Student Communication of Engineering Design Solutions (Fundamental)

Alexandria Muller, University of California, Santa Barbara

Alexandria is a third-year doctoral student working with Dr. Danielle Harlow in the Gevirtz Graduate School of Education at University of California, Santa Barbara. She received her B.S. in Ecology and Evolutionary Biology from the University of Arizona in 2017. She has worked with informal science institutions for the past 11 years, including The Chandler Museum, Tucson Children's Museum, and Biosphere 2. Currently, her research interests are facilitator, curriculum and exhibit development within informal science environments as well as Research- Practice Partnerships to benefit the local community. For more information about current projects and interests, please visit alexandriamuller.com.

Liliana Garcia, University of California, Santa Barbara

Liliana is a doctoral student interested in STEM Education under the guidance of Julie Bianchini at the University of California, Santa Barbara. She earned her B.S in Physics and obtained a single subject teaching credential through CalTeach at UC Irvine. Liliana previously worked with Upward Bound Trio Programs at Occidental College, preparing under-represented youth for successful pathways into college and work environments. Her experiences as a first-generation low-income student and as an educator in the Upward Bound program have shaped her research interests to include a culturally equitable curriculum in science for students in minority communities and science identity for under-represented groups.

Ron Kevin Skinner, MOXI, The Wolf Museum of Exploration + Innovation

Ron Skinner, Research and Evaluation Specialist at MOXI, The Wolf Museum of Exploration + Innovation

Ron Skinner has been involved with science education and research for the past 30 years. He has taught physics, astronomy, and general science in formal settings to audiences from kindergarteners to graduate students in the schools of the Lucia Mar School District, and at Cornell University, University of California, Irvine, and Santa Barbara City College. He has worked in informal STEM education at the Santa Barbara Museum of Natural History and MOXI, The Wolf Museum of Exploration + Innovation. As MOXI's first Director of Education, Skinner created the philosophical vision for the department, mapped out a five-year strategic plan, and built up an education staff of five full-time employees, 20 part-time employees, and over 100 volunteers. He planned, budgeted, and implemented a full slate of informal and formal education programs; collaborating with teachers and school administrators, university departments, science and technology companies, community organizations, and donors.

At MOXI, Skinner's current role in education research focuses on training informal STEM facilitators and engaging visitors in the practices of science and engineering. He is the principal investigator on two collaborative NSF grants and one sub-award with UC Santa Barbara, where he is also pursuing doctoral work in education research.

Skinner's science research experience includes marine science fieldwork along the Northern California coast; plasma physics research at the University of California, Irvine; and nanotechnology research at Sandia National Laboratory. He gained practical engineering experience as a patent reviewer for Lenker Engineering and a software engineer for both Pacific Gas and Electric Company and Visual Solutions, Inc. For 14 years he owned and operated an organic farm, where he developed and directed a yearlong apprentice program in sustainable agriculture, ran informal education programs both on the farm and as outreach in local schools, and designed and fabricated small-scale farming equipment. He holds a B.S. in Engineering Physics from Cornell University and an M.S. in Physics from the University of California, Irvine.

Dr. Danielle Harlow, University of California, Santa Barbara

Danielle Harlow is a professor of STEM education at the University of California, Santa Barbara.

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Introduction

With the introduction of the Next Generation Science Standards [1] engineering is now being incorporated into K-12 classrooms for the first time on a national level. As such, there is an increased need to understand how children communicate during engineering activities to best support their learning. In elementary classrooms, where young students are in the process of developing their verbal capacities, gestures from both the teacher and students serve as a key component of communication of new ideas and the processing of social information [2]. Thus far, research efforts to understand how students of all ages use gestures to communicate and understand new ideas have focused primarily on mathematics and physics [3]-[6]. The goal of engineering is to design and optimize solutions to engineering challenges, making the tasks that students engage in and the ways they communicate ideas different from the ways they communicate ideas in math and physics. In addition, multimodal communication (the use of touch, gesture, talk, body position, and placement of objects) has been identified as a key part of productive communication within engineering design teams and allows for students to better engage within engineering discussions among peers [7]. While we can utilize existing work on gestures in educational settings to begin understanding the role of gestures in engineering education, our understanding of how students communicate through gestures when discussing and interacting with a tangible object of their own creation (a prototype) is underdeveloped. We investigated how students used gestures and prototypes when describing their design solutions in an engineering activity in hopes that a deeper understanding of youth communications around engineering can support educators in leading richer engagements with engineering.

