October 2022

DESIGN ARTIFACTS AS EXTERNALIZED MENTAL MODELS OF CHILDREN'S SCIENCE CONCEPT DEVELOPMENT

Christine McGrail
University of Massachusetts Amherst

DESIGN ARTIFACTS AS EXTERNALIZED MENTAL MODELS OF CHILDREN'S SCIENCE CONCEPT DEVELOPMENT

A Dissertation Presented

by

CHRISTINE M. MCGRAIL

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

September 2022

College of Education
Teacher Education and Curriculum Studies
Math, Science, and Learning Technologies

DESIGN ARTIFACTS AS EXTERNALIZED MENTAL MODELS OF CHILDREN'S SCIENCE CONCEPT DEVELOPMENT

A Dissertation Presented

by

CHRISTINE M. MCGRAIL

Approved as to style and content by:

____
Martina Nieswandt, Co-Chair

____
Jeanne Brunner, Co-Chair

____
Michael Knodler, Member

____
Darrell Earnest, Member

____
Erik Cheries, Member

____
Ezekiel Kimball
Associated Dean for Academic Affairs
College of Education

DEDICATION

When I talked to my children about the dedication, they said “You should dedicate it to yourself.” Funny, because I was thinking I should dedicate it to them. So, I settled on dedicating this dissertation to the many graces in my life:

Love
Books
Laughter
Friends
Listening
Comfort
My cat
Yurt-time
Peace
Hope
Generosity
Beach-time
Loans
Meals
Parties
Snow days
The cemetery

ACKNOWLEDGMENTS

I think I know now how the academy award winners feel when they take the stage, overwhelmed with the emotion that comes from surprise and success, as they shakily extract from a pocket the list of people to thank, hoping not to forget anyone. This dissertation journey of mine has involved a lot of amazing people who have done things large and small to make my PhD dream a reality, and no words will ever be enough.

I must start with my children, Jane, Atticus, Amelia, and Owen. They have grown up during the time it has taken me to complete this. They have sacrificed, endured, cajoled, cheered, and supported me throughout this process. The times when I wanted to quit, I heard "You can't, we've all put too much time into this!".

My Ride-or-Die sisters, Carol and Kathy, who have never failed to celebrate the wins or distract me from the losses on this journey. There has been a lot of laughter, a little booze, a few tears, and a helluva lot of memories made through the years.

The unsung hero from the beginning, my sister-in-law Jennifer, who drove and fed my kids so I could take classes at night.

The Squad, who have read and discussed, countless words, drafts, chapters, and mock presentations.

To my personal Airbnb sources: Martina and Betsy, Stephanie, and Alicia who all provided me with a quiet place to write, which was ESSENTIAL to this dissertation getting written.

To John and Chris, who welcomed me into their circle, who listened, suggested, taught, and championed.

To Jeanne and her "open-door," policy who has patiently read a million early drafts and always believed in my work and believed in me.

My entire brilliant committee, please know I intend to pay it forward by sitting on a dissertation committee one day.

The amazing families that let me into their homes through Zoom during a pandemic and trusted me with their children.

The amazing children themselves who made this study possible.

There have been so many meals cooked, kids driven, bills paid, drafts read, compassionate words and conversations that have helped me more than anyone could ever imagine. I cannot thank you all enough.

ABSTRACT

DESIGN ARTIFACTS AS EXTERNALIZED MENTAL MODELS OF CHILDREN'S SCIENCE CONCEPT DEVELOPMENT

SEPTEMBER 2022

CHRISTINE M. McGRAIL, B.A., SMITH COLLEGE

M.Ed., FITCHBURG STATE UNIVERSITY

Ph.D., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professors Martina Nieswandt and Jeanne Brunner

The Next Generation Science Standards (NGSS) calls for the integration of the practices of science and engineering across all science disciplines beginning in the early elementary grades. Science and engineering education research has determined that engineering design is a productive means for promoting understanding of science concepts. However, design artifacts created during engineering design problem-solving have not received sufficient attention for their potential to embody children's science understanding. The aim of this study was to examine how conceptual development of the concepts of force and motion was instantiated in design artifacts by early elementary age children engaged in engineering design. Twenty-six children, ages 7-8, from 13 states across the United States engaged in the study from their homes. Design artifacts were considered externalized mental models with evidence of conceptual development evaluated according to the type and number of perceptual dimensions present. It was determined that the artifact could have eight possible perceptual dimensions and the addition of perceptual dimensions was considered evidence of conceptual development. Results indicate that children developed mental models ranging from 2-8-dimensions, with 23 participants (88%) adding dimensions to their mental models during the engineering activity. Video-stimulated prompted recall (VSR) interviews were used to corroborate conceptual development viewed through the design artifact, with all participants able to corroborate or partially corroborate their mental model changes. VSR was instrumental in engaging participants in the metacognitive process of reflection, a known mechanism of promoting conceptual development, which is underutilized with young children. VSR assisted some children in overcoming obstacles in problem-solving. Results are specific to the cotton ball launcher and further study is needed to improve generalizability to other engineering design tasks pertaining to force and motion.

TABLE OF CONTENTS

Page

LIST OF TABLES

Table Page

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Reform in science education has expanded to include the practices of engineering as components of a comprehensive science education (NRC, 2012). The NGSS uses a broad definition of engineering in *The Framework for K-12 Science Education* to emphasize the engineering design practices that all citizens should learn (NGSS, 2013). These practices include defining problems, building and testing prototypes and optimizing a solution. Research has determined that engineering design is productive for promoting understanding of science concepts. However much of this work has been conducted in upper elementary (grades 3-5) (Wendell, Connolly, Wright, Jarvin, & Rogers, 2010), middle school (grades 6-8) (Schnittka & Bell, 2011) and high school (grades 9-12) students (Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naanma, 2004), and very little research in the early elementary (K-2) grades (King & English, 2016). Even less of the body of research in elementary engineering education has been focused on developing a deeper understanding of how engineering design serves as a mechanism for science concept development. Almost no research exists to date that examines the design artifact for evidence of conceptual development.

From a constructivist standpoint, conceptual development occurs as existing knowledge is modified to accommodate new information (Pulaski, 1971). The description of conceptual development from Carey, Zaitchik, & Bascandziev (2015) states that it “includes episodes of change in which new representational resources are constructed, which in turn permit thoughts previously unthinkable” (p37). This view is consistent with a constructivist view of learning, indicating that conceptual development requires some adjustment in the way concepts are connected to each other.

Core cognition reasoning systems provide the initial knowledge that then is modified accordingly as new information is perceived. The changes in relationships between concepts result in a new causal framework which helps the learner make inferences and explain complex ideas and increases “expressive power” (Carey, 2004, 2006; Carey, et al., 2015, p 38). As children learn science concepts, they will construct intermediate steps in the process of change from an everyday conception to a scientifically held concept and these steps should be seen as progress (Carey, 2006). To understand a young child’s conceptual development, it is important to gain insight into the conceptual understanding children have in their minds as a starting point, and then identify progress toward the scientifically held understanding. Establishing markers or checkpoints of conceptual development of interrelated concepts can indicate such progress. One way to notice a student’s move towards an understanding of a scientifically held concept, is to look for a change in representations.

Developing an understanding of how student thinking is reflected in the design artifact may be of special importance to early elementary students for whom the endeavor of constructing a design artifact provides optimal perceptual feedback while minimizing the burden associated with vocabulary dependent forms of learning and representations of learning. Furthermore, the NGSS explicitly addresses the inclusion of engineering with science as means for “diverse students to deepen their science knowledge and come to view science as relevant to their lives and their future” (NGSS Appendix I, p2). However, all students remain expected to demonstrate their science knowledge in the same, traditional paper-and-pencil test format.

Science and engineering education has not made adequate strides in understanding how science knowledge, purportedly linked to engineering design practices, may be represented in the outcome of the design. To achieve more equitable assessment strategies, science education must advance its understanding of the myriad ways science learning is represented by young children. It is widely understood that "paper-and-pencil tests do a poor job of assessing many aspects of human competence" (McGinn, Fraser, & Roth, 1998, p 815). Understanding design artifacts as external representations of understanding creates a new pathway for authentic assessment of science concept development.

Rationale for the Study

As a long-time STEM educator, I have worked closely with young children of diverse linguistic and cultural backgrounds. I have watched science and engineering engagement open doors of communication that were not bound by a shared oral language. It was in those moments that I began my journey of discovering the multiple ways of representing science understanding and moving away from the traditional ways of evaluating children's science knowledge.

The Framework for K-12 Science Education states: "From a teaching and learning point of view, it is the iterative cycle of design that offers the greatest potential for applying science knowledge in the classroom and engaging in engineering practices" (NRC 2012, pp. 201-2). In response to this I contend that if the cycle of design offers the greatest potential for applying science knowledge, then the outcome of design must also have great potential for reifying that science knowledge. According to the *Framework* "Children's capabilities to design structures can then be enhanced by having them pay attention to points of failure and asking them to create and test redesigns of the bridge so that it is stronger." (NRC, 2012, p. 70). In response to this I contend that the design process is not one big iterative process but rather a series of small iterations that reflect new knowledge at each stage in the optimization process. Building from Carey, et al. (2015) the engineering design process could be seen as episodes of change in which representations vary from one episode to the next, indicating conceptual development.

For this study, I chose to focus on second grade because research in the early elementary years has provided some starting points for integrating science and engineering topics. Specifically, PS2: Motion and Stability: Forces and Interactions is a performance expectation that incorporates engineering practices as outlined in the NGSS Appendix I (NAP, 2013) because it aligns well with the sequence of topics for bringing engineering to elementary school. It specifies motion, levers, and mechanical advantage for grade two (Rogers & Portsmore, 2004) and builds on young children's everyday experience with physics. Thus, the topics of force and motion as experienced in a design activity with levers, make an ideal starting point for examining young children's science concept development through an engineering design approach.

This study has the potential to broaden the understanding of how the development of science concepts evolves during engineering design and how it is manifest in engineering design solutions. More specifically, answering the following research questions, this study has the potential to provide new insight into children's science concept development as represented through their engineering design artifacts:

1. What mental models of the targeted science concepts do students develop during design artifact construction?
2. To what extent do students' mental models change from initial to target scientific mental models?
3. How do reflections during VSR interviews capture changes to young children's mental models as they make changes to their design artifacts?
4. In what ways do participants articulate differences between their mental model and the artifact?

CHAPTER 2

THEORETICAL FRAMEWORK AND REVIEW OF THE LITERATURE

This study uses the constructs of conceptual development and mental models along with the role of model-based reasoning in science concept development as a theoretical frame. In this section, I will define the constructs and describe the role of design artifacts in conceptual development through engineering design.

Concepts

In simplest terms, concepts are the units of thought that are accompanied by a mental representation (Carey, 2009; Zirbel, 2004). These units of mental representation are products of observing and processing begun in infancy (Baillargeon, 2002; Zirbel, 2004). Concepts have both referential and inferential roles in guiding human reasoning (Carey, 1992). They can represent individual objects or a set of ideas (Zirbel, 2004). In the process of acquiring knowledge, concepts can change in different ways. One way is through differentiation, which means to distinguish one general concept into two, distinct concepts such as weight equals force, becomes weight and force. Another way is coalescence, which is when separate concepts are integrated into one concept such as force in a horizontal plane and force in a vertical plane becoming a bigger concept of force. Concepts can also undergo core changes when they are reanalyzed and restructured to organize relationships between concepts (Carey, 2000; Carey, et al.,2015). From a constructivist standpoint, restructuring of the attributes of a concept (effort force changes lever motion) and modifications to relationships between concepts (fulcrum height changes lever rotation), occurs as existing knowledge is modified to accommodate new information and is seen as conceptual development (Pulaski, 1971).

Conceptual Development

One of the primary objectives of science education is conceptual development of science concepts (NRC, 2013). Conceptual development can be seen as episodes of change in which representations vary from one episode to the next (Carey, Zitchik, & Bascandziev, 2015). The changes in relationships between concepts result in a new causal framework which helps the learner make inferences and explain complex ideas and increases "expressive power" (Carey, 2004, 2006; Carey, et al., 2015, p 38).

As children learn science concepts, they will construct intermediate steps in the process of change from an everyday conception to a scientifically held concept, and these steps should be seen as progress (Carey, 2006). The core knowledge systems emerge in infancy and serve as the foundation for children's learning. They provide the initial knowledge that then is modified accordingly as new information is perceived (Baillargeon & Carey, 2012; Spelke, 2007). As new information is perceived, concepts are modified and revised and become embedded in frameworks that provide causal, explanatory understanding (Vosniadou, 1994, 2002). Children's conceptual frameworks, also considered to be naïve, or intuitive reasoning mechanisms, develop from everyday experience prior to formal learning (Baillergeon, 2002; Carey, 2006). Children can revise their frameworks when confronted with the explanatory limits or inadequacies. Revision yields a new framework with great explanatory power (Amsel, Goodman, Savoie & Clark, 1996; Nercessian, 2008). Conceptual framework revision requires changes in understanding of causal and non-causal influences (Amsel, et al., 1996). It is therefore incumbent upon science education to build upon children's naive conceptions in science and offer them learning strategies that facilitate their conceptual framework revision in order to promote conceptual development.

