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Productive thinking in middle school science students' design conversations in a design-based engineering challenge

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Abstract
Recent education reforms highlight the importance of engineering design as a tool to improve student science learning in this new view of K-12 science education. However, little research has investigated the thought processes students use while engaging in the highly complex activity of design. Therefore, building on theories of productive thinking, we analyzed 6th grade students' design conversations through the following research question: How do 6th grade students employ different modes of thinking when solving a design-based challenge in a science unit? Through a qualitative and descriptive case-study approach using Gallagher and Aschner's (Merrill-Palmer Q Behav Dev 9(3):183–194, 1963) analytical framework for productive thinking, our results indicate students employ a variety of modes of thinking as they engage in design conversations in a science-based design unit. While students planned their initial design, they employed Cognitive Memory, Divergent Thinking, and Evaluative Thinking. This is not surprising since students need to recall scientific facts and hypothesize as they begin to justify their design decisions. As students finalized design decisions and communicated this design to the client, they employed more higher order modes of thinking, since they evaluated and justified their design decisions. These findings provide insights into effective teaching strategies for higher productivity and conceptual performance.

Keywords Design conversations · Productive thinking · K-12 · STEM

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Introduction

Over the past decade, the national reform efforts in improving K-12 science education have focused on integrating engineering practices and thinking into science classrooms. Recent policy documents, such as *A Framework for K-12 Science Education* (National Research Council [NRC] 2012) and the *Next Generation Science Standards* ([NGSS], NGSS Lead States 2013) recognize engineering design and practices as important elements in a new vision for science education.

> [By] the end of 12th grade, all students [will] have some appreciation of the beauty and wonder of science; possess sufficient knowledge of science and engineering to engage in public discussions on related issues; are careful consumers of scientific and technological information related to their everyday lives; are able to continue to learn about science outside school; and have the skills to enter careers of their choice, including (but not limited to) careers in science, engineering, and technology (NRC 2012, p. 1).

Clearly, this new vision of science education has inspired the use of engineering practices in science classrooms—not with the intention that engineering replace scientific inquiry, but rather that engineering supplies an additional range of practices to enrich the teaching of science.

There has been a growing body of research suggesting that meaningful and purposeful integration of engineering into the science instruction increases student achievement and interest in science and engineering (Aranda et al. 2018; Guzey and Aranda 2017; Lachapelle et al. 2017; Silk et al. 2009). However, this line of research on K-12 engineering has generally investigated student learning through the analysis of students' engineering design solutions or content assessments (e.g. Berland et al. 2014; Cantrell et al. 2006; Dankenbring and Capobianco 2016; Park et al. 2018; Mehalik et al. 2008; Schnittka and Bell 2011; Wendell and Rogers 2013). Few studies have investigated the process of verbal interactions, namely design conversations (Adams 2015; Aranda et al. 2018). It is important to study design conversations for understanding the nature of design thinking that occurs as students enact design in an engineering and science-based curricula (Dorst 1995; McDonnell and Lloyd 2009; Rodgers 2013).

Studies of design conversations largely focus on the review of undergraduate students' design conversations to investigate the nature of design thinking, learning, and expertise (Akin and Awolomo 2015; Groen et al. 2015). These studies highlight design thinking of learners, address problems that learners encounter, and reveal learners' application of disciplinary principles. While these studies provide invaluable information about pre-professionals' decision-making in design, they are limited in reflecting K-12 students' design thinking and conversations. Design conversations of K-12 students are different because of students' limited background and experiences in design. Thus, more research is needed in design thinking processes of K-12 students in the context of classroom verbal interaction. We aim to contribute to the K-12 students' decision-making scholarship by investigating students' design conversations in the context of a unit that focuses on the integration of engineering into science content. Therefore, the major research question that guided the study was:

> How do 6th grade students employ different modes of thinking when solving a design-based engineering challenge in a science unit?

