail].

Andrea: They all have to touch.

Alice: Oh yeah, so bounce [moves first shape closer to opening]. Bounce [moves the next shape closer to the opening so that they touch]. Bounce [moves the next shape closer to the opening so that they touch]. Hold on, hold on, I know how to do this [clears off all shapes].

Here, we can see how initially Alice prioritized one criterion, having both openings covered, over other criteria, such as having the shapes touch. When a prompt from her partner caused her to realize that she did not meet all the criteria, she made the decision to move the shapes closer together. After this exchange, Alice started again by placing the shapes at each opening and then filling in the shapes in between, much as she had before, but with them touching.

Team B made the decision to build their prototype differently than their plan and did not focus on the criterion of including a special feature (bridge, dead-end, cap, or tower). After Betsy and Bobby got the shapes they had asked for during planning, Betsy decided to arrange the shapes near the edges of the sheet without connecting or covering both doors. She tried several configurations such as the trail shown in Figure 2 and then she asked for approval from the teacher:

Figure 2. One of the first exercise trails made by Team B. The shapes do not cover the openings and the two sides do not connect to each other.

Teacher: Ok. Make sure he is coming out this hole and going in this hole [pointing out the two doors of the cage]. You need something there [points to one door of the cage].

Betsy: [moves one of the triangular prisms on their initial exercise trail, and places it between the border of the cage and the edge of the sheet paper].

Teacher: No, in between the lines.

Betsy: I did it.

Teacher: No, in between these two lines, this is the door [pointing to the opening of the cage].

Betsy: [shrugs].

Teacher: Now, you have to connect it, connect the tunnels.

In this example, Betsy seems to have misunderstood the representation of the cage, what may have influenced her decision about how to set the shapes. Even though the teacher explained and showed her how to build the trail, she still seemed confused. Betsy removed some shapes and placed others in the same place as before; specifically, the shapes were touching the border of the cage with the line indicating the edge of the cage, instead of covering the door. Subsequently, the teacher explained for the entire class:

Teacher: Ok, this is kind of similar to what you are doing [projects an example of an exercise trail for the whole class to see]. You have a hole on one site of the cage, correct? You have a hole on the other side of the cage, correct? You're building this trail, this exercise trail from one, and you have to meet to the other. Ok? [keeps talking about how to build the special shapes] …and your tunnels, you are not building another cage, you are building tunnels. Ok? Is that help at all?

Betsy: Yes [starts building another trail without placing the shapes in front of the door, but now she made the decision to connect the two separated trails].

In this example, a further explanation from the teacher and a better understanding of the representations that they were using prompted Betsy to make decisions about how to implement her exercise trail. Her improved understanding of how the representations were being used helped Betsy to make decisions about the design that more accurately met the criteria. Although Betsy and Bobby still struggled to place the start and end of the trail in front of the doors' cage, they eventually managed to do it. However, when the teacher was going to evaluate the trails:

Teacher: [speaks to the whole class] If you guys think you are done, you have connected the two openings, you don't have more than 10 of any shapes, you don't have more than 20 pieces…

Betsy: [counts the number of shapes by pointing each one].

Teacher: …make sure you have one of these: a bridge, a tower, a cap or a dead-end, and make sure he can't escape, all pieces must touch…

Betsy: [looks at the trail, takes a rectangular prism and a triangular prism to make a tower] I made a tower [says to Bobby].

Bobby: Ok.

The teacher's prompt caused Betsy to realize that they had missed the criterion of including a special feature in the prototype and prompted her to make the decision to modify the trail by including a tower. Nevertheless, by doing that, she separated two pieces that should have been touching. Thus, she initially had forgotten the criterion of having a special shape, and while she tried to correct it, she forgot the criterion that all shapes should touch.