Literature Review

There has long been a push for schools to integrate engineering into K-12 education. Advocates of K-12 engineering argue that engineering provides opportunities for students to integrate multiple subject areas and to develop critical problem-solving skills [8]. In addition, studies have found that, in comparison to other children, elementary school students who participate in engineering activities have an increased understanding of science, engineering and technology [9]. A study by Yoon and colleagues [10] found that students in classrooms that integrated engineering concepts into the curriculum performed better on written assessments measuring student knowledge of science, work of engineers, the engineering design process, and technology than those who did not participate in an integrated classroom environment. English and Mousoulides' [11] study found that elementary students who were exposed to engineering were better prepared for high school and college-level coursework and had a greater appreciation for how their learning of STEM topics in school connected to the real-world. Unfortunately, teachers express discomfort teaching engineering within their classrooms [12]. As such, several groups have worked to develop engineering curriculum and teacher supports for elementary school teachers to use in the classroom (see *Engineering is Elementary* [13]; and *Engineering Explorations* [14]). These curricula include opportunities to assess student learning through verbal discussions in small groups or as a class, or through written assessments such as engineering portfolios or worksheets outlining their thought processes during the design phases. These assessment tools, however, do not capture the rich sources of student thinking found in the embodied expression of student ideas and descriptions which may point to a hidden layer of student understanding not found in oral or written works.

In young children, communicating through physical movement develops before oral communication [15]. Due to the early use of the physical body in communication, children may feel more comfortable communicating through physical movements than through verbal communication. In this paper, we follow literature that defines gestures the physical movements made by the youth that contribute to the communication of ideas [16]. Gestures are not subject to the same codification of oral or signed speech and, as such, can take on many forms to represent ideas that cannot be adequately portrayed through speech [17, 18]. Conscious gestures may be used to intentionally strengthen communication of certain ideas expressed verbally (pointing while giving directions) or may serve as a secondary modality to express ideas (modeling how two cars collided in a car crash). Gestures can also be a subconscious attempt to communicate underlying thought processes or ideas that are not expressed in speech [18, 6]. For example, if a student mentions that their family is going to New York for the summer while making a sweeping motion with a flat hand, similar to a plane taking off, we can postulate that the student intends to fly to New York rather than drive or take a train which would have different gestures associated with them. These subconscious gestures are a potential window into speakers' thinking [6].

Researchers on gestures have identified three main categories of gestures: physical object representation, abstract object representation and nonrepresentational hand motions [18]-[21]. Physical object representations are gestures where the hands represent objects that are physically present in the situation being discussed. For example, if a student is discussing the trajectory of an object in motion, they may use their hands to model the pathway. In this study, because students held a physical prototype in their hands while communicating, we expanded this category to include representations of physical objects as well as gestures that used the prototype. Abstract object representations are gestures where the hands represent abstract concepts as though they were concrete forms. An example of this would be if a student compared two different testing environments and created a circle with their hands to the left of their body indicating a certain grouping of ideas for one testing environment and another circle with their hands to the right of the body to indicate the second. Lastly, nonrepresentational hand motions are gestures that do not represent any ideas but rather provide context for the spoken word such as pointing when providing directions to someone. This does not represent either a physical object or an abstract concept, but rather is an embodied component of the verbal exchange.