Literature review

We applied Guilford's (1956) theory of productive thinking to frame the study, since studies have shown that productive thinking leads to more effective decision making in engineering (Brown and Katz 2009; NRC 2001). According to Guilford, productive thinking consists of five operations: memory, cognition, divergent thinking, convergent thinking, and evaluative thinking. Using these types of operations of thinking, individuals draw upon past or present ideas and information to produce new ideas or solutions to problems. Cognition is seen as the basis of memory, divergent thinking, convergent thinking, and evaluation; thus, these processes cannot occur without cognition. Memory operations represent simple reproductions of new information based on recall of facts or rote memory. Convergent thinking requires analysis and integration of information to come off with one single expected result or end-product. Divergent thinking, on the other hand, requires intellectual operations to create alternative solutions through an open-ended approach. Finally, evaluative thinking represents judgment and choice.

In the context of K-12 science education, when engaging in design process to solve a defined problem, students brainstorm possible solutions, evaluate and prioritize alternative solutions, and then decide among existing alternatives. Engineering design process is not a single process or method in which a fixed set of steps are followed. In fact, the design process is highly iterative and open to the idea that a design problem may have many possible solutions. In this complex decision-making process of engineering design, students use Guilford's (1956) operations for productive thinking. For a successful solution, students need to bring several design elements into a harmonious balance (Guzey and Aranda 2017). This means focusing on design limitations, requirements, personal experiences, and science and mathematics knowledge. Students face uncertainty in this decision-making process (Jordan and McDaniel 2014). Navigating between and among these design elements requires more productive thinking and creativity when working in design teams.

Research on K-12 engineering provides some promising results related to improved student learning and achievement in science as a result of participating in engineering design activities (Berland et al. 2014; Cantrell et al. 2006; Dankenbring and Capobianco 2016; Park et al. 2018; Mehalik et al. 2008; Schnittka and Bell 2011; Wendell and Rogers 2013). Few studies, however, have investigated student design conversations which provides information about student learning and decision-making process that students engage in as they solve a give challenge (Akin and Awolomo 2015; Atman et al. 2005; Wolmarans 2015). These design conversations have also shown to make individuals decision-making and their thought processes visible as they move through the process of design (Adams 2015; Luck 2009; McDonnell 1997). The act of design is very creative and complex and requires students to make evidence-based decisions for successful design solutions, and there is a major gap in literature that analyzes how students in a K-12 space think about these complex decisions.

Much of the research in design conversation analysis has come from undergraduate design courses, where students work in teams to engineer solutions to capstone design projects. These studies tend to reflect a thorough examination of design processes, instead of focusing on how students think about the content within this context. For example, Atman and colleagues (2005) compared upper-division engineering undergraduate students to freshman engineering students as they developed protocols to different design challenges. In this sense, design processes refer to the steps in the design process, such as modeling, feasibility analysis, evaluation and decision-making. The conversations of engineering students in their freshmen and senior years were analyzed as they solved two design problems which tests their mechanical and analytical skills, and also their ability to solve problems in a real-life context. Their results reflect the increased level of sophistication in upper-level students as they solved an engineering challenge, which is not surprising as these students have increased knowledge of engineering and design processes. However, this framework does not account for the types of productive thinking that occurs as students solve these challenges. Understanding how students use different modes of thinking might shed light on the thought processes that occur as students solve these design challenges.

In another capstone design course, Wolmarans (2015) followed three design teams through their design review and evaluation to investigate undergraduate engineering students' use of disciplinary knowledge and practical knowledge in a specific design context. Analysis of teams' design discourse demonstrated that the teams performed differently while all teams successfully created a working prototype. The most successful team was found to made contextually dependent decisions based on both theoretical and practical considerations. Findings indicate that it is difficult for students to apply disciplinary knowledge into a specific context of a design problem. Natural design discourse seems to unfold development of ideas for design solutions.

Gathered collectively, studies have shown a major gap in the literature in understanding students' thought processes that occur as they enact a design challenge–particularly for K-12 students' thinking as they enact a science and engineering unit. With education reform standards highlighting the importance of integration of both science and engineering, work is needed to understand how design conversations might contribute to student's learning of both science and engineering. In the present study, we aim to shed light on these processes by analyzing the modes of productive thinking that occur when students solve a design-based engineering challenge in a middle school science curricular unit.