Mechanisms of Conceptual Development

Some identified mechanisms responsible for conceptual development are mental modeling, revision, and reflection (Carey, 2004; Vosniadou, 1994). Mental modeling is the process used in the construction of conceptual frameworks which provide a personal understanding that explains how something in the natural world works). An individual's mental model is the site where new information can be incorporated. Mental models are representations of parts and their relations of how things work in the natural world, used to make predictions and explanations of observed phenomena (Vosniadou, 2002). Mental models help people draw on their implicit knowledge to answer a question or solve a problem and can be "constructed on the spot to deal with the demands of a specific situation" (Vosniadou, 2002, p. 359). In this way, mental models mediate understanding of new information, leading to revised conceptual framework.

Reflection is the metacognitive process of referring to the mental model. Children need prompting to access their mental models and conceptual frameworks, and a lack of metaconceptual awareness prevents children from understanding or questioning their own naïve frameworks, thereby inhibiting the potential for conceptual development (Vosniadou,1994).

In order for children's existing conceptual structures to be revised, they must be made self-aware of which conceptual structures should be built upon and which need to be revised. In order for this type of revision to occur, students need "considerable metacognitive, epistemic, and representational abilities as well as the understanding that our beliefs about the physical world are hypotheses that can be tested and falsified" (Vosniadou & Skopeliti, 2014, p 1441). This means that learners need opportunities to test their ideas, reflect on their own thinking, and make revisions as needed.

Force And Motion

Force and motion are two physical science concepts that are closely related to the sensory experiences and physical reasoning that children begin developing in infancy (Baillargeon, 2004; Carey, 2009). Force is generally considered a central concept in the study of physics (Osborn, 1985). It is also widely accepted that the teaching and learning of force and motion are fraught with durable misconceptions (Tao & Gunstone, 1997). Therefore, for conceptual development of force and motion to be evident, it can be assumed that initial conceptions and misconceptions must be overcome. For all of the above reasons, force and motion were chosen as the focus of this study.

In this study, children's understanding of the concepts of force and motion are investigated through the context of simple machines, specifically levers. Levers are a type of simple machine consisting of a bar that moves on a support called a fulcrum. Levers function by applying effort at some point along the lever to move the load located at a different point on the lever. Mechanical advantage is gained by coordinating distance and magnitude in applying an effort force to move the load force (Amsel, Goodman, Savoie and Clark, 1996). McGinn, Fraser & Roth (1998), in their study of children's understanding of levers, established the key dimensions of length of lever arms and fulcrum position, weight (force), lever action (mech advantage), pivot, and lever rotation. These key dimensions are used in the determination of conceptual development in this study.

Engineering Design and Conceptual Development

Engineering design is an iterative, cyclic process that engineers use to solve a problem (Fortus, et al., 2004). It is not comprised of simple trial-and-error, but rather a systematic and iterative process with a specific goal shaped by specifications and constraints (NAE&NRC, 2009). Specifications make explicit what the intended outcome is, and constraints are limitations such as size, materials, and cost. Because the engineering design process is iterative, designs are tested, evaluated, and optimized during the design process.

Engineering design has been identified as a productive approach to helping students learn science concepts (Schnittka & Bell, 2011) through engineering design tasks (Portmore, 2013). A classroom-based engineering design task typically begins with an ill-structured problem, followed by students brainstorming possible solutions, then drawing the proposed design solution, then constructing the design solution. The design solution is typically tested, evaluated, and revised by an individual or team without teacher guidance (Dankenbring & Capobianco, 2015).

Engineering design tasks provide play-like experiences that are not dissimilar to a young child's everyday experiences. Play-like experiences are instrumental to the sensorimotor learning which lays the groundwork for conceptual development (Carey, 2009; Hadzigeorgiou, 2008). Engineering design tasks capitalize on children's natural inclinations to engineer and design and scaffold learning from play-like experiences (Gopnick, 1999). Children are natural engineers who easily and spontaneously design and build sandcastles, forts, and towers with a variety of materials during play (Driver, 1994; Gopnick, 1999; NRC, 2012). Therefore, engineering design activities provide a learning strategy that is simultaneously developmentally appropriate both cognitively and physically for young learners. Another reason engineering design tasks have the potential to promote scientific concept development in young children is because they provide a pragmatic problem-solving condition that is known to be an external condition that supports the internal processes of reflection and revision, which are mechanisms for conceptual change (Vosniadou,1994). Engineering design tasks also employ ill-defined problems and readily engage a student's unique prior knowledge, thereby allowing students to confront their initial understandings in a most visual and concrete manner (Fortus, et al., 2004; Roth, 2001). Furthermore, because in an engineering design task there is not just one solution, learning with engineering design tasks allows students to solve problems and arrive at multiple workable solutions, building off of their unique prior knowledge and experiences (King & English, 2016).

Artifacts as Representations of Mental Models

The products of classroom-based engineering design tasks are commonly known as artifacts (Roth, 1996). Design artifacts are physical models which change through the iterative process of engineering design. The work of constructing an artifact provides many benefits to a learner. First, it provides the sensory and motor input as children manipulate materials during construction (Hadzigeorgiou, 2008). This is essential to conceptual learning because children's initial knowledge is modified accordingly as new information is perceived (Baillargeon & Carey, 2012; Spelke, 2007). Second, an engineering artifact provides a context in which the science concepts work together in a system, making the relations between concepts more salient and revealing the limits of the child's own explanatory framework. Furthermore, artifacts set limits to a learner's reconstructions which helps them focus on those salient aspects (Ackermann, 2007).

In an engineering design task, an artifact is not just a solution to a problem but an evolving tool, through the process of evaluation and revision in the engineering design process (Penner, Lehrer & Schauble, 1998). A successful artifact of the design activity requires students to test, evaluate, and modify their existing conceptions, while making conceptual development progress toward a scientific understanding. Embedded in that artifact creation are representational resources that change over the course of the design process, ultimately resulting in a representational resource product that is more powerful than the resource at the outset. Therefore, an artifact of design is both "a tool to think with" (Roth, 2001, p 36) and a representation of previous thought.

Vosniadou (1994) recommends that science education "create environments that allow students to express their representations of situations, to manipulate them, to test them and to have the experience of revising them successfully" (p.24). Through the engineering design process, the child reflects on their own thinking as they interact with the designed features that work and those that do not work. Because the engineering design process is systematic, it minimizes the impulses of trial and error and makes decisions and actions more intentional. Therefore, as a child works to solve the problem in the engineering design task by designing, testing and redesigning to improve the performance of the artifact, changes to the artifact reflect micro-changes in thinking and scientific reasoning.

Design Artifacts Reflecting and Supporting Scientific Reasoning

Engagement with engineering design tasks affords learners opportunities to engage with underpinning science concepts through their unique reasoning and problem-solving strategies. The engineering design process affordance of multiple workable solutions means that there is not just one pathway toward a solution. Viewing these multiple pathways can yield insight into an individual's reasoning and changes in understanding. Since design is viewed as a form of problem solving in which reasoning is made visible through the construction of an artifact (Penner, Lehrer, & Schauble, 1998), it is reasonable to conclude that cognitive change that occurs during an engineering design task will be made visible through external representation in the design artifact.

Viewed from a constructionist perspective, knowledge is derived from experience and learning is the product of knowledge construction that happens within the individual with the aid of external objects-to-think-with (Ackermann, 2007; Papert & Harel, 1991). In this way, external objects act as supports to anchor the development of new knowledge to existing prior knowledge. This view draws upon the ideas of constructionism from Papert and Harel (1991), predicated on the ideas of cognitive adaptation from Piaget (Psenka, 2017) along with a perspective on reasoning with student constructed external representations (Ackermann, 2007; Clayson, 2018; Cox, 1999; Prain & Tytler, 2012;). The work of constructing an artifact in an engineering design task provides the external supports for learning the science concepts that underpin the task.

The representational construction affordances (RCA) framework of Prain & Tytler (2012) positions design artifacts as representations that "productively constrain the focus of student meaning-making" (p. 2753). The R for representation in the RCA framework includes oral and written language, mathematical calculations, graphical, statistical and physical models. Models are visual representations used to help people understand a system as a collection of interacting pieces that helps mediate or link theories and the natural world (Frigg, 2017; Nercessian, 1999; Zytkow, 1999). The practice of creating a model is a practice of both science and engineering, used to predict or explain what might happen in particular circumstances. Design artifacts of classroom-based engineering design tasks are visual representations that students construct while developing an understanding of how the pieces interact, therefore they can be considered physical models. Sadler and colleagues (2000, p304) state that "Design is a form of cognitive modeling that crystallizes a conceptual model into a physical embodiment, either on paper or in a physical entity."

The physical models students create are not perfect representations of all of their understanding. However, the assumptions and decisions embodied in their designs are a window into their understandings of the target science concepts (Wendell, 2013). When children have an operational understanding of how a physical variable relates to the functionality of a device, their design constructions likely reveal that understanding (Kolodner, 2003). Therefore, children's design constructions—both in final form and in intermediate iteration—reveal a great deal about children's understanding of scientific concepts.

Building from Papert and Harel's (1991) idea of the iterative process of building one's own tool to think with and connecting it to the engineering design process with moments to test, reflect, and improve, it is reasonable that a design artifact is an increasingly complex object that both reflects and supports scientific reasoning.
The very act of externalizing one's mental images allows those mental images to be disambiguated (Cox, 1999, p 353). Once mental images are externalized, they are now

available as stimuli that provide “perceptual assistance” (p 353). Making our ideas tangible in an outward form is considered by Ackermann (1996) to be instrumental to cognitive adaptation because it allows for one’s perspective to change from “stepping in to stepping out” (p 7). When viewing cognitive adaptation through mental models, it becomes possible to evaluate change in the physical representation of the mental model. With each iteration, there is a new perspective on the system the artifact is modeling, and the artifact designers become their own “observers, narrators, and critics,” which is essential for object construction (Ackermann, 1996, p 4)). Essentially that object to think with becomes an interlocutor, communicating with the designer and moving the designer’s thinking forward (Ackermann, 2007).

Evaluating Conceptual Development

Reflecting on one’s own thinking is a mechanism that promotes conceptual change. Through the engineering design process, the child reflects on their own thinking as they interact with the designed features that work and those that do not work. Therefore, an engineering design task is likely to advance conceptual development. However, research on engineering design as a mechanism of conceptual change is complex because design change can happen quickly and appear unintentional. Consequently, strategies are needed to view conceptual development that occurs through engineering design tasks.

Mental models are a means to evaluate children’s conceptual development because the mental model allows the individual concepts to be viewed as part of the system (Pradhan, Pai, Radadiya, Knodler, Fitzpatrick, & Horrey, 2020). Mental model refers to an individual's internal, mental representation (Chiou & Anderson, 2009). Because mental models are internal cognitive representations, they are not directly accessible and must be accessed through externalized representations.

It has been demonstrated that the mental model construct provides a comprehensive account of conceptual development in an individual (Dankenbring & Capobianco, 2016; Vosniadou, 1994). In fact, mental models have been used to investigate a wide range of phenomena in science including reasoning about day and night cycle (Vosniadou & Brewer, 1994), the water cycle (Ahi, 2017) and energy expenditure (Pasco & Ennis, 2013). This research has demonstrated that children's mental models change and develop as children acquire knowledge of the physical world (Vosniadou, 1994). In the majority of the research mentioned above, the phenomena under investigation have all had one best possible answer. In engineering design, however, there are multiple solutions, making understanding a student's mental model more complicated.

In their work of examining mental models of sun-earth relationships as a result of engagement with an engineering design task, Dankenbring & Capobianco (2016) evaluated changes in mental models by looking at the individual components in student drawings and interview responses. This study builds on that work by using dimensions as the item level to examine mental models and investigate artifacts as externalized mental models.

Using Design Artifacts as Externalized Mental Models

From a cognitive perspective, meaning making resources are seen as changes in mental strategies, namely the mental model, so the coordination of meaning making resources becomes realized in the mental model. Because mental models are not directly accessible, research on these internal cognitive representations must rely on proxies and methods of mental model elicitation such as drawings and verbal responses to interview questions. According to the National Academy of Engineering (NAE & NRC, 2009) "Ultimately, models are embodiments of thought processes, insights and discoveries in a form that communicates them to others" (p 88). Therefore, physical models constructed during an engineering design task instantiate student understanding as external representations of internal mental models. Consequently, as mental models change during the phases of the engineering design process, the physical model reflects these internal changes. Here, the accretion of changes to the mental model is evidenced in the design artifact, thereby instantiating knowledge construction of science concepts. Changes of the design artifact can then be evaluated for increased complexity as evidence of conceptual development of science concepts.

From a conceptual change standpoint, students begin an engineering design task with an initial mental model of the target concepts that originated from their prior experiences. As students construct their design artifacts, they reflect on artifact performance and revise the physical models to change the performance. Children receive perceptual feedback from manipulating the artifact, the perceptual information interacts with their existing cognitive structures to produce a revised mental model. The cognitive changes are then observable in the revised artifact. In this way the artifact provides evidence of conceptual change of science concepts. For example, in the engineering design task used in this study, children attempt to rotate the lever by adding more weight. Then, after the effort arm of the lever hits the floor or table they are working on, they use the perceptual information from the contact to revise their understanding. Typically, they come to understand that they need more room for one end of the lever to press down, which leads to understanding that they need to raise it up. Confirmation of conceptual change can then be elicited through examination of student's reasoning about changes made to the artifacts based on recall.