Methods

Research Context

Engineering Explorations is the result of a Research Practice Partnership (RPP; [22]) between an interactive science museum and a university in southern California. The goal of Engineering Explorations is to develop modules that connect classroom learning to field trips at the interactive science center [14]. Each module includes two activities that are completed in the classroom prior to a field trip. These activities are designed to provide opportunities for students to develop ideas that relate to the engineering design challenge that will be presented in a subsequent field trip. The students then attend a field trip to the interactive science center where they engage in an engineering design challenge. Finally, the modules also include a post-activity done in the students' classroom that provides opportunities for students to reflect on and expand upon the learning from the three previous activities. Each of the four activities within each module is designed to take 50-60 minutes (thus the full module is approximately four hours of instructional time). For this study, we focus on one module, *Riding the Rising Air*. The four activities that make up this module are described below.

Activity 1 (Classroom): The first classroom activity introduces students to the relationship between surface area of an object and its rate of fall. Working in small groups of 3-4 students, students construct a small, medium, and large parachute using lightweight paper, tape, string and a penny or metal washer. They then drop the parachutes simultaneously from a height of one meter and record the parachute that fell the slowest (landed last). After collecting data from ten drop tests, students then create a bar graph of their data and engage in a whole class discussion about why the larger parachute fell the slowest more often than the smaller parachute.

Activity 2 (Classroom): The second classroom activity leads students through a guided engineering design process in which students apply their developing understanding of the relationship between surface area of a parachute canopy and the rate of fall of the parachute. Students reflect upon their findings from activity 1 and are then presented with the engineering design challenge: To design a craft that slows the fall of a washer or penny. In this challenge, they are not given string and thus cannot just recreate a parachute. Students first work individually to brainstorm and construct their first design. Following the construction of their design using only paper, tape, and a penny or washer, they perform a drop test from a height of one meter to compare their craft's performance to that of a free-falling washer. After this test, they iteratively improve their design two times, performing a 1-meter drop test after each improvement. Following a 20-minute period of iterative design, development, and testing, students engage in a class discussion to compare their design solutions.

Activity 3 (Field trip): At the science center, students engage in a visual thinking strategy [27] exercise where they observe an image of a city with a wildfire in the background (see [24] for a description of the activity). They discuss their observations and inferences from the image while a facilitator highlights student ideas that emphasize the movement of the smoke which appears to be rising from the fire. Students are then presented with the engineering design challenge for the day—design a craft that will hover in the column of upward moving air above the fire while holding a penny-sized sensor to collect data for firefighters. Museum facilitators guide the students to the wind column exhibit (see Figure 1), which serves as the test environment for student design solutions, where they demonstrate how a flat and crumpled piece of paper behaves in the rising air. Students then draw their initial designs and develop their craft using paper, tape, and hole punchers with a penny to represent the sensors. Following a period of development, students test their designs in the wind column exhibit and iteratively improve upon their initial models. At the end of the field trip activity, students draw a representation of their final designs to serve as a "blueprint" for activity 4.

Figure 1. Image of wind column exhibit at museum.

Activity 4 (Classroom): In the classroom, students reflect upon the field trip activity as well as the other two classroom activities. They discuss the differences between the classroom drop tests and the museum wind column tests and create a T-table (two column table) identifying key differences and subsequent design choices the students made in each design. After, each student receives a "blueprint" of a classmate's final design from the field trip. They work to reconstruct their classmates' designs and discuss design choices with the original creator to ensure fidelity. Afterwards, they perform a drop test to observe how the craft designed to hover slows the fall of a washer or penny. After noting the design's performance, students then alter the design to better slow the fall of a washer or penny in the classroom environment. They end the activity with a full-class discussion about why certain design changes were made.

Together, the Riding the Rising Air module provides students with opportunities to develop an understanding of balanced forces, work on engineering designs, and discuss their ideas with peers and with the whole class.