Research design and methods

Study design

In this qualitative and descriptive study, we explored how students think as they enact an engineering design challenge that served to integrate engineering into a genetics curriculum. Here we employed a case study analysis, which provides an in-depth examination of the different ways students thought about science (Yin 2014). This case is bound by the days in which students focused on solving their engineering design challenge, which occurred at the end of the curriculum.

Participants

For this case study, we examined a sixth-grade classroom from a Midwest suburban school, which was selected through purposeful sampling. This class was taught by Mr. Fisher (pseudonym), a teacher with almost 10 years of teaching experience who had previously implemented several engineering design-based science curricula (Aranda et al. 2018). We chose this classroom due to Mr. Fisher's willingness to implement this unit, high comfort level with teaching science and engineering, and his knowledge about engineering in K-12 classrooms.

Mr. Fisher participated in a 5-year professional development (PD) project, which aimed to help upper elementary and middle school science teachers improve their understanding and practices of reform-based science instruction. Teachers met each summer for 3 weeks, which provided teachers with many opportunities to engage in activities designed by the authors that focus on science and engineering teaching. Teachers completed a variety of engineering design-based science activities as students during the PD. At the end of the PD, teachers were asked to design a curriculum unit that teaches science and engineering in an integrated manner, and Mr. Fisher played a critical role in the design of the curricula in the present study, and its previous iterations (Aranda et al. 2018).

The school serves predominantly middle-class Caucasian students (75%) in a Midwest state. There were no English Language Learners, and only 3% of students were considered special education. The classroom examined in this case-study had 26 total students with an even distribution of males and females. Two student target groups were examined in this study, which contain four students per group that were representative of the classroom demographics.

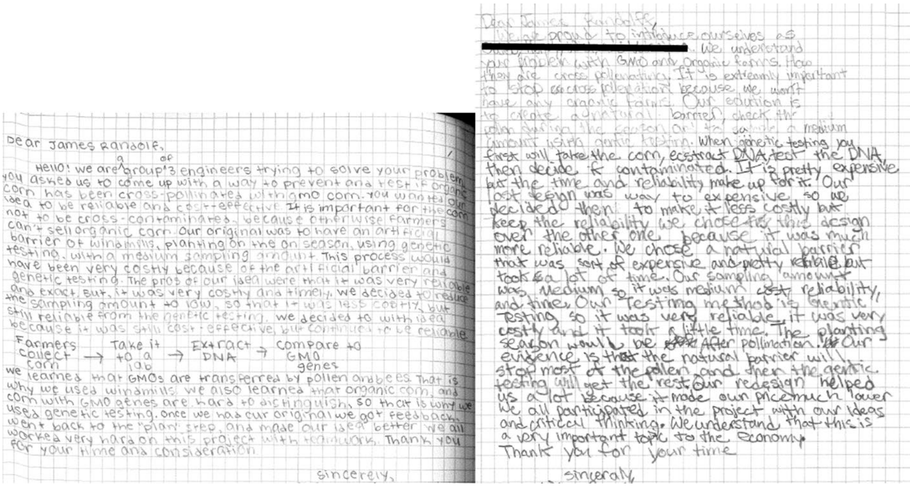
Curriculum unit

This unit was developed by three middle school science teachers (including Mr. Fisher), a graduate student with over 8 years of teaching experience and the first author of the study, entitled *Got GMOs*? The unit focuses on inheritance and variation of traits in the context of GMO plants. In addition, the unit includes science and engineering practices, such as defining problems, developing and using models, planning and carrying out investigations, analyzing and interpreting data, using mathematics and computational thinking, designing solutions, engaging in argument from evidence, obtaining, evaluating, and communicating information.