Borrowing from Cox's (1999) work on external representations, it is feasible that as new features are added to the artifact, each feature provides perceptual support. For example, when the child adds height to the fulcrum, it changes the rotation of the lever, even with the same force. Once a child can resolve the amount of force and create rotation, then they have the perceptual supports to focus on launch height and angle. Thus, each feature is really a perceptual dimension of the artifact, wherein the addition of perceptual dimensions represents conceptual development.

Video-stimulated Recall Prompted Interviews

It is the overarching assumption that the artifact becomes an externalized mental model and that changes made to artifacts during an engineering design task reflect changes in scientific reasoning as changes to the mental models of those making the artifacts. Video-stimulated recall prompted interviewing is a method intended to triangulate inferences made about mental model changes during construction of an engineering design artifact. Video-stimulated recall (VSR) is a method whereby researchers show research participants a video of their own behavior to prompt their recall of an event in order to understand their thinking during the event. Here, the events used for prompting recall are specific changes made to the artifact during the engineering design task such as changing the location of the fulcrum. The micro-changes are identified in video data of the child working through an engineering design task, and VSR interviews are used to confirm the micro-changes as the child explains the reasoning behind the changes.

VSR has been used widely in education and medical research to understand participants' thoughts and reasoning (Lyle, 2003). However, researchers are only beginning to explore its use with children. Dewitt & Osborne (2010) used VSR to understand how children make meaning of their experiences with science center exhibits. Meier & Vogt (2015) used VSR to understand the learning processes of young children engaged with inquiry-based learning. I aim to extend this initial work by investigating changes to young children's mental models during engineering design activities. VSR are used to better understand children's rationale for their design changes made as they construct and test their artifacts during the engineering design task of making a cotton ball launcher. Recall, reflection, and revisions are mechanisms of conceptual change (Vosniadou, 1994), therefore VSR-provided opportunities to reflect on revisions made to artifacts during the engineering design task and opportunities to articulate one's thinking at the time of making the design change may yield confirmation of changes to mental models as viewed through artifacts.

Review of the Relevant Literature

Overview

The role of the engineering design process in knowledge construction of science concepts of force and motion has received very little attention in the literature. Accessing student mental models of these target concepts has received even less attention. However, five studies help situate this study and will be elaborated on in this section.

Using Engineering Design to Promote Development of the Concepts of Force and Motion

Two important studies help ground the premise of this research study using engineering design to support elementary students' development of the concepts of force and motion through the principles of leverage. Wendell, Connolly, Wright, Jarvin, & Rogers (2010) studied the use of engineering design curricula for the purposes of teaching science to upper elementary school age students. Pencil-and-paper science content tests were used to compare the learning outcomes in science classes taught with teachers' own typical science lessons with classes taught with an engineering design approach. They found that learning about the topics of sound, material properties, and simple machines was facilitated by engineering design as a pedagogical approach. The topic of animal adaptations was the only one in their study that was not supported by engineering design. The authors speculate that elementary teachers have better developed pedagogical practices for teaching life science topics compared to topics in other domains. Although the grade level population of this study was older than the target population of this study, the investigation supports the use of engineering design as an approach to promoting conceptual development of physical science concepts such as the target concepts of force and motion through the principles of leverage.

Penner, Lehrer & Schauble (1998) used model-based design as a context for developing third-grade students' understanding of the science concepts of leverage (the relationship between lever length, fulcrum point, and force) and biomechanics. Instead of using the steps of an engineering design process model, the classroom-based project was segmented into two phases. The first phase was the design phase in which students created a model that worked like the human elbow to lift a book bag. The second phase was the biomechanical investigation phase, during which researcher constructed models were used to explore the mechanics of an arm lifting weight and the relation between force and muscle position. Student understanding of the principles of leverage was evaluated only after the biomechanics phase. Graphical representations of data were generated and required substantial teacher scaffolding to help the students move beyond simple summarizing of data to understanding of the scientific concepts that produced the data patterns. Penner and colleagues' study (1998) supports the context of using design to examine elementary students' understanding of the scientific concepts of force and motion through the principles of leverage. However, unlike my research study, the engineering design process was not employed, and the Penner and colleagues' study examined neither design artifacts nor student's mental models of the targeted concepts.

Student Constructed Design Artifacts

Two studies (Wendell, 2013 and Portsmore, 2013) examined student constructed design artifacts of young children as representations of cognition. Wendell (2013) examined the design constructions of third grade students as representations of student understanding of the science of sound. In the study students were encouraged to consider how the relationships between the visible and the invisible characteristics of sound could inform their designs for a new musical instrument. Students worked in pairs to design and construct their instruments, separating this study from my research study in which students will construct artifacts individually, thus enabling the artifact to reflect the reasoning of an individual. Wendell claims that the artifact alone is insufficient to understand all of a student's understanding of the concepts and recognizes that oral discourse was an important additional representation of student understanding. This work confirms that students' design constructions are both "tools and windows" (p 204) to view and support knowledge construction. Further, the importance of oral discourse to understanding the cognition embodied in student artifacts underscores the planned use of video stimulated recall with episodes from the engineering design process to verify student reasoning.

In a study of how first grade students make use of their planning stage drawings and understand the problem to be solved, Portsmore (2013) compared drawings from the planning stage of the engineering design process to design artifacts. Findings from this study show that very young children were able to comprehend the nature of the problem and the best way to implement the materials to create a solution to the problem. This study examined the relationship between the initial drawings and the constructed artifact, rather than evidence of learning in the artifact itself. However, the findings support that early elementary age children are able to reason about the problem to be solved in an engineering task and use materials accordingly towards creating a solution to the problem.

Examining Mental Model Changes as a Result of Engaging in Engineering Design

The construct of mental models has been used abundantly in science education research (Ahi, 2016; Clement, 2008; Dankenbring & Capobianco, 2016; Vosniadou, 1994). Vosniadou's (1994) seminal work in conceptual change theorizes that the mental models of children change and develop as children acquire knowledge of the physical world. This work also claims that mental models are an essential construct for providing a full account of conceptual development in an individual. However, very little research has been conducted in the area of examining changes in mental models as a result of engaging in engineering design.

Dankenbring and Capobianco (2016) captured the mental models of fifth grade students to examine their conceptual understanding of the four seasons, using multiple choice knowledge assessments, draw and explain activities, and semi-structured interviews. They compared the mental models of students taught with teacher-directed science activities to those of students taught with engineering design. This study employed the SLED engineering design model. The SLED model was generated by the Science Learning through Engineering Design (SLED) group at Purdue University as part of an integrated STEM approach in grades 3-6 (Capobianco, 2013). The SLED model was chosen because of its alignment with the purpose of this study and the simplicity of the five-step process: identify a problem, develop a plan, create and test, communicate results, and improve results. Student mental models were characterized by identifying essential features of the mental models, rather than for scientific accuracy. No significant differences in learning gains were found between the two groups. However, the engineering design group did demonstrate a greater variety of features of their mental models. These findings indicate that engineering design might promote more synthetic mental models, or in other words, promote conceptual development on the continuum from initial conception to scientific concept. Students' working models were not accessed through design artifacts as in my research study, but results support using engineering design to promote changes to the mental models of young children.

Though the research body is small, the cited studies demonstrate a gap in our understanding of how the engineering design process promotes the construction of conceptual science knowledge. Thus, examining early elementary students' design artifacts as externalized mental models of the development of their science concepts of force and motion will be a valuable contribution to the literature.

Conceptual Framework Overview

Figure 1 depicts the conceptual framework that guides the proposed study. It describes the view of a child's design artifact as an external representation of their mental model and how the engineering design process promotes changes to the mental model. Children enter the engineering design task with an initial mental model, created through their everyday experiences, that informs how they begin the task and construction of the artifact (design 1). Through the engineering design process (EDP), the child reflects on the mental model as they interact with the designed features of the artifact that are optimized and those that are not. As a child works to solve the problem in the engineering design task by designing, testing and redesigning to improve the performance of the artifact, changes to the artifact reflect micro-changes in the mental model (design 2 and 3). Because the EDP is systematic, it minimizes the impulses of trial and error or tinkering and makes decisions and actions more intentional. The final artifact is then a representation of the new mental model which was formed through the accretion of micro-changes (design 4). The micro-changes are identified in video data of the child working through EDP, and video-stimulated recall (VSR) is used to confirm the micro-changes as the child explains the reasoning behind the changes.

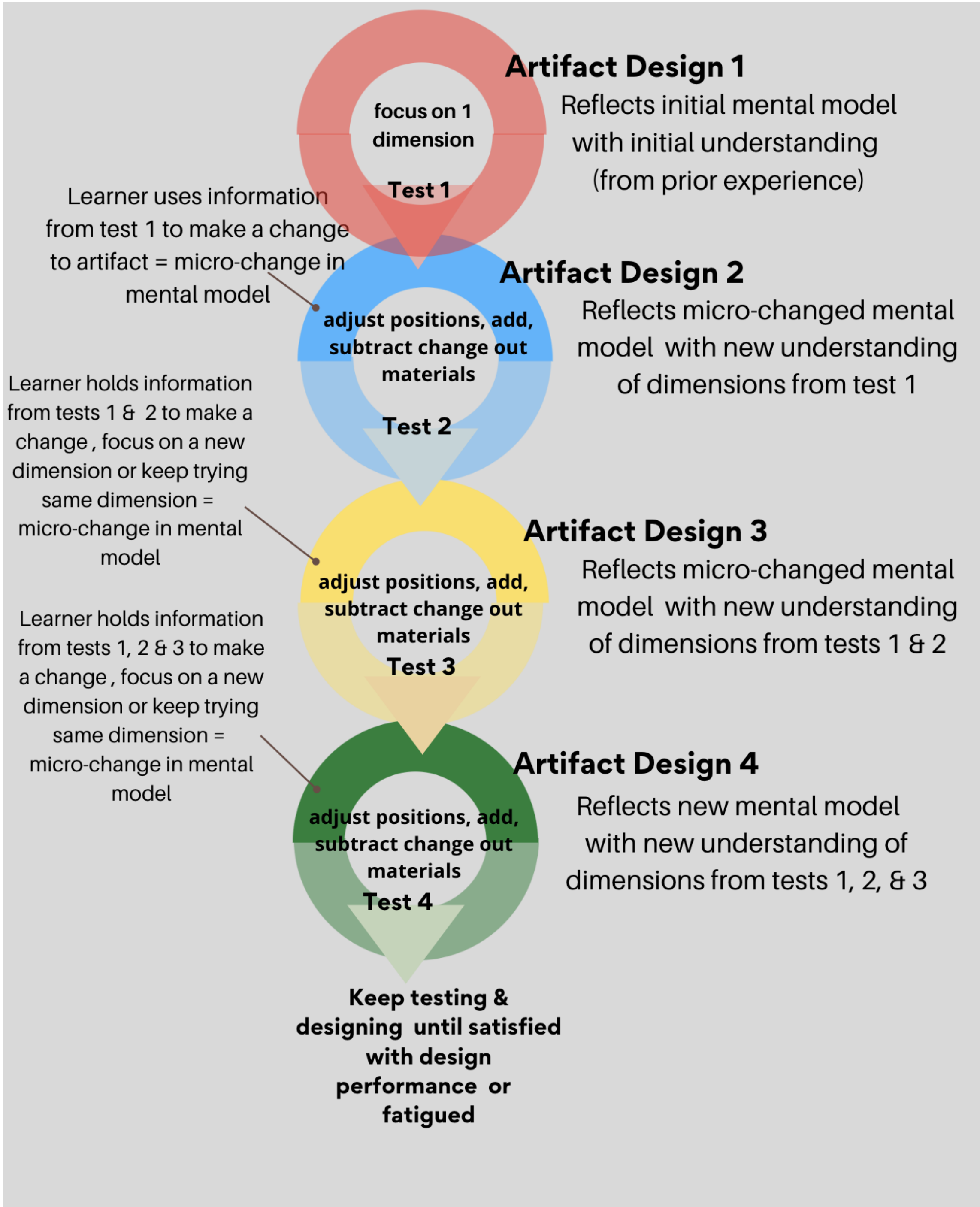


Figure 1. Design Artifacts as Externalized Mental Models

*Note: Test = launching a cotton ball from the cotton ball launcher

Conceptual framework for design artifacts as external representations of mental models

Problem Statement

Authentic performance tasks require students to apply their learning to a new situation that requires judgment and innovation, with a real-world context, that involves a complex task for which there may be no right answer (Wiggins,1998). Authentic assessments are valuable because they are more interesting and more motivating to students than traditional pencil-and-paper tests, but most importantly, because they provide information about what students have succeeded in learning. In education we know that the best and most organic learning builds on what students already know, and an asset-based approach, meaning "pedagogical, material, and social structures designed to value, center, and promote cultural and heterogeneous ways of knowing and doing" (Gravel, Raymond, Wagh, Klimczak, & Wilson, 2021, p277) to science and engineering education is key to disrupting the status quo with its narrow ways of doing and being in STEM. Artifact design has the potential to act as an authentic performance assessment that employs an asset-based approach because it does not privilege dominant ways of knowing and representing knowing.

Engineering design has shown promise as an approach to the teaching and learning of science concepts, however little is known about how an artifact of design reveals conceptual development.