Data sources

The field trips were implemented with over 200 classrooms over the course of two years. Of these, 14 classrooms (ranging from Kindergarten to grade 6, ages 5-12) from three focus schools participated in the full *Rising the Riding Air* module as described above. During the implementation of this module in these classrooms, we collected teacher interviews and written surveys before and after the module, student work, video and audio recordings of classroom and field trip activities, museum facilitator reflections, and project team field notes. For this study, we chose to focus on the video recordings of students discussing their design solutions. The initial collection of video observations was not informed by the intention to study student communications through gestures and physical representations of their design solutions, but rather was aimed at capturing student ideas communicated verbally. As such, the videos readily available that clearly captured student movements during a discussion were limited. We identified seven video recordings from a single first-grade (6-7 years old) class that captured students communicating their ideas about their design solutions while holding their physical representations, or prototypes, of their design solutions that were used in this study. The videos were selected due to their focus on an individual youth's thought process when designing and testing their design solutions. All videos consisted of a single student whom an adult had asked to explain their design solutions to be recorded. An adult facilitator from the research team asked questions throughout the interaction to further the discussion. Table 1 describes each of these videos which range from 16 seconds to 56 seconds with 4 different students. All student names have been changed to pseudonyms to protect their identity.

Table 1.

Descriptions of Videos Identified for Analysis

Youth Pseudonym	Video Description	Module Section	Length of Video
José	Student describing design meant to hover in wind column prior to testing	Activity 3 (Field Trip)	00:56
José	Student describing design changes after testing. Is currently re-testing design during this interaction	Activity 3 (Field Trip)	00:48
Melody	Student describing design meant to hover in wind column prior to testing	Activity 3 (Field Trip)	00:54
Samantha	Student explaining design prior to testing	Activity 2	00:15
Kyle	Student explaining design that was meant to slow the fall of the washer after having tested it in the classroom	Activity 2	00:47
Kyle	Student explaining design that was meant to slow the fall of the washer after having tested it in the classroom	Activity 2	00:16
Kyle	Student comparing design behavior of a design intended for the wind column in the wind column and in the classroom	Activity 4	00:43

Data Analysis

Each video was first transcribed for verbal communications to serve as a map for gestures. We then proceeded with two phases of analysis to first identify all gestures used by the students and followed by an in-depth analysis of gestures that used the prototype present in the youths' hands. These phases are described below.

Phase 1: Coding for Gestures. Each video was analyzed and coded for gestures made by the student. Gestures, as defined above, are any physical movements that contribute to communication. Starting with a transcript of students' talk, movements that were made in connection with discussion topics were identified and coded as a gesture. For example, if a student said "because the air can float it up" while lifting their design solution above their head, this was coded as a gesture. Each gesture identified in the videos was then classified as one of the three types of gestures: physical object representation, abstract object representation and nonrepresentational hand motions [18] – [21].

Phase 2: Coding for Use of Prototypes. One key difference between this project and the existing work done in math and physics education on embodied cognition, as well as the work on the use of gestures in learning and communicating, is the presence of student prototypes that are central to the activities. Research on math education has looked at how students use physical objects, referred to as manipulatives, as a cognitive off-loading tool [23]. In contrast to manipulatives in math education that are designed and produced for students, in engineering, students construct physical objects – or design solution prototypes– as an essential part of engaging in engineering practices. In each of the videos selected for this study, students hold their prototypes that represent their design solutions. After identifying the gestures used by the students, we further investigated the gestures coded as physical object representations. In this study, all gestures coded as physical object representation used the prototype rather than their hands to represent a physical object.

Using emergent coding, we identified common themes for how students used their prototypes when gesturing. The full codebook can be seen in Appendix A. One researcher (Muller) identified emergent themes from all seven videos and constructed a preliminary codebook for coding the use of physical representations of design solutions in communications. Two researchers (Muller and Garcia) then coded 19% of the data to establish an interrater reliability of 80% for coding of gestures, and 80% for coding of use of physical representation of design solutions. After establishing interrater reliability, all videos were re-coded using the complete codebook (See Appendix A).

Results

We identified five ways that students used their prototypes as a tool within their communications: (1) as a reference tool, (2) to demonstrate the flight path of the design, (3) to answer questions non-verbally, (4) to assist in the mental process of constructing an answer to a question, and (5) as an anchoring point in the discussion through the showcasing of their prototypes.