Table 1 shows the objectives and summaries of each lesson. Briefly, in this unit, students completed several science experiments and inquiry lessons to explore cells, to consider the relationship of the structure and function of DNA, to study sexual and asexual reproduction, and to explain basic heredity patterns found in nature. At the beginning of the unit, students were introduced to the concept of Genetically Modified Organisms (GMOs) and the client, a Midwestern University's Agricultural Extension Office, who requests that students design a process to both prevent and test for cross-pollination of non-GMO fields from GMO fields. As the unit was implemented in a Midwest state, this scenario provided an authentic context for the students to both learn engineering and scientific principles. It is important to note that while many design-based units require students to physically design and build a product, the present curriculum asks students to focus on the process of design instead. The authors of this unit purposefully chose to redesign this unit as such because previous iterations of the unit (Aranda et al. 2018) suggested students focused on the physical act of building instead of the genetic principles—where the goal of the present curricula was to focus more on both engineering and design principles and also genetics concepts. In this version of the unit, students are asked to consider constraints such as planting season, time and cost requirements of genetic testing methods, reliability of the testing methods, sampling amount and techniques for testing. In groups, they make design decisions to address these constraints in two phases: an initial design phase and then a redesign phase. After redesign, students then write a letter to the client discussing their designs. We provide two examples of reports written for the client in Fig. 1.

Table 1 Overview of the Got GMOs? unit

Lesson	Days	Content focus	Lesson summary
1. Introduction to the engineering challenge	1, 2,	Engineering, Science	Introduction to engineering challenge and GMOs
2. Introduction to DNA structure and function	3, 4,	Science	Introduction to structure/function of DNA; build DNA model
3. Genes and trait expressions	5, 6	Science	DNA connection to genes and alleles; PTC strips activity; DNA extraction experiment
4. Introduction to heredity	7	Science	Introduction to heredity and reproduction; stations to explore inheritance, a/sexual reproduction, plant fertilization via pollination
5. Applied heredity	8	Science, Mathematics	Introduction to heredity and probability with Punnett squares
6. Genetic modification	9	Science	Intro to genetic engineering; plasmid cutting activity
7. Designing a solution	10, 11, 12	Engineering, Science	Students use their knowledge of genes and heredity to brainstorm ideas on designs that describe how to prevent, sample and test for GMO cross-contamination
8. Redesigning a solution	13, 14	Engineering, Science	Students work to improve and redesign their testing strategy, while incorporating the constraints of cost, reliability, and time
9. Communicate with the client	15, 16	Engineering, Science	Students choose their best design strategy and justify their decisions in a presentation to the client



Dear James Randolf,
Hello! we are a group of 3 engineers trying to solve your problem. you asked us to come up with a way to prevent and test if organic corn has been cross-pollinated with gmo corn. You wanted our idea to be reliable and cost-effective. It is important for the corn not to be cross-contaminated, because otherwise farmers can't sell organic corn. Our original was to have an artificial barrier of windmills, planting on the on season, using genetic testing, with a medium sampling amount. This process would have been very costly because of the artificial barrier and genetic testing. The pros of our idea were that it was very reliable and exact. But, it was very costly and timely. we decided to reduce the sampling amount to low, so that it was less costly, but still reliable from the genetic testing. we decided to with idea because it was still cost-effective, but continued to be reliable.
Farmers collect corn → Take it to a lab → Extract DNA → compare to GMO genes
we learned that GMOs are transferred by pollen and bees. That is why we used windmills. we also learned that organic corn, and corn with GMO genes are hard to distinguish, so that is why we used genetic testing. once we had our original we got feedback, went back to the "plan" step, and made our idea better. we all worked very hard on this project with teamwork. Thank you for your time and consideration.
sincerely,

Dear James Randolfe,
We are proud to introduce ourselves as [redacted]. We understand your problem with GMO and Organic farms. How they are cross pollenating. It is extreamly important to stop cross pollenation because we won't have any organic farms. Our solution is to create a natural barrier, check the pollen during the season and to sample a medium amount using gentic testing. When genetic testing you first will take the corn, ecstract DNA, test the DNA, then decide if contaminated. It is pretty expensive but the time and reliability make up for it. Our last design was way to expensive, so we decided then to make it less costly but keep the reliability we chose this design over the other one because it was much more reliable. We chose a natural barrier that was sort of expensive and pretty reliable but took a lot of time. Our sampling amount was Medium so it was medium cost, reliability, and time. Our Testing method is genetic Testing so it was very reliable, it was very costly and it took a little time. The planting season would be After pollination. Our evidence is the natural barrier will stop most of the pollen and then the gentic testing will get the rest. Our redesign helped us a lot because it made our price much lower. We all participated in the project with our Ideas and critical thinking. We understand that this is a very important topic to the economy.
Thank you for your time
sincerely,