Study Purpose

Based on the gaps in the literature on and the need for increased understanding of how design artifacts instantiate children's science concept development, the aim of my research is to understand the relationship between 7-8-year-old children's changes to their design artifacts during the iterative process of artifact construction and changes to their mental models of the targeted science concepts of force and motion in the context of levers.

Focusing on the early elementary grades has the potential to reveal important developmental considerations for helping children grasp the foundational concepts that their science and engineering education will be built upon.

Young children's mental models and their changes during the construction of an engineering design artifact are explored using video-stimulated prompted recall interviews. Understanding conceptual change in young children as it is happening is a significant step toward understanding how engineering design can be implemented as part of an integrated STEM learning approach.

CHAPTER 3

METHODS

In this section I describe the research design, sample, data collection methods, and data analysis methods for the study.

Research Design

This study employed a design-based research approach with qualitative data collection to answer the following four research questions (RQ):

1. What mental models of the targeted science concepts do participants develop during design artifact construction?
2. To what extent do participants' mental models change from initial to target scientific mental models?
3. How do reflections during VSR capture changes to participants' mental models?
4. In what ways do participants articulate differences between their mental models and the artifact?

Methods Overview

Design-based research "typically aims to create novel conditions for learning that theory suggests might be productive but are not common or well understood" (Sandoval, 2014, p22). This study engaged a novel methodology, video-stimulated- recall prompted interviews, within a novel context, engineering design via Zoom, with a novel participant age-group, 7-8-year-old children. Due to the novel study conditions, it was important to understand how the features of the study design work together. Design research is iterative, interactive, and flexible (Alghamdi & Li, 2013), which makes it suitable for novel conditions. I was examining learning through the conditions of using engineering design tasks through Zoom while Zoom experience was still limited for most people, and I would not have the ability to help children in person if they struggled with the materials, task, or interpersonal interactions with me. Design based research methods allowed me to make the change from collecting artifacts as the conclusion of the design session to allowing participants to continue building after their VSR interviews

I presented the design challenge of creating a cotton ball launcher to 26 seven- and eight-year-old children over Zoom and recorded their process over three sessions. In the first session, students became familiar with the materials and with the engineering design process. In the second session, they drew an initial model and then constructed their device based on that drawing. This allowed me to determine their initial mental models. They were able to modify and improve their designs, which allowed me to follow the way their mental models shifted. The third session was a time for students to reflect on their models, and I provided them with video clips from the second session that were intended to stimulate recall of their thinking.

To address RQ1, I developed a coding scheme for the eight perceptual dimensions that comprised the scientific mental model of force and motion, using the design artifact as a mental model proxy. I used this coding scheme to determine the number of perceptual dimensions in each participant's final design artifact at the conclusion of the design session which represented their concluding mental model. To address RQ2, I used the same coding scheme to determine the number of perceptual dimensions in each participant's initial build of the design artifact which represented their initial mental model. I then evaluated the change in number of perceptual dimensions in the initial artifact to the concluding artifact which represented the change in the mental model. To address RQ3, I developed a coding scheme for the VSR interview responses based on recursive refinement of codes generated for the three categories of participants' responses. The interview consisted of four episodes and each episode was categorized using the coding scheme. To address RQ4, I used a deductive content analysis of video data from each design session to analyze how students responded when provided with opportunities to communicate challenges or difficulties with manipulating the physical materials during the design session. Secondly, I analyzed the VSR interviews for instances where participants said they were trying to do something but were not able to do it or where they showed signs of frustration or changed the course of their work.

I elaborate on my sample, data collection, and data analysis in the following sections.

Research Context

Data collection was conducted while schools across the United States were closed due to COVID-19. All participants were at home because of school closures and participated in the study through Zoom. The focus on the research was 7-8-year-old children learning about force and motion through engineering design.

The domain of force was chosen as the focus because phenomena of force and motion are common to everyday life and children typically have many prior experiences with these phenomena (Tao & Gunstone, 1997). Using engineering as the learning approach was chosen for three main reasons. First, because it is consistent with a constructionist perspective that learning is supported by designing and building meaningful artifacts (Papert & Harel, 1991; Rogers & Portsmore, 2004). Second, it provides the sensorimotor experiences that have been shown to support children's understanding of mechanical equilibrium and balance beam (Hadzigeorgiou, et al., 2009). Third, it supports science content knowledge construction (Wendell, Andrews, & Paugh, 2019).

The age range of 7–8-years old for participants was chosen as the focus for two intertwined reasons. First, these ages are the upper level of the K-2 grade band in *A Framework for K-12 Science Education.* This allowed me to explore the benchmark provided by the Disciplinary Core Idea PS2: Motion and stability: Forces and Interactions (NRC, 2012). Second, children in this age group are largely underrepresented in the literature that examines the development of science concepts through engineering design as much of the work has been conducted with upper elementary (grades 3-5) (Wendell, Connolly, Wright, Jarvin, & Rogers, 2010), middle school (grades 6-8) (Schnittka & Bell, 2011) and high school (grades 9-12) students (Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naanma, 2004). Thus, research on this age band provides an important first look at science learning outcomes in young children from an engineering design activity approach.

Participants

A convenience sample of 26 children, between the ages of 7 and 8, located in 13 states across the United States was recruited were recruited via a flyer advertising the study posted on Facebook (Appendix A). To be included in the study, participants had to meet the following criteria: completed grade 2 by summer 2020 or enter grade 2 in the fall of 2020, be between the ages of 7 and 8, have access to a computer or phone with a camera and high-speed internet access, have some familiarity with participating in learning experiences via Zoom, be in the care of an adult at the time of the data collection who will be available to encourage the child to persist through meetings and activities and assist child with accessing Zoom meeting links (as needed). Participant demographic data is detailed below in Table 1.

Table 1. Demographics for Participants

Gender	Self-identified Female	16 (62%)
	Self-identified Male	10 (38%)
Race	White	19 (72%)
	Hispanic	3 (12%)
	Black	2 (8%)
	Asian	2 (8%)
US Geographic Region	Northeast	10 (38%)
	Mid Atlantic	4 (15%)
	Southeast	3 (12%)
	Southwest	2 (8%)
	Midwest	2 (8%)
	West	5 (19%)

Gaining Informed Consent

All interested parties emailed me to express interest in the study. I then set up a Zoom call to meet with parents so I could tell them the specific details and determine if they remained interested. Once parents understood the scheduling requirements of 3 Zoom sessions in one week and that all sessions would be recorded by Zoom, some did not pursue participation. If they were still interested, I sent the Informed Consent and Assent forms (Appendix B) by DocuSign as instructed by the Institutional Review Board. I had 32 potential participants but gained consent for 26 participants. I had to turn down additional potential candidates after data collection ended on January 1, 2021. No participants withdrew from the study at any time.

<u>Engineering Design Activity</u>

The cotton ball launcher engineering-design-based activity (Appendix C) sets forth a challenge to build a machine to launch a cotton ball as high and far as possible. I chose this specific activity because it addresses the concepts of force and motion, which the study was designed to examine along with the principles of leverage. This is a successful scaffold for force and motion as suggested by Penner, Lehrer & Schauble (1998). It also used child-friendly materials that are simple—something that a child might have seen before—and easy to manipulate, specifically paint sticks, cups, spools, and tape.

Furthermore, it has been vetted by PBS Kids Design Squad, by Engineering Go For It (eGFI), and by the American Society for Engineering Education (ASEE) for teaching elementary school age children about force and motion. Approval from these well-established organizations was considered by the researcher an important component of gaining parental consent for the children in their care to participate in this study.

Structuring the Engineering Design Challenge

At the outset of the engineering activity, I told each child the design challenge (problem to be solved), the requirements (which children understood as the "rules"), and the constraints (the only materials they could use to build with). To solve the design problem, participants needed to construct a contraption to launch a cotton ball the farthest distance. A launch zone or target was designated somewhere in range of the camera prior to commencing any testing.

Engineering Design Task Kits

Each participant in the study was sent an engineering kit to their place of residence, addressed as requested in either the child's name or adult's name. Each kit was a rectangular box that contained all the materials for the three study sessions. In order to facilitate communication between the researcher and student through Zoom, materials were painted and labeled by color (e.g., the green stick) to eliminate the burden of vocabulary associated with names of each of the items.

Each kit included the following materials: Paint stirrer sticks (3) painted grass-green, 3 oz. paper cups (2), masking tape (1 roll), wooden spools (2) painted bubble-gum pink, child-safe scissors (1), cotton balls (3), ping pong ball (1), small wooden people-shaped figures (2) painted orange, medium-sized wood people-shaped figure (1) painted blue, unlined paper (3 sheets), and pre-sharpened pencils (2), crayons (1 box of 16 assorted colors), and sticky dots (10).

To ensure that participants did not gain prior experience with the materials in the kit I used two strategies. First, I asked the adult to keep the kit secured from the child and gave instructions that the box should not be opened prior to the first session. Second, the kit boxes were sealed with packing tape and a safety seal was placed over the packing tape on three sides of the box. This configuration allowed me to identify if a box had been opened prior to the first session and allowed me to watch a participant open the box and encounter the materials for the first time. No participants opened the box before the first session.

Study Structure Overview

The study took place in three sessions over the span of seven days with each individual participant. Each session lasted approximately 45 minutes to one hour. Participants completed all activities over three sessions within the span of seven days. The main purpose of session one was to normalize all participants' experience with levers and allow all children to gain experience manipulating materials. Participants and I met, participants opened their kits, and learned the names of every item in the kit. The main purpose of session two was to conduct the engineering design activity. Participants were introduced to the activity objectives and constraints, made an initial design drawing, and completed the engineering design challenge to create a cotton ball launcher. The main purpose of session three was for participants to complete a VSR prompted interview. Each session is described in the following sections.

At the time of data collection, Zoom was still a relatively new experience for children and adults, and it was a novel way for children and educators to interact. I found several strategies I used repeatedly to make the experience more engaging and successful for working with children when they had never met me, nor I them. These are elaborated on in Appendix E.

Session 1

During session one, the researcher and participant meet to create a rapport. The participant opened the kit and encountered the materials inside. Participants were introduced to the sequences of making predictions before manipulating materials. Participants' experiences with balance were normalized by making a seesaw for the two sizes of wooden figures. Participants were introduced to the experience of being given a challenge and then manipulating materials to complete a challenge. Lastly, participants were introduced to the topic of the engineering design process and an engineering design challenge to spark interest and enthusiasm for session two.

Session 2

In session two, participants completed the engineering design activity in four stages. In the first stage participants were introduced the principles of the design process (see Table 2 for sample prompts used in all stages). In the second stage the specific design activity was introduced, framing it as a challenge. In the third stage I facilitated participants moving through the iterative process of designing, testing, and evaluating their solutions to the challenge. This stage has two parts. Part A. was introducing testing of the artifact and Part B was discussing the outcomes from testing the artifact. Stage 4 was the conclusion of the design session.

Table 2. Protocol for Each Stage of Session 2

Stage	Protocol
1.	We are going to do some things with the design process today 1. Do you know about the design process and what it is 2. It's a series of steps, we think about it being a circle, and you start with hearing the challenge or the problem 3. And then you come up with a plan in your mind of how you might solve it 4. You start to draw your plan 5. Then you're going to build your plan 6. What do you think you might do after you build it? 7. Then you test it (exactly) 8. When you test something what do you find out? 9. Right, if it works or not. And, if you could improve it, or what is working and what's not working 10. So then, after that you can improve it and re-test it 11. Sound good?
2.	1. For today, your challenge is going to be to build a machine that will launch a cotton ball that will launch a cotton ball as far it will go 2. Maybe you can get it to hit the ____and I pick a target somewhere in the room the child is in 3. So, there are some rules: 0. You have to use some of the materials 1. The machine has to stay flat, if you're working on the table it has to stay on the table. 2. You can't hold it in your hands, you can't blow on it or use a fan 3. You can't hold the cotton ball, you can only pick it up to move it, but you can't hold it in your hands 4. You only get to use: 3 green sticks, 2 pink spools, 1 clear plastic cups, all the tape you want 4. Can you tell me what the word launch means to you? 5. What is an example of something that you have launched, or you've seen launched? 6. Do you know what it takes to launch something? 7. And what can create___ (what student response was) 8. So you have a plan in your mind? 9. Now I want you to put what's in your mind, on a piece of paper. When you start planning, you're going to start by drawing on paper. And when you're drawing, I want you to think about what the machine will look like when you use those materials and where the power for the machine is coming from and try to put that in your picture too. 10. Does that sound good? 11. So start with a picture. Take a piece of paper and a pencil out of the box. Put a big number 2 on the top corner of the paper. Start drawing with pencil, and then go over it with some crayon so I can see it. 12. Any questions? 13. Go ahead and draw the first thing that comes to your mind about how you can use those materials to make a machine 14. Now talk me through your picture
3A	1. How many tests should you do before you make any changes 2. Was that a successful launching of the cotton ball? 3. What was the feedback from your test? What did you learn from the test? 4. What was good? 5. Is there anything that didn't work well? 6. What changes are you going to make? 7. Is there anything you can do to make it more powerful?
3B	1. "So, you just did a test. What is your feedback from the test?" 2. "What worked well about your design? What do you want to keep? Is there anything you want to change?" 3. "Do you want to make an improvement?" 4. "Are you thinking? Do you have an idea?" 5. "Could you do anything to make the cotton ball go even higher and even farther?"
4	1. You need to pack everything up until next time. Your brain can be thinking about it but your hands can't touch it.