Referential Use

When communicating, all students used the prototypes of their design solutions to refer to the aspect of their design they were discussing.

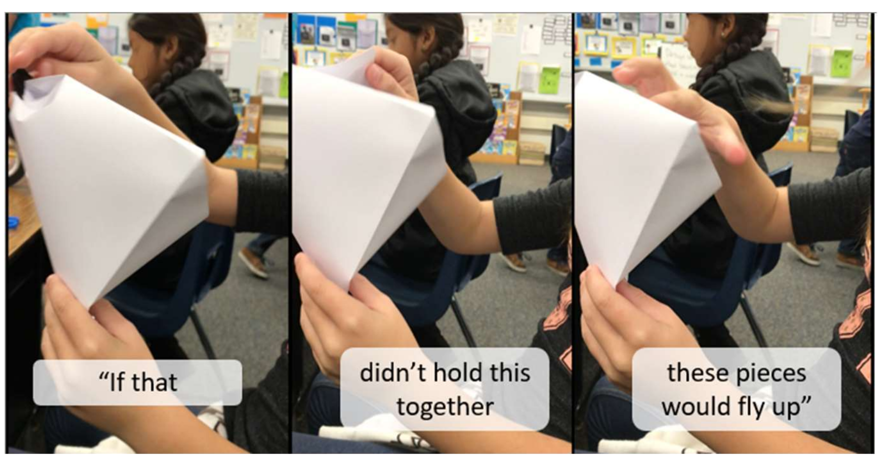

Figure 2. Samantha providing a frame of reference by pointing to different parts of her design solution while speaking.

These motions included pointing, pinching, or positioning the design solution so a specific part could be seen. All gestures coded as non-representational motions (motions connected to speech that did not represent any ideas) used the prototypes in the movements. An example of this can be seen when Samantha explained why she taped the top of her design solution (Figure 2). Each time she refers to a different part of her design craft using demonstrative pronouns (that, this, these), she moves her hand to gesture to the area she is discussing. When saying "that" she points with her forefinger to the taped portion of the craft, when saying "this" again later, she pinches and lifts the flap on the top of her craft, and when saying "these" she points to two points on the craft. Without these gestures, the adult would not be able to understand what Samantha was referring to in her explanation. The physical object and the gestures were used in connection with each other to fully communicate ideas.

Demonstration of flight path with prototype

As a part of the design challenges presented in this module, students either dropped the prototypes of their design solution to see how they fell in the classroom environment (activity 2) or placed them in a wind column at the museum during the field trip (activity 3). In both instances, the crafts were released and moved through their air. Students used the prototypes as