Fig. 1 Example reports from student engineering notebooks to the client

Data collection procedures

We aimed to explore how students think as they enact an engineering challenge within an engineering design-based science curricular unit. Therefore, our data collection was centered on student discussions of two small student target groups (4 students in each group). Student conversations were captured through audio recorders placed on the center of the table as they enacted the unit. The target student groups were teacher-assigned and mixed in both sex and academic performance. Mr. Fisher identified the two target groups for the study.

It is important to note that while the unit took 16 days total to complete, audio recordings were only analyzed on the days of the unit that students were focused on the engineering design challenge (days 10–15). These days include the lessons that focused on planning a solution, redesigning, and communicating their solutions to a client, which allows us to address our research question of understanding the modes of thinking that occur during these design conversations. On the other days of the unit, students were engaged in only science activities or whole-group discussions following science activities which were not analyzed in this case study since these did not include any design conversations.

Data analysis

To investigate the ways students think as they engaged in the design challenge, we employed conversation analysis approach (Psathas 1995). This allowed us to analyze the naturally occurring conversations during the implementation of the unit. This analysis occurred in several stages, where we first transcribed all audio data from the two target groups during the days focused on the engineering-design challenge (days 10–15). Then we identified specific segments of recorded conversations, namely coherent, conversational units or episodes (Psathas 1995) that focused on science and engineering as they planned, redesigned, and communicated their design decisions to the client. These episodes were sequentially organized as students moved through the engineering challenge and also varied in length, ranging from a few brief statements between students to slightly longer conversations, but all episodes encompassed a scientific and engineering discussion as they enacted engineering design. It is important to note that we did not focus on Day 16 of the unit because this day focused on the post-assessment for the curricula and no design conversations were observed.

To analyze these episodes, we employed Gallagher and Aschner's (1963) analytical framework to describe thought processes of the two student target groups. This framework was originally developed by Guilford (1956) to examine productive thinking and has been widely adapted to investigate the types of thinking that occur as students and teachers ask questions in the classroom (i.e. Vogler 2005; Humphries and Ness 2015). Here, we employed the framework to analyze student utterances for the types of thinking that occur in each episode as they enact the engineering design challenge. This analysis includes four distinct ways of thinking and can be classified in increasing levels of sophistication. At the lowest level of classification, Cognitive Memory, students simply recall scientific facts or processes and also define what it is that they specifically need to know. Convergent Thinking is a higher level of classification because this requires students to apply and analyze knowledge. In this type of utterance there is typically only one answer, meaning it is not an open-ended statement or way of thinking. In contrast, Divergent Thinking describes a more sophisticated type of utterance because these responses lead to multiple answers and responses as students hypothesize and predict information. At the highest classification of thinking, Evaluative Thinking, students must defend and justify their choices as they evaluate information.

Our version of the coding framework was modified to focus on student utterances instead of student questioning and is illustrated in Table 2 with representative examples of each code. Of the 5 days of student-centered data, 50 episodes were chosen for analysis to examine how their knowledge of science was reflected during the engineering design challenge. After initial training with the coding framework, each episode was coded by two coders. These coders met regularly to check for discrepancies and then coded to consensus.

Results

Our examination of two student target groups revealed that students employ a variety of modes of thinking as they engage in design conversations during an engineering design-based science curricular unit. The engineering challenge within the curricular unit is divided into three distinct stages, and our results suggest that students' thinking differ in each stage, as reflected in their group conversations. Our results are therefore divided into each of these stages: Plan a Design, Redesign, and Communicate to the Client.