Session 3

Session three took place the day after session 2 and focused on the VSR prompted interview. During the VSR prompted interview, participants were shown, through Zoom, an average of 4 episodes of their design process during the design session and asked to recount what they were thinking about during each episode. Participants were asked to tell me aloud their stepwise directions for building their artifacts to elicit any possible differences between the artifact and the mental model.

Data Collection

In order to answer the research questions, several different sources of data were collected. The main data were participants' artifacts, video-data of sessions 2 and 3, and VSR interviews which are described below. Participants' initial design drawings and their verbal directions for artifact construction served as supplemental data sources. These data aided in the interpretation of the ideas embodied in design artifacts because one representation is unlikely to reveal an individual's complete understanding.

Data collection took place in sessions 2 and 3. All sessions were recorded using the record session feature of Zoom (see Table 3).

Table 3. Data Type and Alignment with Research Question

Session	Data Type	Used to Answer
Session 2	1. Video recording of session	RQ1
	2. Initial design drawing	RQ2
	3. Design artifact	
Session 3	1. Video recording of session	RQ 3
	2. VSR prompted interview	RQ 4
	3. Stepwise instructions for building artifact	

Video-stimulated recall prompted interview (VSR)

The purpose of the VSR prompted interview was to afford participants the opportunity to reflect on their thinking and decision-making during the design process to gain further insight into conceptual development.

The VSR prompted interview lasted an average of 20 minutes on the day following session two. This timeline was chosen based on a suggestion in the literature that there be a very short delay between the behavior and the recall for higher likelihood of participants remembering their behavior (Meier and Vogt, 2015). I developed a protocol, elaborated on in the section below, to explore children's thinking and decision-making processes. I showed four episodes from the artifact construction process to most participants.

In the VSR prompted interview, participants were shown the selected video episodes from session 2, that highlighted changes participants made to their artifacts. For convenience of sharing the episodes over Zoom the episodes of the VSR interview were shown to the participants in chronological order. Participants were asked to reflect and elaborate on what they were thinking at these points in the construction of their artifacts. Participants were asked not to engage with any materials during the interview. The criteria for selecting the episodes for VSR are detailed below in the phase one data analysis section.

VSR Prompted Interview Protocol.

The VSR prompted interview protocol consisted of first introducing an overview of the format and purpose of the interview (i.e., "To find out what you were thinking when you were building your machine.") and providing example statements (e.g., "This is where I ask you to tell me a little bit more about what made you make a decision." "I'm going to share my screen and you let me know if you have any trouble with seeing or hearing." "We are going to move to different time points when you were building.")

Then participants viewed each episode, stopping after each to complete the interview. Interview questions consisted of:

- Do you remember when you were doing this?

- Can you tell me about what you were thinking when you were (insert specific detail)?
- Where did you get the idea for (insert specific detail)?
- What helped you decide (insert specific detail)?
- Each interview ended with the final prompt "What is the biggest change you have made to your machine since you first started building it?"

An example of a shared screen VSR prompted interview moment is shown in Figure 2. In the example, the same child is seen in both images. Image A is the episode from session 2 that shows Noe talking and holding one of the materials from the kit. Image B is Noe *during* the VSR interview in session 3, watching video from her design session.

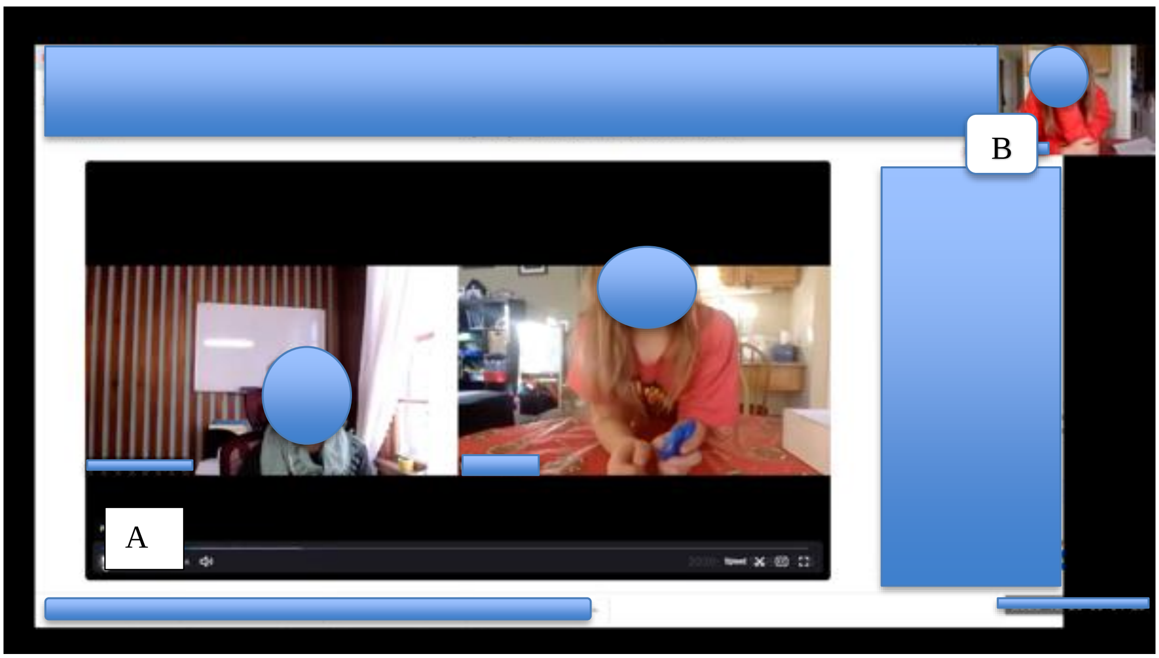


Figure 2. VSR Watching

Data Analysis

Data analysis was conducted in two phases. The first phase occurred immediately following data collection in session 2 in order to select key episodes of struggle or change for the video-stimulated recall prompted interviews in session 3. The second phase occurred after all data collection was completed.

Phase 1 Data Analysis

In phase 1, I analyzed all video data from session 1 and selected two to five episodes of approximately 1 minute for each participant. These episodes were used for the video-stimulated recall interview in session 3. Thus, phase 1 data analysis was not used to answer the research questions

Each episode centered around an instance of change made by the participant during the design process. Change was defined as moments in the design process when a child made a visible alteration to the artifact structure, materials, or position of the artifact as response to an idea that has occurred through observation or manipulation of the materials. Thus, the episodes focused on solving an artifact design goal. I also included episodes in which a participant exhibited an unknown or unspecified goal (e.g., moving pieces without a clear purpose) in order to better understand their thinking at the time of design construction. Videos in which the participant was focused on general performance but not design changes (e.g., adding more tape) were not selected because these were not likely to indicate mental model changes.

Table 4 provides an overview of the codes used to determine episodes of change. The episode selection process revealed that participants made changes to their artifacts for three purposes: (1) to solve a design artifact goal (i.e., stacking two spools); (2) to improve general performance of the artifact, but not change the design (e.g., changing from a sticky dot to tape); and (3) to exhibit an unspecified or unknown goal (e.g., taping a green stick).

Table 4. Codes for Selection of Change Episodes

Themes	Descriptors	Codes	Examples
Solve an artifact design goal	Communicates an identified goal for the artifact	Intention to make a change in artifact toward design goal	Works toward objective (e.g., its needs to be higher, faster, heavier, roll, push) "So I need weight to put there to launch the ball" pointing to one end of the lever"
Improve general performance but not change design	Communicates a problem with the existing parts of artifact	Intention to problem solve	Works toward problem solving (e.g., artifact is tipping-over, a piece is too loose, too tight, or falls off, wants to secure or loosen, adds, removes, or replaces tape that is no longer sticky or changes out tape for sticky dot or vice versa "It's tipping over" Changes out tape for sticky dot or vice versa
Unspecified or unknown goal	No specific problem identified or communicated	Aimless manipulation of artifact Unable to move forward without prompts	Moving artifact pieces around quickly, aimlessly Child appears or indicates feeling unsure or stuck Lays a green stick over the lever, quickly picks it back up, quickly moves the sticks around "I don't know what I'm doing right now"

Typically, the episodes came from a continuous segment of video that highlighted a participant making a change. However, at times it was necessary to piece together two segments of video with the first segment showing the artifact before the participant made a change and the second segment showing the artifact after the change. This allowed me to ask participants about the changes they made. I watched the complete video data of the design session for a participant and created time stamps for episodes of change. I then created a chronological sequence with four episodes that depicted changes throughout the design session. I narrowed down to four episodes based on what I thought could be easily recognized by the participant as a time when they changed their thinking.

Phase 2 Data Analysis

I used a content analysis approach to analyze the data. Content analysis is a qualitative analysis method that focuses on analyzing and deriving meaning from communication products such as text from interview transcripts, and documents (Patton, 2002). Content analysis provides the basis for drawing inferences and conclusions about the content found in the forms of communication because it goes beyond the immediately observable and relies on the symbolic qualities of the communication product (Krippendorf, 1989).

In this study, design artifacts are the primary unit of analysis. The artifact itself serves as a communication product but the science content embedded in the design is not directly observable and must be inferred. Concept analysis provides a systematic approach for drawing inferences about the manifestation of conceptual understanding represented by an artifact. It is therefore an optimal method for analyzing the conceptual understanding of the concepts of force and motion present in the artifact of engineering design.

Table 5 provides an overview of the data source used to answer each research question. Data analysis for each research question is described in detail below.

Table 5. Alignment Between Data Source and Research Question

Research Question	Data Sources Used to Answer
RQ 1 Mental model types	• Video recording of session 2 • Design artifact • Initial Design Drawing
RQ 2 Extent of change	• Video recording of session 2 • Design artifact • Initial Design Drawing
RQ 3 VSR reflections	• Video recording of session 2 • Video recording of session 3 • VSR prompted interview
RQ 4 Differences between artifact and mental model	• Video recording of session 2 • Design artifact • VSR prompted interview • Stepwise instructions for building artifact

Data Analysis Procedure for Research Question 1

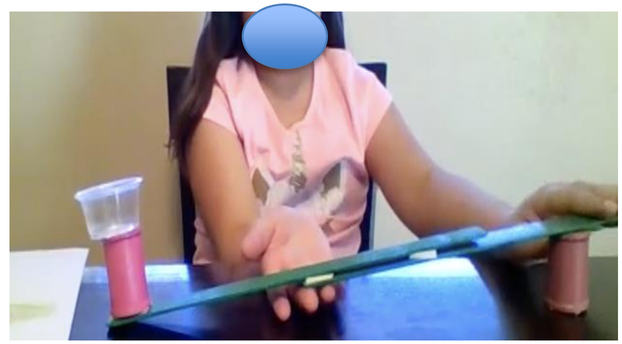
To answer research question 1, paraphrased as "Types of Mental Models Participants Form," I used video data from the Zoom recording of session 2, the design artifact as viewed through the recording and screen shots, and initial design drawings. The video data was used to examine the artifact during design for the dimensions present at each design iteration. The initial design drawing was used to help support an understanding of the dimensions present in the initial mental model. Mental model types were described by the number of perceptual dimensions present in the concluding mental model at the end of the design session.

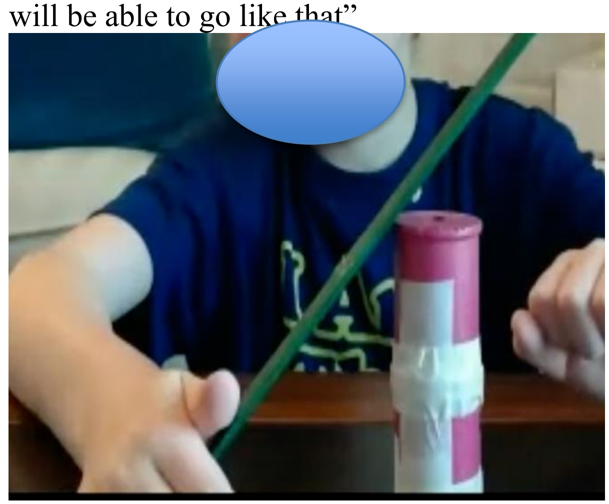
I used a combination of deductive and inductive coding to identify perceptual dimensions. To begin the process, I worked in collaboration with two colleagues, one a physics education professor and one a STEM education graduate student, to generate the deductive codes for the aspects of the concepts of force and motion that could be addressed in the engineering design activity. We watched half of the video data corpus and then inductively came up with new codes and iterated on the codes as we re-watched the same half the video data corpus. The new codes were labeled perceptual dimensions. Working with each colleague to determine the reliability of my coding scheme, we coded the video data of 3 participants together. We then coded one separately and compared. All video data was watched again and coded for the perceptual dimensions.