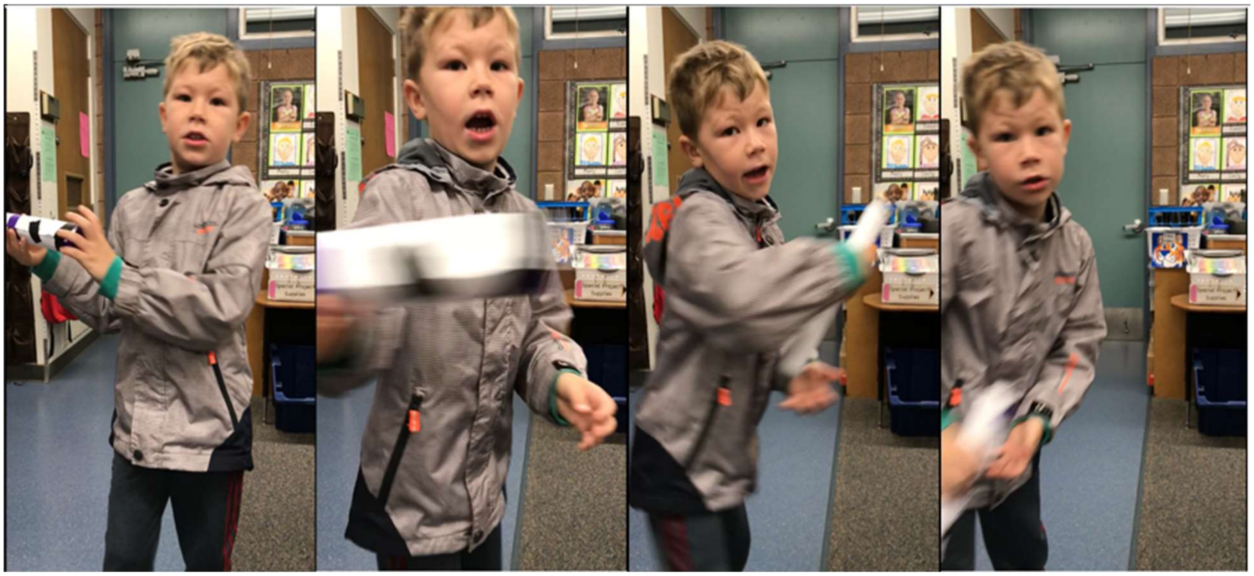

Figure 3. Kyle using the prototype of his design solution to demonstrate the spiral path of his craft.

part of their gestures to demonstrate the flight path of their crafts. For example, when describing how his design solution would perform when dropped it in the classroom, Kyle demonstrated two possible movements of his craft. He described, “there’s holes so air can still get in when it goes down” at which point he released the prototype of his design solution from eye level into a freefall towards the ground. Following this, he explained how a change in the releasing of the craft would alter the flight path. He explained, “when you do it like this” demonstrating moving his craft like how one would throw a paper airplane or football, “it goes like a paper airplane kind of except it goes kind of fast.” He then proceeded to move his prototype in a counterclockwise spiral motion towards the ground (see Figure 3). These two different types of demonstrations (free fall and controlled) were common across the data.

Answering Questions Non-verbally

Students were able to answer questions posed by the adult without the use of words. During the field trip activity, Melody was asked where the air would go when testing her parachute-inspired design solution. Rather than verbally responding to the question, she rapidly pointed to the under-side of the canopy of her prototype (see Figure 4). She later responded, “right there;” however, having her the prototype of her design solution allowed her to provide a quick answer to the adult’s question while giving her time to construct a verbal response.

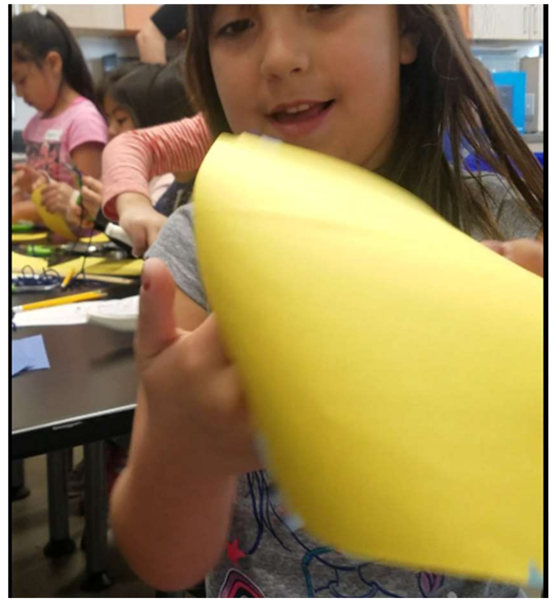

Figure 4. Melody responding to a question non-verbally by pointing to the underside of her prototype.

Constructing an Answer to a Question

Throughout these interactions, the adult posed several probing questions to better understand the student’s thinking. Three of the four students observed used the prototype to help formulate a response to the adult’s questions. After being asked a question, students turned to their prototypes, manipulated them in some way, and then verbally responded to the question. For example, during the field trip activity, Melody mentioned that she had folded the square paper used to create her parachute-inspired design. When asked “what is the fold going to do?”