Plan a design

The first stage of the design process requires students to plan their design solution to both prevent and test for cross-contamination from GMO plants to non-GMO plants. In this initial stage, students first review the engineering challenge and the scientific and math principles they learned throughout the unit, which they then use to formulate a plan to solve the engineering challenge. In the present curriculum, students are required to make design decisions to both prevent and test for cross pollination of GMO plants to non-GMO plants

Table 2 Coding framework for student utterances. (Adapted from Gallagher and Ascher 1963)

Statement classification	Description	Examples
Cognitive memory	Operations that involve recalling facts, formulae, and other content Also involves defining, identifying, or designating	Plants need pollen to reproduce
Convergent thinking	Involves analysis and integration (application) of given/remembered data It leads to one expected end-result or answer	If we include these changes, how much will our design cost?
Divergent thinking	Operations where the individual is free to generate their own solution Requires students to predict, infer, hypothesize, and/or reconstruct information	We can change where they pollinate and who they pollinate with
Evaluative thinking	Deals with actions involving judgement, value, and choice Requires students to defend and justify their choices	What about the pollen that these crops produce? Won't it be bad for the organic ones? Unless we use [student's] idea of organic crops, then that may work

instead of physically building any design they create, as often seen in other engineering design-based science curricular units.

During this stage, we observed that there was a similar proportion of episodes that contained either Cognitive Memory, Divergent Thinking, or Evaluative Thinking (Fig. 2). It is not unexpected that there was proportionally high occurrence (31% of episodes) of Cognitive Memory-type responses since students needed to recall the science content to formulate their plans (Fig. 2). Interestingly, we observed many instances of Divergent and Evaluative Thinking (25% and 29%, respectively). We observed several instances of Divergent Thinking meaning that students were developing their plans by hypothesizing and predicting what they thought would occur, and these predictions lead to a variety of possibilities. For example, the exemplar quote describes how students are predicting what might happen in their effort to prevent cross-pollination from occurring:

Student 1: Yeah, you open the door, and pollen gets in.
Student 2: Well, I think the chances are slighter than just–
Student 3: Much, much slighter.
Student 1: Yeah, but that's still a chance. You want something to be completely different. You can have barriers, except you have to have a certain amount of space in between, instead of having it like literally right next to each other.

These types of conversations allow students to not only recall knowledge and apply what they know but allows them to extend their ways of thinking to hypothesize what would happen with their design decisions.

In addition to Divergent Thinking, we observed several instances of even higher-order thinking, meaning that students employed Evaluative Thinking as they planned their designs. This type of thinking is characterized by justifying their decisions and was observed in conversations where students needed to justify their proposed designs to their peers. For example, the following quote highlights a student defending their ideas

Student 1: I would actually go with low [sampling] because genetic testing is super costly, and if we go with medium that's going to be much more costly.

Here, the student is justifying one of their design decisions for how much corn to sample, and then defends their choice for a low sampling amount of corn because they want to

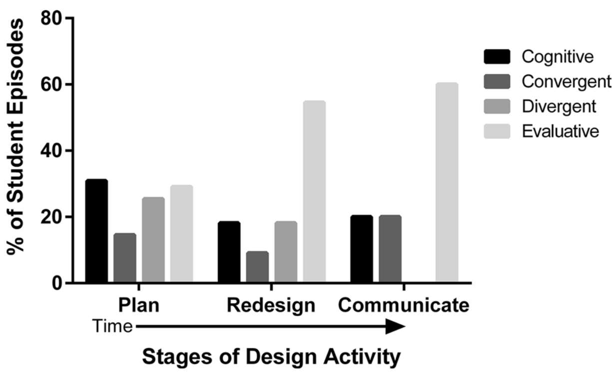


Fig. 2 Observed frequency of student episodes aligning with statement classifications according to the adapted productive thinking framework. Observed

employ a more costly method to test for cross-pollination. The trade-off between cost and effectiveness provided a context for students to evaluate their design decisions.