Finally, Team C built their prototype directly from their initial sketches and considered almost all the criteria. Connor and Clara laid both of their drawn plans on the table next to their mat as they were building their design. They consistently turned their heads to look at both the plan and what they were building and pointed to specific places on their plan as they were building that indicated that they were following their plan and were making their decisions about how to build their design based on this plan, as demonstrated in the following excerpt:

Clara: We got two of these two [Pointing to their plan and confirming the quantity of the shapes in their plan by counting the number of shapes they have in their design]. And then fourteen [pointing to the plan] one, two, three, four… fourteen [counting the pieces they have in their design]. So actually we have all the shapes.

Teacher: [Speaking to the whole class] When you find the design you like stop changing it. Make sure you do not have more than 20 [shapes] double, double check, okay? When you are done don't change it.

Clara: Let's check it [she starts to count the shapes in their prototype]. Yeah..

In this example, Clara is checking how closely their actual implementation is to what they have built. The images below in Figure 3 demonstrate how the pair has their plan laid out (third sheet of paper from the camera), the design their are implementing, and their shape order form. Clara is pointing between these different resources and making decisions based on all the information they have.

Figure 3. Team C laid out their plan, their building mat, and their shapes order form next to each other and often referred to compared the different sources of information.

In the end, Team C implemented their design quickly, compared with the other observed teams and were able to balance the criteria in an efficient manner.. However, the teacher in this class forgot to present the criterion of using less than ten pieces for each shape so the students could ask for 14 cubes. Regardless of the missed criterion by the teacher, the students were seen making decisions based on the established criteria as they were paying attention to avoiding using more than 20 shapes, connecting both openings, including a tower (special-shape), and assuring that all shapes touch.

Testing and redesign decisions

The students made testing and redesign decisions throughout the engineering design challenge. During testing and redesign, the students needed to decide if their exercise trail would be successful, how to modify their trail when it did not meet the criteria, and if they wanted to "send" the design to the client or redesign another prototype. Although we saw other testing and redesign decisions, these three were the more common across the three teams.

One of the testing and evaluating decisions that they needed to make was if their exercise trail would be successful. As written in the curriculum and presented by the teacher, the testing procedures asked the students to use a picture of a hamster that was attached to a pencil to simulate the motion of the hamster through the exercise trail. This test forced the students to walk through the prototype step by step and check each part of it for holes or other issues that would prevent it from meeting the criteria. For example, Figure 4 shows how Betsy was testing her prototype with the hamster. She moved the hamster over the trail, and decided there was a hole; then, she moved the hamster far from the exercises trail, as if it were escaping.

Figure 4. Betsy tested the prototype using the hamster. She moved the hamster over the trail, and when she found a hole, she moved the hamster far from the trail, as if it were escaping.

The students made decisions about how success their trail was from the beginning of the engineering design challenge. Although the students often decided if the trail would be successful by testing the prototype with the hamster, we observed some cases where they made the decision using their initial sketch. For example, when Betsy drew her exercise trail, she did not connect the two doors of the cage; instead, she left a hole between the trail's end and the door's edge. Then, she tried to cover the hole by drawing a line that closed the doors' cage as Figure 5 shows. Betsy looked at her sketch and called the teacher:

> Betsy: Ms. Moira [She calls the teacher, pointing out the line that she had drawn].
>
> Teacher: Get open the door, you [the hamster] can't get out.
>
> Betsy: Ms. Moira he [the hamster] can escape, [she erases the drawn line], because he can still get out [Betsy points to the hole between the trail's end and the door]
>
> Teacher: No, just draw this line to here [she shows how to connect the trail's end with the door's edge, so it was not generated a hole (see Figure 5)].