Figure 5. Melody unfolding and refolding her design solution when formulating a response to the question “what is the fold going to do?”

she looked down at her prototype and stretched it out with the washer in one hand and the canopy in the other. She then grasped the canopy in both hands, unfolded it and then re-folded it (see Figure 5). After going through this process, she responded “I don’t know.” Despite not being able to articulate a verbal response describing her intentions behind the fold, of which there may or may not have been since she followed the design from a previous classroom activity, she demonstrated the use of her prototype in her thought process when trying to answer the question.

Showcasing of Prototypes

In all the videos that captured the beginnings of the interactions between the adult and youth, students started by presenting their prototypes to the adult, by moving the design solution closer to the adult and sometimes lifting it closer to eye level. This movement served as an anchoring point for the resulting discussions with the adult. For example, Kyle presented his design solution as the adult was approaching to engage him in conversation. As the adult approached and asked how the design solution performed in the wind columns during the field trip, Kyle moved his prototype along the desk closer to the adult prior to

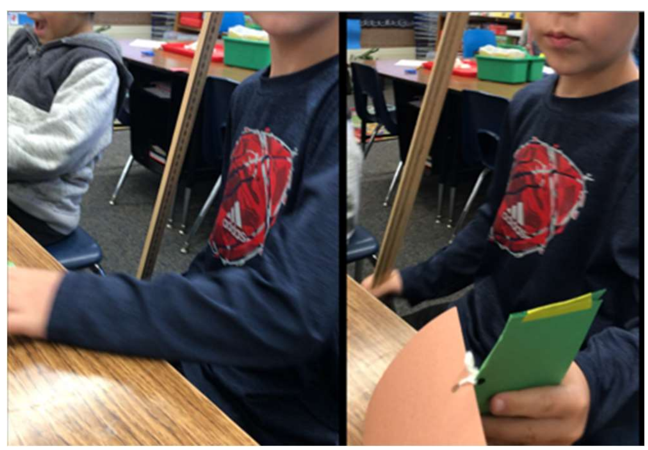

Figure 6. Kyle repositioning his design solution prior to responding to the question posed by the

responding to the question (see Figure 6). This movement permitted a clear view of the design solution being discussed without specifically stating such.

In addition to starting conversations with a showcasing of the prototype, students also showcased their designs when a new person entered the conversation. In the fieldtrip to the interactive science museum (Activity 3), José was demonstrating the expected flight path of his design solution to the adult when a student seated next to him interrupted to comment on José's thought process during development. Upon the second student entering the conversation space, José moved the design solution away from his body into a raised position between himself, the new student, and the adult. This movement is depicted in Figure 7. Thus, the showcasing of the design was not present solely at the beginning of child-adult interactions, but also arose when additional voices entered the conversation space.

Figure 7. José moving his prototype to the center of the conversation speech when a new student joined the conversation.

Discussion

Engineering centers around the design and creation of a design solution, often represented by physical prototypes. The presence of the prototypes of student design solutions when children are explaining their ideas allows for richer communication and supports thought processes. This study examined a sample of first grade students' communication with adults about their design solutions across multiple engineering activities. The presence of the prototypes deepened verbal communications of youth when using vague demonstrative pronouns (i.e., “this” or “that”) by providing additional context for the speaker to understand what the student is referring to in their design, as well as allowing students to demonstrate how their prototype moved in their testing environments. In addition, the prototypes of design solutions allowed students to communicate ideas non-verbally. As students work to connect their everyday concepts learned outside of the classroom environment with their scientific concepts learned inside of the classroom, there may be a disconnect between every day and scientific language [25]. By being able to augment their verbal discussion through manipulations of their prototypes, students may be able to overcome these disconnects between their everyday language and their ability to communicate their understanding of the phenomenon learned within the classroom. This may also be important for students of all ages who are not comfortable with the discourse within a classroom and offer another mode of communication of ideas with the teacher and fellow students. For students who are unfamiliar with the primary language spoken by the teacher, they may be better able to communicate their ideas through gestures and the use of their physical representations of their design solutions. While older students enrolled in engineering courses have likely developed more complex vocabulary, they may always be at the edge of the ideas that they can communicate verbally. In addition, students may choose to use the prototypes of the design solutions to communicate their ideas more clearly even if they communicate their ideas verbally. The presence of the physical representations of their design solutions may permit them to engage deeper in discussions with instructors and peers.