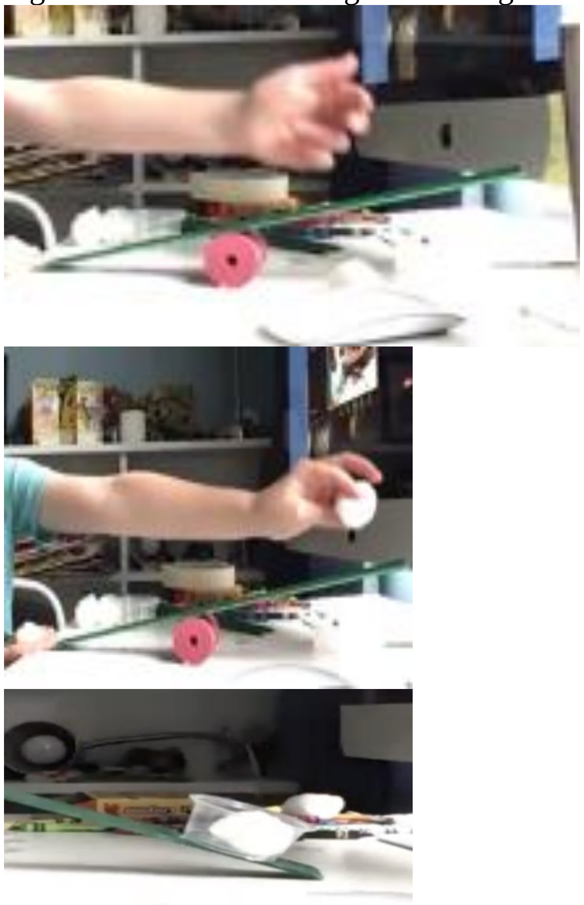
I recruited a third colleague to help me determine the reliability. After training her on the coding procedure, she randomly selected 20% of the video corpus and brought clarification questions to me. We worked together to modify the codebook to address her questions and re-examined the dimensions in question. We discussed those we disagreed on until we reached 100% agreement. I then reviewed and adjusted my coding for the remaining participants based on the revised codebook and collaborative coding. The final codes can be seen in Table 6 below.

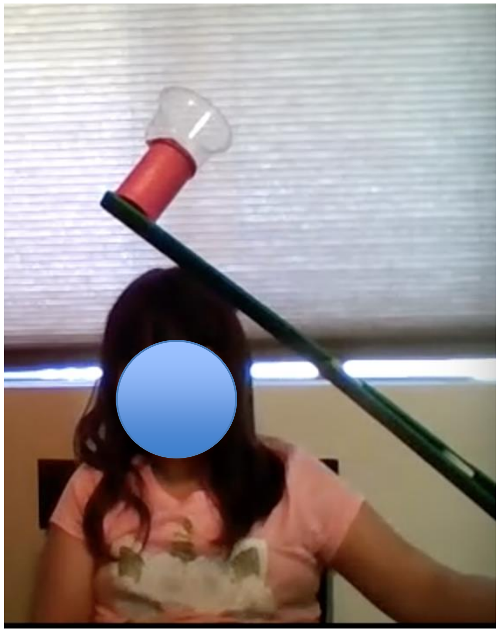
Table 6. Perceptual Dimensions Codebook

Dimension	Code	Definition	Indicators	Example from Data	Explanation of Example
Force	F	Power applied to make the cotton ball launch	Looks like hitting, dropping, or pressing using harder or heavier object with which to push or pull	"Because I put all its weight in my hand, and I put all my weight. If I sat on it, it would have blasted way further" 	She confirmed that she means more weight equals more force and more force is needed to launch the cotton ball.
Mechanical Advantage	MA	Power in one direction to create movement in opposite direction	Looks like a push down on one side, so that other side comes up	"I can make a see-saw and I can drop something heavier on one side and the cotton ball will go flying" 	He shows that he is going to put force from the spool on the "up" end of the lever to make the "down" end come up

Dimension	Code	Definition	Indicators	Example from Data	Explanation of Example
Fulcrum Position	FP	The placement of the support under the lever arm in the horizontal plane	Looks like one lever arm is longer and one is shorter, and the support is not directly in the center of the lever.		She placed the fulcrum near one end of the lever, so she has a very small amount of lever effort arm and a very long lever load arm,
Fulcrum Height	FH	The position of the support under the lever arm in vertical plane	Lever if higher off the table or floor work surface. Looks like stacking spools or objects under the lever to raise it up		She stacked two horizontal spools and placed them under one end of the lever to raise it up

Dimension	Code	Definition	Indicators	Example from Data	Explanation of Example
Pivot	P	The point of contact where the lever meets the fulcrum	Attending to the way the lever sits or moves on the fulcrum	“If I put that tape right there it is almost like a little lever” “So I think it might actually get some more lift” 	He determined that the lever could not pivot correctly on the flat top of the spool, so he placed a tiny loop of tape on the top of the spool to make a place for the lever to pivot.
Rotation	R	The amount of movement of one end of the lever in an upward direction in response to force at the opposite end of the lever	Trying to get one end of the lever to come up higher when pushing down on the other end of lever. Evidence is seen in creating more room to press down on load arm. Looks like placing fulcrum upright or moving to the edge of the table	“I think it’s because this can go higher. If I put the same amount of force on it, it just goes this much but if I put it (the green stick) way back it will be able to go like that” 	He discovered that the shorter side could rotate more when the lever is higher

Dimension	Code	Definition	Indicators	Example from Data	Explanation of Example
Launch Height	LH	The height at which the cotton ball is released from the artifact	Attending to the height that the lever comes up or the height the cotton ball comes out. Evidence is seen in adding a cup to hold the cotton ball, or moving the support to get the lever to come up higher	” It only lifts this high up, so like I need it higher because all it's doing is its lifting it” 	He put the cup at the end of the load arm to contain the cotton ball so it would not fall off the stick before it was raised high enough

Dimension	Code	Definition	Indicators	Example from Data	Explanation of Example
Launch Angle	LA	The angle at which the cotton ball is released from the artifact	Used to address the trajectory of the cotton ball (arc)		She added the spool under the cup to the change the angle at which the cotton ball leaves the cup
Other	O	unanticipated aspect of the artifact design and performance that the child acknowledges and addresses	Attending to the weakening of the force over the longer lever length. Looks like taking off one stick for a total of 2 sticks long.	“It didn’t push on the ball a lot” 	She reduces the lever length to 2 sticks after testing 3 and finding out the force on the cotton ball was less than when the lever was 2 sticks-long

Using the perceptual dimension coding scheme, I created a profile for each participant detailing the dimensions present in their concluding artifacts, and thereby in their concluding mental models, at the end of the design session. I determined mental model types according to the number of dimensions in concluding mental models.

Data Analysis Procedure for Research Question 2

Research question 2, paraphrased as "Extent of change to mental models," used the same video data and coding of perceptual dimensions as Research question 1. However, the focus of this research question was on comparing the differences between the initial mental model (i.e., from the initial drawing and design) and the final mental model (i.e., from the final artifact). The perceptual dimensions added throughout the design session was recorded along with the sequencing of the added dimensions. The number of dimensions present in the concluding mental model was determined by examining the final artifact for dimensions. To arrive at the extent of change, the number of dimensions present in the initial was subtracted from the number of dimensions present in the final. That number represented the extent of change from initial to final mental model.

Data Analysis for RQ 3 -How VSR Reflection Captures Change

To answer research question 3, paraphrased as "How VSR reflection captures change," I used video data from recordings of sessions 2 and 3, and VSR interview data. All VSR interview data was watched and analyzed using inductive content analysis to understand and develop themes for participant responses to the video prompts. These themes were change corroborated, change not corroborated, and change partially corroborated.

After themes were developed, all VSR interview data was watched again, and codes were generated to capture participant's ability to articulate their focus, their intention, and their rationale for making changes in their artifact. These factors were chosen because they provide the most insight into participant's cognizance of the changes in their thinking. All interview data was then analyzed using the coding described in Table 7 below. Codes applied to participants' language and sounds (e.g., onomatopoeia), gestures/movements, and facial expressions while reflecting during the VSR prompted interview on their session 2 videos. The only exception to this is the "revelation" code, which was used when students made a new insight into a possible design change during the VSR prompted interview (i.e., they had an "aha" moment during the interview).

Table 7. Themes and Codes for VSR Data Analysis

Themes	Description	Codes	Examples
1.Change corroborated	Articulates intentional choice to address a specific dimension	Clear rationale	*"I was adjusting the stick so I can make it go a little bit farther"* *"I thought maybe if we put it higher then maybe it will go farther. Because it would shoot it into the air higher and when things go higher the also go further in the process"* *"The cup helped the cup was holding the pom pom so it wouldn't fall of while it was launching"*
2.Change not corroborated	Does not articulate an intentional choice to address a specific dimension, yet the artifact indicates that the design change solved a specific dimension	Does not remember No intention Does not provide a clear rationale Aimless manipulation of artifact Stays stuck Needs prompts	*"I don't remember"* *"It was an accident"*
3 Change partially corroborated	Articulates intentionality but no specific dimension is identified, dimension is unclear, or there is a dissonance regarding solving the dimension Inconsistency in responses	Intentional but not clear	*"I thought it would work better if I put it in the middle, but I don't know how"*
3a. Change partially corroborated and within VSR interview a new idea is evoked		Revelation	*"I know what to do now"* *"I have a new idea"*

Data Analysis for RQ4 - Differences Between Mental Model and Artifact

To answer research question 4, paraphrased as "Differences between mental model and artifact," I used data from video recordings of session 2 and session 3, the design artifact, VSR prompted interview data, and stepwise directions for constructing the artifact. The purpose of this research question was to separate the physical and conceptual aspects of the engineering design activity. That is, I wanted to determine if the participants had an artifact design that they wanted to make but were not physically able to.

All video data was watched and analyzed using deductive content analysis to determine how participants responded when provided with opportunities to communicate challenges or difficulties with manipulating the physical materials during the design session. I paid particular attention to times when the participant discussed success of their drawing and artifact design, when I probed if there was any material they wished they could have used, and when participants provided stepwise instructions for building their design artifact. I also specifically probed if there was any material they wished they could use, anything they would change, and any advice they would give a friend. Based on these responses, participants were coded as either having a difference in their mental model and artifact or not.

CHAPTER 4

FINDINGS FOR RESEARCH QUESTIONS 1 & 2

Content analysis of the data, with multiple rounds of inductive and deductive analysis, allowed me to extract meaning from children's design artifacts, drawings, and interview responses and answer my four research questions. In Chapter 4, I describe the findings from my content analysis for perceptual dimensions that answer research questions one and two. In Chapter 5, I describe the findings from my content analysis of participant's articulations of their focus, their intention, and their rationale in their design changes in their VSR interview responses to answer research question 3. The findings from my deductive content analysis of design session video data for instances of challenge or difficulty with the physical materials that inhibited their instantiation of their mental model in their artifact to answer research question 4 is also described in Chapter 5.

I begin with a reminder about what the perceptual dimensions are and how they comprise a mental model and then describe the findings that answer research questions 1 "Mental model types," and 2, "Extent of change." I present findings to answer these two questions together because they are interrelated with both derived from analyzing participants initial mental models for perceptual dimensions present in initial drawings and initial artifact design, the number and sequence of dimensions added, and the perceptual dimensions present in the concluding mental models. I will address the types of mental models that participants formed based on the number of perceptual dimensions present and explain the extent to which mental models changed from initial to concluding, including descriptions of patterns of change during mental model development.

Perceptual Dimensions

As described earlier in Chapter 3, through collaboration with a physics education expert and a STEM education researcher, I arrived at 8 perceptual dimensions that were deemed reasonable to anticipate that a young child could recognize and address during the design challenge of building a machine to launch a cotton ball used in this study. The design challenge required participants to build a design artifact as a solution to the challenge. The design artifact is itself a system made of separate parts (the green sticks, the pink spools, plastic cup, and tape) that works as a whole. It is nearly impossible to change one part without effecting change in the whole. I have, however, designated a separation between each part of the system by identifying the specific aspect the participant is focused on and intentionally addressing in a moment of making a change to the artifact. Therefore, in this study, the term perceptual dimension is used to create a separation between the intertwined aspects of the system of a design artifact created to solve the design problem of launching a cotton ball. It is these perceptual dimensions that are considered to comprise a scientific mental model of the concepts of force and motion as they relate to the launch and projectile motion of a cotton ball. Each perceptual dimension and its abbreviation is explained in Table 8 below.

Table 8. Perceptual Dimensions

Perceptual Dimension	Abbreviation	Explanation
Force	F	Weight or pressure applied to create movement
Mechanical Advantage	MA	Product of force applied in one direction that creates movement in another direction
Fulcrum Position	FP	Moving the location of the fulcrum relative to the lever so that one arm (LL or LE) is longer than the other
Fulcrum Height	FH	Expressing that elevating the lever will help with launch because there is more room for the lever to be pressed down
Pivot	P	Attending to the way the lever sits on/moves on the fulcrum
Rotation	R	The amount the lever rotates in an upward direction when one end is pressed on
Launch Height	LH	Extending the lever on the load end or doubling the lever length (attaching sticks together) to make it come up higher when it rotates
Launch Angle	LA	Attending to where the ball will come out based on where the lever lifts to when opposite end is pressed down

Types of Mental Models Developed During Design Artifact Construction

Participants' mental models were evaluated for perceptual dimensions in initial design drawings and initial artifacts, during design changes and in the artifact at the conclusion of the design session. Mental model development resulted in mental models ranging from 2-dimensions to 8-dimensions. Figure 3 shows how many participants developed each type of mental model, based on the total number of dimensions present in each participant's mental model at the time of the completion of the design activity. No students developed a 1-dimension mental model. Three participants (11%) developed a 2-dimension mental model. Five participants (19%) developed a 3-dimension mental model. Four participants (15%) developed a 4-dimension mental model. Seven participants (27%) developed a 5-dimension mental model. Four participants (15%)

developed a 6-dimension mental model. Two students (8%) developed a 7-dimension mental model. One student (4%) developed an 8-dimension mental model.