Redesign

The redesign stage in the design process is characterized by students reviewing how well their first solution to prevent GMO contamination and testing for GMO crops performed. Students received feedback from the client, allowing for the opportunity to improve upon their initial design. Here, we observed an increase in the proportion of episodes (87.5% increase) that contained Evaluative Thinking statements from the students (Fig. 2). This was expected to some degree, as students were encouraged to evaluate how well their initial design performed. Students recognized the shortcomings in their first design and had to alter several aspects of the design in response to client feedback. In the following example, students recognize that their initial solution was too costly for the client:

Student 1: If we wanted to, we could lower the cost again. Yeah, we should just do the other one [genetic testing] after 10 years, because that would make the conflict much easier.
Student 2: But that'd also lower the reliability.
Student 1: Not that much.
Student 2: But it's still lower by a point, and the cost would only go down a point. So, it'd probably be the same.
Student 1: No, the cost would go down double.
Student 2: No, exactly the same. And our time would go up.
Student 1: Time would go up. But I think we already have 5.

In order to stay within the budget, the students had to make compromises by examining one of the aspects of their design—genetic testing. Specifically, they alter the frequency of the testing to reduce the cost, despite reducing the reliability of their testing strategy. This represents a key feature of evaluative thinking—assigning value and making decisions based on each components' assigned value. The consideration of limitations and affordances in a design is frequently observed throughout the redesign episodes and is a key feature of this stage.

Similar to the Plan stage, students had to modify old solutions or generate new ideas. This is represented by a profile (proportion of coded episodes) similar to the plan stage, albeit slightly less, of cognitive, convergent, and divergent-type statements (Fig. 2). In the following example, we observe dialogues similar to the planning stages:

Student 1: Well, actually… the blue corn, you can tell that-
Student 2: Wait, blue corn?
Student 1: Yes. You can tell that it tastes pretty normal, okay? But you can tell if they've been modified, there's no blue kernels. That's when you can tell that has been modified, but when everything is already yellow.
Student 3: Well…
Student 1: It's a brighter formed yellow.
Student 4: Well, yeah.
Student 3: So you can have like two pictures up on your monitor.
Student 4: Visual observation can also be there. That's also good observation.

In this student episode, the students are considering alternative methods to detect GMO crops. Student 1 recalls that natural corn may have blue kernels, whereas GMO corn strictly has yellow kernels. The group further reasons that this visual difference between organic and GMO corn could be a method for identifying contamination of organic corn fields. The student converges upon this idea and incorporate it into their revised design.

Communicate to the client

This stage of the design process allows for students to consolidate their thoughts on the solutions that they generated throughout the planning and redesign stages. For this activity, students had to create a presentation to give to their client. The presentation essentially followed a sales-pitch format, where they try to convince the client to choose their group's design. Throughout the drafting of their presentation, students highlighted the ideas that fit the criteria and constraints and reflected upon the shortcomings of their design. We did not observe any Divergent statements during this stage, which is not surprising in the context of the design process, as this stage did not lend itself to idea generation. There were several instances where we observed Cognitive and Convergent Thinking, as these were mainly recalling facts and drawing consensus among the group on what ought to be included in their client letter. Instead, we observed that students were reflective of their designs, in order to convey the successes and shortcomings of their solutions to the client's problem. Of the student episodes, a majority contained Evaluative thinking with some Cognitive and Convergent Thinking as well (Fig. 2). The following conversation illustrates the level of Evaluative Thinking:

Student 1: "Explain why it's important for cross-contamination for the crops for the… " What? Oh. "Explain how it's important to prevent cross-contamination for the crops for the farmers."

Student 2: It is not… I can't say anything because it isn't the root of the problem in the first place. So, I don't know what I'm supposed to say.

Student 1: What do you mean? Why don't you agree with the problem of cross-contamination?

Student 2: I think we shouldn't worry about cross-contamination because we need the GMOs, okay? So we shouldn't be spending a whole bunch of money trying to prevent GMOs from cross-contaminating when we should actually spend our money on creating more GMOs that help us more.

Student 1: But you do realize that that helping us will kill other species? Remember, those bats have been dying up… there's actually a GMO, I believe that there's a bat disease that's been killing a lot of brown bats, and it's a… white-nose something. That's a symptom of …

Student 2: Isn't that the fungus? I think I've heard of it.