Here, Betsy was concerned if her trail would be successful in terms of avoiding the hamster escapes. She probably tested the design in her mind, determined the hamster could escape by the hole, and decided to close it by drawing a line. However, she was not sure about her solution and asked the teacher for approval. The teacher responded with an alternate solution.
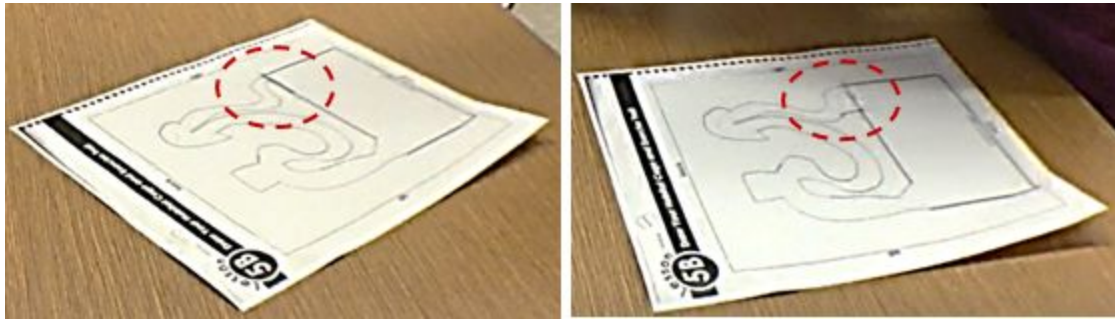
Figure 5. Betsy's initial and corrected plans for the trail. Left: she closed one cage's door with a line to cover a hole between the trail's end and the door's edge. Right: she tried to erase the line and corrected the trail's end by connecting it with the door's edge.

Another testing and redesign decision the students made was how to modify their trail when it did not meet the criteria. When they recognized that had missed any criteria, they usually changed their prototype. Sometimes they started the prototype all over again and other times they just modified one section. For example, when Team A had finished building their design, they had the following exchange:

Alice: Hold on, hold, we need to...to test it. Ok we need to test it.

Andrea: It doesn't connect to this one [pointing to one of the cage openings].

Alice: I know! It will just go through this and then [waves hand in the air]. It will just walk.

Andrea: Or run. [pause] We're going to need a couple more shapes to connect it [pointing to opening]. 1, 2, 3, 4, 5 [pointing her finger at the empty space between the edge of their trail and the opening, estimating the number of shapes they will need].

In this example, although they did not conduct a thorough test, the students did think about if they had met all the constraints and what they needed to change to fix their design. Andrea made the decision that they needed more shapes to fix their design and started to work on finding a solution but figuring out how many shapes they needed.

Another place where there was evidence of decision making was once the students finished their prototype, they had to decide if they wanted to "send" this design to the client or redesign another prototype. Team A decided to build a new prototype. Although they had finished their prototype, when they had the opportunity to redesign it, they asked for new shapes and decided to build a completely new one. This involved exchanging all of their shapes and starting from scratch. On the other hand, after Team B had planned and built their design, the students realized that their design used too many of one type of shape, therefore, it did not fit one of the criterion. They had the following conversation:

Teacher: [Reads the criteria checklist aloud to the class so students can double check if they have met them all]. I have met the following criteria? Number one [...]. Number two, I have used no more than 10 of any one shape. So if you have a lot of squares, count it and make sure you do not have more than 10.

Bobby: [Starts to count the number of squares]. Eleven.

Betsy: [Recounts it and whispers something to Bobby].

Bobby: We have twelve? [Looking concerned].

After a few more instructions from the teacher:

Teacher: ...we are gonna take a picture of it [the prototype].

Bobby: [To Betsy] We'll change it.

Teacher: [Still reading the criteria to the class. She interrupts the reading and says to a specific team:] so can you take a better choice? Show me what is the better choice. Thank you.

Betsy: [She recounts the squares more than once with a worried expression. Looks at her teammate and tells him something inaudible].

Bobby: It doesn't really matter. I am happy still. We [...] got a tower [pointing to the tower in their prototype, speaking a few more words about the tower which are not clear].

Teacher: [She approaches the team and checks their prototype]. I think everything looks good. You don't have more than 20 pieces, right? Okay. [She gives the final worksheet where the students need to complete a checklist to ensure they have met each criteria].