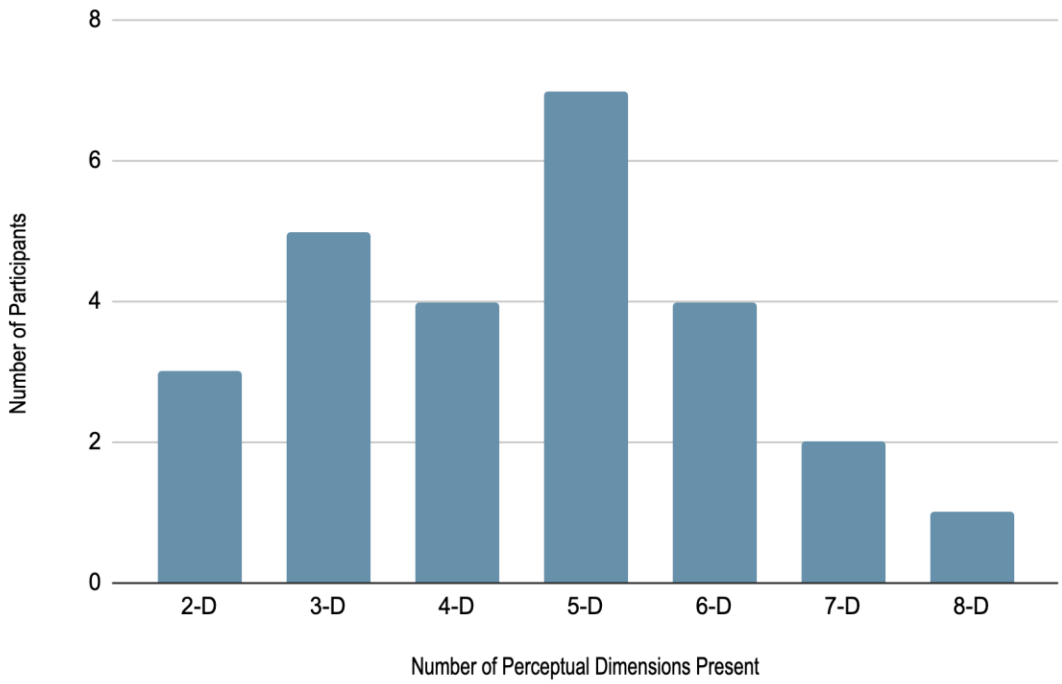


Figure 3. Concluding Mental Model Types

To better understand the change in mental models from initial to concluding, I unpacked each mental model type to determine the types of dimensions present in each. Table 9 below shows the distribution of perceptual dimensions present in the concluding mental models of participants within each type of mental model. The only discernible pattern of perceptual dimensions in the different mental model types is the presence of force and mechanical advantage. All other dimensions appear in the different mental model types without a pattern. The dimensions of force and mechanical advantage are present in all but one mental model (N=25), regardless of the total number of dimensions, and are the only two dimensions that consistently manifest together. One of the two fulcrum dimensions, either fulcrum height or fulcrum position, was present in all but one of the mental models that expanded beyond 2-dimensional (N=22). This finding indicates that force, mechanical advantage, and fulcrum are likely to be foundational concepts that must be acquired to expand a mental model with additional dimensions.

Table 9. Dimensions in Concluding Mental Model Types

2-D	3-D	4-D	5-D	6-D	7-D	8-D
F, MA	F, MA, P	F, MA, FP, R	F, MA, FP, LH, R	F, MA, LH, R, LA, FH	F, MA, FH, FP, P, R, LH	F, MA, LA, P, R, FH, FP, LH
F, MA, FP, -FP	F, MA, FP	F, MA, FP, LH	F, MA, FP, R, P	F, MA, FP, R, FH, LH	F, MA, FH, R, P, LH, LA	
F, MA	F, MA, FP	F, MA, LH, FP	F, MA, LH, FP, R	F, MA, R, FP, LH, LA		
	F, MA, FH	F, MA, P, FP	F, MA, FP, LH, LA	F, MA, FP, R, LH, LA		
	FH, FP, LA		F, MA, FH, FP, H			
			F, MA, FH, FP, LH			
			F, MA, FH, R, P			

Note: F=force, MA=mechanical advantage, FP=fulcrum position, FH=fulcrum height, P=pivot, R=rotation, LH=launch height, LA=launch angle, -FP = fulcrum position subtracted from concluding mental model

Figure 4 below provides a different view of the frequency with which each perceptual dimension appears in participants' concluding mental models. Again, we can see that force and mechanical advantage are two dimensions that occur most frequently in 96% (N=25) participant's mental models. Fulcrum position was the next most frequently occurring mental model dimension in 69% (N=18) of participants. Launch height appeared in the mental models of half (N=13) of participants', with rotation in 46 % (N=12) and fulcrum height in 38% (N=10). Pivot appeared in only 27% (N=7) and launch angle was the least common dimension at 23% (N=6) which indicates that they may be two of the most sophisticated dimensions for a child in this study.

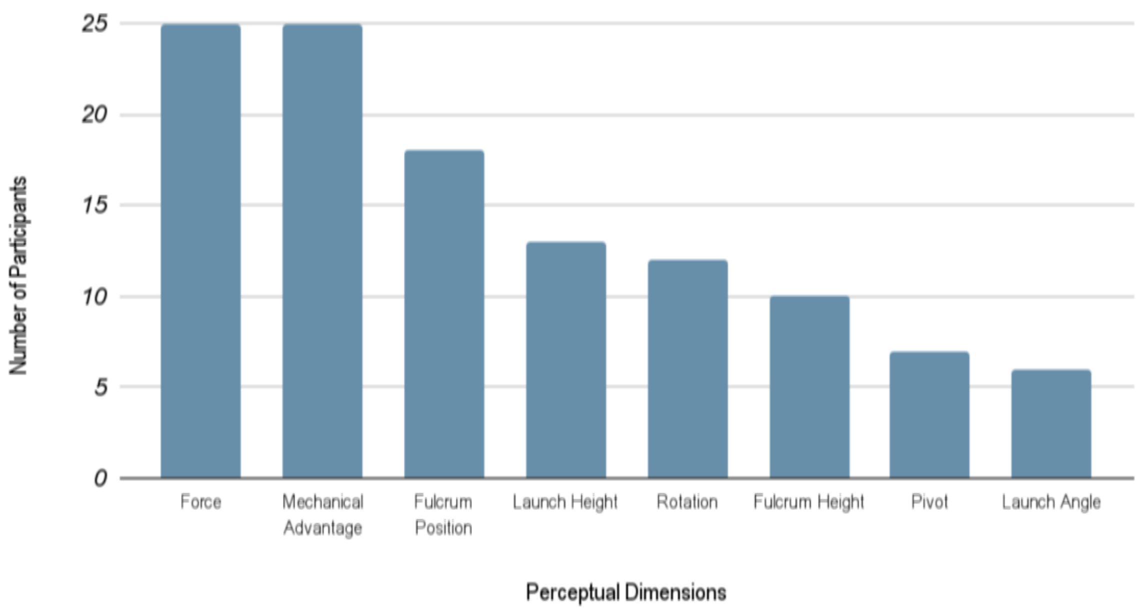


Figure 4. Frequency of Dimensions in Concluding Mental Models

Another way to look into the change leading to the participants' concluding mental model is to look at the extent of change from initial mental model to concluding mental model and to look at the sequencing of the dimensions that comprise the changes.

I will begin with describing the extent of change and proceed to describe the sequences of the changes.

Extent of Changes to Mental Models

Of the 26 participants, 23 (88%) developed a concluding mental model with more dimensions than their initial mental model. Figure 5 shows the extent of the change in mental models from initial to concluding. Five participants (19%) added one dimension to their mental model. Six participants (23%) added two dimensions to their mental model. Five participants (19%) added three dimensions to their mental model. Three participants (11%) added four dimensions to their mental model. Three participants (11%) added five dimensions to their mental model. One participant (4%) added six dimensions to their mental model. Two participants (8%) experienced no change in the number of dimensions present from initial to concluding mental model and one participant (4%) lost one dimension from their mental model during the design session. Adding two dimensions was the most common positive change and adding six dimensions was the least common positive change.

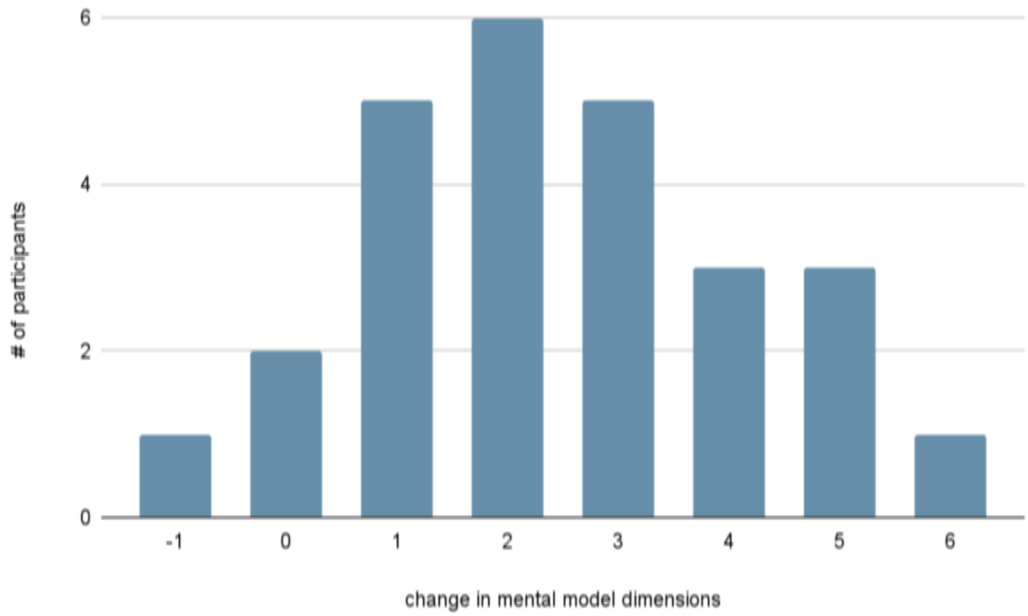


Figure 5. Extent of Changes to Mental Models

Sequence of Change to Arrive at Concluding Mental Model

The sequence in which each participant added to their mental model is presented in **Error! Reference source not found.** below. The dimensions in blue were present in a participant's initial mental model (i.e., represented by initial design drawing and initial artifact). The dimensions in black were added in the sequence presented during the iterative design process. The sequence reveals that 96% (N=25) of participants demonstrated force and mechanical advantage first, before adding any other dimension. Two participants who demonstrated just force in their initial mental model, added the dimension of mechanical advantage next. One participant who had no dimensions in their mental model, added force first and mechanical advantage second.

Table. Sequence of Change Toward Concluding Mental Model

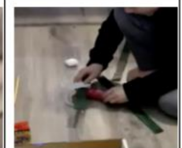
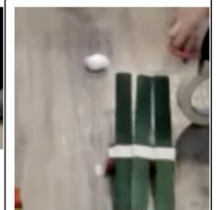
2-D	3-D	4-D	5-D	6-D	7-D	8-D
F, MA	F, MA, P	F, MA, FP, R	F, MA, FP, LH, R	F, MA, LH, R, LA, FH	F, MA, FH, FP, P, R, LH	F, MA, LA, P, R, FH, FP, LH
F, MA, FP, -FP	F, MA, FP	F, MA, FP, LH	F, MA, FP, R, P	F, MA, FP, R, FH, LH	F, MA, FH, R, P, LH, LA	
F, MA	F, MA, FP	F, MA, LH, FP	F, MA, LH, FP, R	F, MA, R, FP, LH, LA		
	F, MA, FH	F, MA, P, FP	F, MA, FP, LH, LA	F, MA, FP, R, LH, LA		
	FH, FP, LA		F, MA, FH, FP, H			
			F, MA, FH, FP, LH			
			F, MA, FH, R, P			

When looking at the sequence of perceptual dimensions added in mental model development, it appears that the concept of force appears to be a prerequisite for developing more complex mental models. Recall, almost every participant (N=25) developed a mental model that included the dimension of force. Furthermore, all participants who developed a mental model that included force (N=25) also developed a mental model that included the dimension of mechanical advantage (N=25). Only one participant, Dio, did not develop a mental model that included neither the dimension of force nor mechanical advantage, and Dio was never able to expand his mental model beyond the initial three dimensions.

Only one student, Sam, demonstrated a decrease in the number of dimensions in their mental model, with an initial 3-dmodel that diminished to a 2-dimension concluding mental model. Sam demonstrated an understanding of the position of fulcrum in his initial drawing and in his initial artifact with a longer LL. During the engineering design process, he took away the longer LL, moved the fulcrum to the center and did not move the fulcrum again, and instead focused on magnifying the force on the LE arm of the machine. In spite of a successful launch in which the ball went very high, Sam was focused on the fact that the machine broke apart—"It launched it up and then it broke"—so then even after a successful launch he was focused on the breakage which he said was related to the "sides," meaning the lever arms on either side of the fulcrum.

Table 10 below shows a sequence of images (1-1d) of Sam addressing and testing the dimension of fulcrum position during the design session.