Thinking beyond the students’ communication of ideas, having a prototype of the design solution present during discussions allowed a glimpse into students’ thought processes when developing and understanding their design solutions. Students demonstrated contemplative behaviors when formulating their responses to questions posed, suggesting that the ability to manipulate their creations to supported student thinking and the formulation of a coherent response to questions. Having a prototype in hand serves as a useful tool for communication about engineering thinking.

The findings from this study align with research in other disciplines around the use of manipulatives and attention to gestures in learning. McNeil and Jarvin [26] similarly concluded that manipulatives provide students alternative methods of communication while also allowing them to access memories through physical actions in mathematics education; however, they also warn that manipulatives can be misused as opportunities for play rather than supplemental to student learning depending on the teacher's attitudes towards the manipulative. We showed that the presence of the design prototype provided alternative forms of communication through supplemental gestures (i.e., referential uses) or as a tool for non-verbal communication. By understanding the important role of design solution prototypes in students' communication of ideas, teachers can position students' use of their prototypes as a key aspect of engineering communication and the assessment of student understanding. This study helps highlight the uses of the prototypes in student communication to assist teachers in identifying various communication pathways of their students in engineering activities.

This study was situated in a larger investigation intended to understand teacher learning and understanding of engineering within their classrooms [14], [24]. As such, the videos used in this study were not the result of intentional capturing of student explanations of their design solutions. This may have limited the amount of information collected and analyzed through these videos, and students may have used their physical representations of their design solutions in additional ways that were not uncovered in this study. In addition, this study only focused on a small subset of students who were engaging in an extended engineering learning module.

Additional research is needed to understand the use of the physical representations of design solutions when communicating engineering ideas. This study focused on first-grade students' communications of engineering; however, engineering is included in the NGSS for all students throughout the K-12 school years and in post-secondary education for students pursuing some fields of studies. Additional research may investigate how the use of the physical representations of design solutions evolves as students progress to more complex engineering design tasks. Also, this paper looked into student thinking as they communicated their ideas around their design solutions but did not look into how gestures and design solutions could be used to understand what students learned from engaging in an engineering design challenge. Additional research into how students use their prototype design solutions when communicating with peers could prove fruitful in furthering the development of multimodal assessments of student learning in engineering.

By looking only at student written work and verbal communications, teachers potentially miss a significant amount of information about student understanding of their design solutions and the engineering design process. Curriculum developers and teachers should create space within their engineering activities for students to communicate with peers and the instructor using the prototypes of their design solutions. Attention to these uses and their underlying insight into student thinking may contribute to richer conversations around the engineering design task and allow teachers to better understand student thinking when engaging in engineering.

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Appendix A.

Complete codebook used to identify and label uses of gestures and prototypes of design solutions

Analysis Phase	**Code**	**Definition**
Phase 1: Gestures	Physical Object Representation	Gestures where the hands represent objects that are physically present in the scene being discussed or the prototype is used to represent itself.
	Abstract Object Representation	Gestures where the hands represent abstract concepts through concrete forms.
	Nonrepresentational motion	Gestures that do not represent any ideas but rather provide context for the spoken word such as pointing.
Phase 2: Gestures using Prototypes	Showcase	Student presents whole design to another person.
	Demonstration (controlled)	Student demonstrates the flight path of design using the design while maintaining a hold on the design the entire time to control movement.
	Demonstration (free)	Student demonstrates the flight path of design using the design but releases it, so they do not control all the movements.
	Thinking/processing	Student manipulates design during and following a posed question that leads to a response to the adults' questions.
	Referential	Students use design to provide context for verbal explanations such as pointing or positioning design.
	Non-verbal responses	Students use design to respond to questions without verbal responses.