Student 1: It's pretty infamous. GMOs, they will help us, but… if there's a way we could make a GMO not kill the environment, we'd need more GMOs.

Here, these two students evaluate the necessity of GMOs to our society. While they see how GMOs benefit human society, they also see the potential of GMOs to have negative ramifications on ecosystems, using brown bats as an example. This conversation highlights the complexity of the client issue, and the consideration of related issues surrounding GMOs.

Discussion

In this study, we analyzed student group discussions in a sixth-grade science classroom enacting a design-based science unit. Our work contributes the growing body of literature on design thinking, particularly highlighting and characterizing the types of verbal interactions that occur among students participating in design-based science curricula. This study specifically examined the composition of productive thinking operations (Cognitive, Divergent, Convergent, and Evaluative) throughout three stages of the students' design process. Students had to recall science and engineering information, generate potential solutions, and make decisions in order to meet the criteria and limitations posed by the client, which led to rich discussions that effortlessly blended science and engineering thinking.

Using a productive thinking analytical framework (Gallagher and Achner 1963), we identified two overarching phases that captured student thinking throughout the design process: idea generation and the reflective stage. Idea generation is characterized by a balance of each of the four thinking operations, as was observed during the planning stage of students' discussion. During this phase, students had to recall relevant science content and apply that information to generate multiple possible solutions. Additionally, students debated on which of these ideas would best address the client's criteria and eventually converged on a set of design decisions. These discussions fluently vocalized each the four types of thinking operations to produce students' first design. Their initial designs weren't without faults, which led to the subsequent redesign stage. The reflective phase is characterized by a shift towards Evaluative operations, which took place during the redesign and communication stages. This intuitively makes sense, as students were encouraged to reflect upon the shortcomings of their initial design. Furthermore, students only needed to generate solutions regarding aspects of their design that fell short of the client's criteria, which possibly explains the decreased amount of Divergent and Convergent operations. The communication stage also parallels the redesign stage in that students' conversation were predominantly evaluative in nature. Students judged which aspects of their two designs fit the client's criteria and determined how to present such information.

Design is a complex task and as supported by our findings, it provides many opportunities for students to engage in various thought processes. The engineering design process is highly iterative and encourages the use of disciplinary knowledge and practical knowledge in specific design contexts (NRC 2001). It equips students to recognize the interconnections among various design elements. Cycling through generating ideas and deciding among existing alternatives is inherent in the engineering design process (Brown and Katz 2009). According to Lawson (2005), "designers must solve externally imposed problems, satisfy the needs of others and create beautiful objects" (p. 153) which reflects this need for designers to implement different modes of thinking as they embrace creativity in design. Students' use of Divergent modes of thinking during this engineering design challenge shows how it is an essential part of the engineering design process and an engineering-design based curricular unit provides an avenue for students to explore their creativity.

As engineering design has been slowly integrated into K-12 science classrooms (NRC 2012; NGSS Lead States 2013) teachers should provide opportunities for students to engage in productive design conversation. For purposeful and successful engineering integration, we recommend that teachers use engineering as a vehicle to teach science. In our experience teaching engineering in K-12 science classrooms, we have found it more effective to implement engineering design challenges that require students to apply science to their design solutions. We believe that as students apply scientific knowledge in the design context they engage in high level thinking processes. In addition, engaging in redesign is critical for students since it allows them to pay attention to their product and reflect on the process. We also see that design at the K-12 level can be varied and students employ different thought processes depending on the design task and their content knowledge. But recognizing the fact that design is new to many K-12 students, teachers should assist students to successfully navigate challenges and make evidence-based design decisions.

Conclusions

In this study, we propose that K-12 students engage in various thinking processes as they engage in an engineering design challenge. Simply put, engineering design allows students to practice different thought processes. In the Divergent phase of a design problem students create choices or alternatives while in the convergent phase they make choices. Making choices require students to evaluate, analyze, and synthesize competing solutions against one another. These cognitive processes are vital for students since design is highly complex. Future research can further explore these various cognitive processes within this context and how this relates to student learning of both science and engineering principles.

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