Bobby: I do not know how much do we have. I think we have sixteen.

Teacher: Recount it.

Betsy: [She starts to count how many pieces they have total].

Bobby: [After listening his teammate count in loud voice]. Nineteen, so we cut it out one more.

In this example, the students realized that their design did not fit all the criteria. They had listened to the teacher's instructions and counted their shapes multiple times in order to confirm this. However, they decided not to change their design, even though it did not fit the criteria because they were "happy" with their design.

Teamwork decisions

Teamwork played a role in many of the students' decisions. These decisions included how they would divide roles in the team and how/if they would combine ideas from both team members' plans. One significant teamwork decision that we observed was who was going to lead the group during the engineering design challenge. Although, each team had a clear leader, this dynamic played out differently in each team. Team C, for example, showed sophisticated

teamwork practices that showed compromise in their decisions based on ideas from both students. For example, the students in Team C had the following conversation as they were starting to implement their design:

[Students lay both plan next to each other on the table]

Clara: [to partner] Did you like mine [plan] or yours, which one did you like?

Teacher: And you can pick some of your things you liked and some of this you liked. [Pointing to both plans]

Connor: I like my tower.

Clara: I like your two towers and I like mine, so let's combine our two towers together, so we also have two towers. So we need some cubes… [counting how many cubes needed by looking at both plans].

Connor: [also starts to count how many cube shapes they need]

Clara: Hold on, we should [use] two towers so it makes yours a little shorter as well mine so we don't use all… [both look at each other and nod their heads positively].

In this example, both students are respecting their teammates ideas and making efforts to use ideas from both partners in their decisions. Although, as with the other pairs, one of the students, Clara, was in more of a leadership role than the other, she asked Connor questions about what he wanted to do and considered his ideas in her decisions, such as by directly asking him what he thought, and made sure they were included in the final design. These students were very efficient in their process, they finished relatively quickly, and they both seemed very satisfied with their final design and proud of themselves.

On the other hand, in both Teams A and B, one student decided to do the bulk of the work and the other student followed along. For example, in Team A, Alice went so far as to tell her partner that she could not touch the shapes:

Andrea: [touches her lips].

Alice: Ok, now that you sucked on your finger, you can't touch these [shapes] ok [pointing to shapes]. I can only touch these [shapes] because you just sucked your finger.

Alice continued to not let Andrea touch the shapes, but Andrea appeared to be fine with this and stayed engaged throughout most of the process and continued to offer her ideas. In Team B, Betsy did the bulk of the work as well, but was reluctant to use Bobby's ideas. For example, at one point, Bobby wanted to use a particular shape and Betsy did not think it should be in the design. Bobby pestered Betsy to include the shape he wanted and eventually she gave in. Both of

these pairs had arguments over these decisions that eventually led to a decision, but not until their emotions were high and they appeared frustrated with each other.

Discussion

Decisions about the criteria played a central role in many decisions that the students made throughout all phases of the design process. Although all the teachers explicitly discussed the criteria at the beginning of the lesson and kept the list of criteria posted in the classroom, it was often a struggle for the students to balance all of the criteria. Instead, they usually focused on one or two criteria and made their decisions based on those. For example, when making their plan, some of the students decided to first focus on the criterion to cover both openings to the cage and ignored or forgot about the criterion to only have 20 shapes total. This is in line with other studies that have found that balancing multiple criteria is a challenge for beginning designers [5], [9].

Social interactions with others influenced the students' decisions. For example, when a student forgot or ignored a criterion, it was often a prompt from another, either their teacher or a peer, that prompted them to notice that problem with their solution and make a decision to change it. Prompts from teachers came in the form of reminders directed to the class as a whole and interactions with small groups of students. The scaffolding the teachers provided here was important for the students' understanding of the criteria and the successful completion of the design project [9], [11]. Examples of decisions made based on prompts from peers were observed throughout the design process. These examples included during planning such as when students gave suggestions to their partner as well as during testing and evaluating when students pointed out places where the hamster could escape, prompting decisions to make changes such as moving the shapes closer together. Additionally, some of the students were able to demonstrate sophiscated compromise skills. Students negotiation skills have also been shown in other studies [8]. These prompts would not have occurred if the students had not been working in a team or if they did not have the freedom to make decisions and see who they played out in the design [12], [16].

The students made many decisions based on their interaction with or translation between representations. In this design challenge, the students had to take an idea they had in their mind, represent it through drawing their plan, transfer that idea to the physical prototype, and be able to convey their ideas to others with their spoken language. These translations posed a lot of difficult decisions for the students. Sometimes, the students were able to use evidence from these representations to make their decisions. These examples included when Team C used their plans directly to talk about and implement their design and when Team A used the hamster picture to test their design and decide if it met the criteria. Other times, students struggled to use the representations, such as when they had trouble conveying their ideas on their plan drawing or

when they got frustrated choosing shapes because they could not figure out how to make them stretch from one opening to the other. Our observations indicate that students are starting to develop the skills to use evidence from the tools available to them to make decisions, but that is often a challenge [7].

The students appeared to make some decisions without using evidence, which is not unusual for young students [5], [9], [13]. The students' decisions were influenced by their emotions and ideation strategies. For example, when Team B decided not to redesign their solution even after they realized it did not meet all of the criteria, they demonstrated that they were emotionally attached to their idea and were unable or unwilling to continue to brainstorm ways to improve their design. A similar example occurred in Team A when the students were ordering the shapes and Alice became so frustrated that she was almost in tears and wanted to give up. Although her partner was able to calm her down and together they made a decision about how to proceed, the decision was based more on how to avoid more frustration, rather than on hard evidence about what the best solution was.

Implications

In this study, we found that first grade students made a large number of varied decisions while generating a solution to an engineering design challenge. Our results point to several implications for teachers, curriculum developers, and researchers.

For early elementary age students, criteria for the design challenge need to be spelled out, either in the curricula or through the design process. In this study, the teacher explicitly stated the criteria for the students multiple times and kept the list of criteria posted in the classroom throughout the engineering design challenge. The students used the criteria to evaluate their designs at multiple stages of the design process. This often initiated iteration to improve the design when the criteria were not addressed satisfactorily. However, this was not always the case. Sometimes, the students were not able to overcome idea fixation.

However, even with these supports, it was challenging for the students to balance all of the criteria. The students often needed prompts to remind them of the criteria. Some of these prompts came from the teacher, pointing to the importance of scaffolding from the teacher. It was important for the students in this study for the teacher to remind them of the criteria and to ask them thoughtful questions about the implications of how they addressed the criteria.

Interactions with peers played a large role in the students' design decisions, supporting other research that working in teams, even at this young age, is advantageous to the success of the design, their social learning, and mitigating frustration. Additionally, working in teams provided opportunities to compromise and decide on how to work together and helped the

students when emotions ran high. Additionally, as the students were working if one student checked on meeting the criteria sometimes helped the other to make a new design decision

Finally, this study supports that students need opportunities to practice with representations, and translating between them. For example, we found that successful communicating of their design was often based on how well they could represent their ideas. Additionally, external representations served as a means to test the design against the criteria which can cause them to change their design.

Conclusions

In this study, we examined the decisions of first grade students working in pairs on an engineering design project. We were able to observe the students making a vast array of design, including during planning, implementation, redesign, and about teamwork. We found that students often struggled to balance all the criteria of the problem and showed varying levels of compromise with their teammate. Students' decisions were also affected by their idea fixation and emotions. This study adds to the literature about the decision-making processes of early elementary students and has implications to improving how students learn to make engineering design decisions.

Acknowledgements

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