Table 10. Sam Losing Fulcrum Position

Image #	1	1a	1b	1c	1d	1d
Time stamp	11:26	14:20	18:15	18:21	19:15	
Image and description	 Initial design drawing shows fulcrum position	 The pink spool is under the green sticks closer to the LE end of the sticks	 He is ready to test this design	 The launcher broke apart during the test	 He is repairing the launcher that came apart when he tested it	 This is his design after he repaired his launcher with the fulcrum now in the middle
Researcher questions and Sam's responses	R:*"Do I see one green stick and one pink spool?"* S:*"I don't know"*	R:*"Can you tell me about where you put the green sticks because it looks like there is a long side and a short side?"* S: *"I was trying to do, do the short side, because my hand is small."*	R:*"What worked well and what didn't work as well as you want?* S: *"It went up. But then it broke. I didn't want it to break."*	R:*"Are you going to change anything?"* S: *"I think I'll just keep it the same. Might put some more tape on it"*	R:*"Did you change where the green sticks are? It looks like they moved."* S:*"When it broke I decided to make it go like up like a little more like in the middle to see if it would work."*	R:*"What was the reason for that?"* S: *"When it broke I thought it was about the sides so I decided to change them."*
Researcher interpretation	He is ready to start building his design.	He intentionally made one lever arm longer than the other with his placement of the sticks over the fulcrum.	He recognized that the launcher parts need to stay together even during launching.	He does not intend to change anything in the design, just repair it.	It looks like he has changed the fulcrum position and the LE and LL are now the same length.	He intentionally put the launcher back together differently even though that was not his original plan and now the LL and LE the same length, meaning he lost FP.

The one participant, Sam, who lost the fulcrum dimension, did not expand beyond a 2-dimensional mental model. This finding further supports the previous finding that the dimensions of force, mechanical advantage and one fulcrum dimension are foundational and need to be present prior to expansion of the mental model with additional dimensions.

More Initial Dimensions Do Not Yield More Final Dimensions

Regarding the number of dimensions in a participants' concluding mental model, a logical assumption would be that the more dimensions you start with, the more you end with. However, this was not the case in this study. The pattern of mental model development appeared to be random and some participants, (e.g., Kai and Ara) who started with just two initial dimensions went on to develop more concluding dimensions than a participant with 4 initial dimensions (e.g., Tru). However, Figure 6 below shows that while there is no direct relationship between number of initial and number of final dimensions, there is a relationship between the presence of three specific initial dimensions, namely force (F), mechanical advantage (MA), and fulcrum height (FH), and the number of concluding dimensions. Four participants (15%) had force, mechanical advantage, and fulcrum height in their initial mental models and added four dimensions during the design session. This finding is consistent with the finding stated earlier that force, mechanical advantage and fulcrum height appeared to be foundational concepts in the development of a scientific mental model of the launcher system.

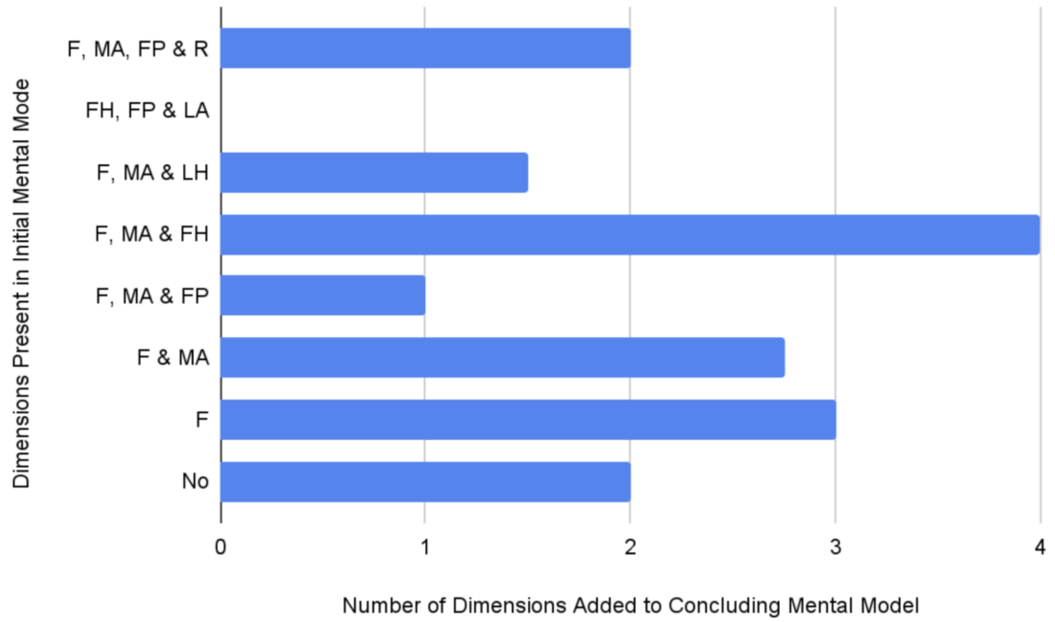


Figure 6. Relationship Between Initial Dimensions and Average Number of Dimensions Added

Observed Patterns in Mental Model Development

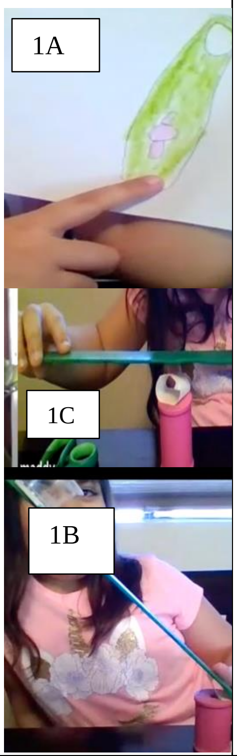
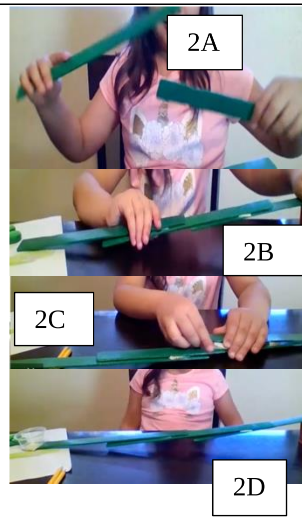
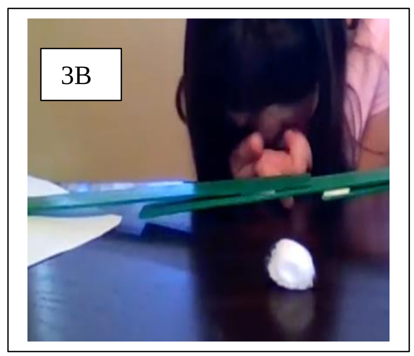
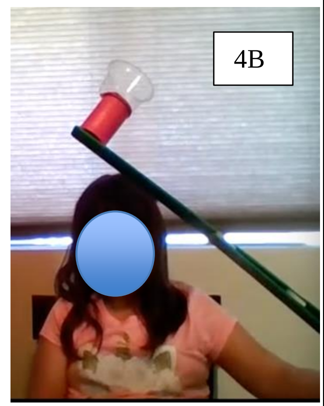
In the following section, I describe patterns observed in participants' mental model development as externalized through design artifacts. The five observed patterns are: (1) Adding two dimensions, one-at-a-time, to mental model, (2) adding an unanticipated dimension to mental model; (3) adding the maximum number of anticipated dimensions (six), one-at-a-time, to mental model; (4) adding multiple dimensions at once in one design move; and 5) incomplete change in mental model. I provide a detailed description of one representative participant for each of the observed patterns below.

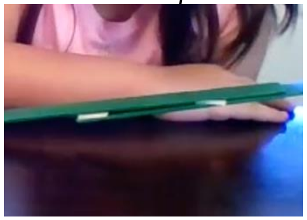
Adding Two Dimensions, One-at-a-Time, to Mental Model

The most common change was the addition of two dimensions (N=7). I have chosen to focus on one participant, Ali, who added the typical two anticipated dimensions to delve into detail of what that mental model development pattern looked like. I have chosen to focus on Ali because she was not able to communicate well in speech but was efficient and precise in communicating through her artifact. Ali did not make a lot of rapid changes to her artifact, and instead was very deliberate and calm. Ali did not want to answer questions from me while she was constructing and testing her artifact and she did not voluntarily talk much about what she was thinning, so the artifact does the majority of Ali's communicating. Further, Ali also demonstrated adding the unanticipated dimension of force over distance to her mental model.

Table 11 below depicts Ali's process of adding two dimensions and an unanticipated dimension to her mental model during the design process. In image 1A is Ali's initial design drawing showing one green stick for the lever and the pink spool at one end of the lever creating a long load arm. In image 1B, Ali's first design looks like her drawing with a longer load arm, and in 1C she is testing her artifact. Ali's initial artifact design reflects that her mental model includes the dimensions of force, mechanical advantage, and fulcrum position. After she tested the first design, Ali expressed that she intended to increase the length (of the load-arm) to make it go farther. In image 2A, she is shown adding two more green sticks to the lever. In 2B she is taping them together along the top side, in 2C she is taping them together on the underside, and in 2D she has attached the three sticks together. She could not put into words why she thought a longer lever would work to launch the ball farther, but she is certain increased length will help launch the ball farther, indicating that she is considering the dimension of launch height. In image 3A, she tests the 3-stick-length lever, and observes that it does not launch even as far as one stick and in image 3B she sees that it sags so she decides to decrease the lever length to two sticks. Then she tests her design that is 3-sticks-long, and discovers that when it is 1-stick-long or 3-sticks-long it does not work as well as when it is 2-sticks long.

Table 11.Ali Adds Two Dimensions, Plus one Unanticipated Dimension, One-at-a-Time

Scene	1	2	3	4	5
dimension					
dimension					
dimension					
Time	15:46	18:54	24:37	32:57	39:12
					**Final Artifact**

Scene	1	2	3	4	5
	“*The stool has to be right there so it has a little space where I can hold it and it can launch*.” Artifact reflects force and mechanical advantage and fulcrum position (FP) which is identified by the longer load arm and shorter effort arm.	“*I can probably make it go farther by putting these sticks like that”*	“*Taking off one stick. Probably make it go farther*.” *I think two* (sticks) *will work a lot better than one and three.”* *“I can see it “sag*” as she places her finger there and lifts is up a little. *“I don’t really know how to explain it.*” she says as she takes off one stick “*It was better than three and one* (stick)” “*The second stick is sort of doubled on the first stick.”*  Reflects force over distance	“*Could make the clear container go higher by putting a spool underneath so it can go farther*.”	
	F, MA, FP	**LH**	**FD**	**LA**	**F, MA, FP, LH, FD, LA**

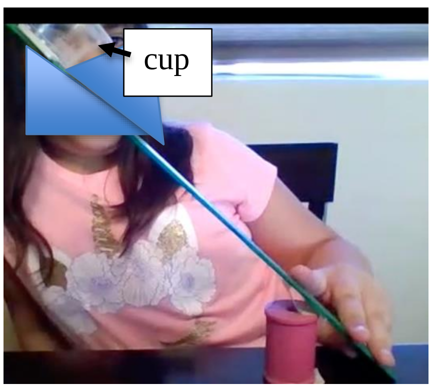
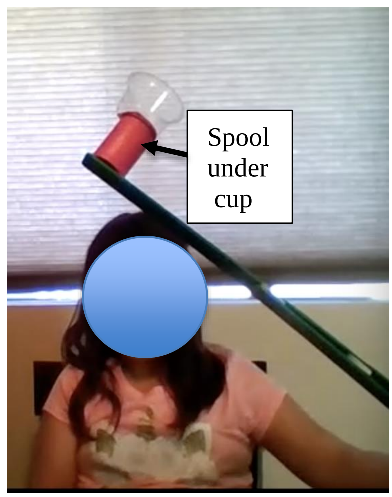
Key:

Force	Mechanical Advantage	Fulcrum Height	Fulcrum Position	Pivot	Rotation	Launch Height	Launch Angle	Force Distance

Bold color = complete addition, shaded color = incomplete addition, arrows indicate the dimension was carried into the next iteration

The close-up images in Table 12 show how Ali changed the launch angle from her initial artifact (a) to her final artifact (b). In image a, the clear cup is attached directly to the green stick lever. In image b, Ali has added a spool under the cup to change the angle that the cotton ball leaves the cup. This artifact change indicates the addition of the dimension of launch angle to her mental model. Ali's addition of the unanticipated dimension is described in the section below.

Table 12. Close-Up of Launch Angle

a	**b**	
		Ali did not change the angle of the lever on the fulcrum. Instead, she changed the angle at which the ball exits the cup by putting the pink spool under the cup

Development of Unanticipated Dimension

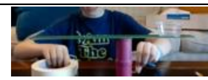
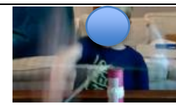
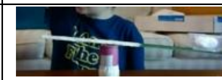
Three participants demonstrated the development of the unanticipated dimension of force over distance as discovered during analysis: Dav, Tru, and Ali. To describe the mental model development of the unanticipated dimension, I revisit participant Ali, who was described in the section directly above, because she did not make rapid changes, and was slow and deliberate in her design process.

In Table 11 (above), in scene 1, Ali used a single green stick in her initial artifact design. She observed the launch performance of this design and decided that the lever needed to be 3-sticks long to make it launch farther. She went to work taping 3 sticks together, making sure to tape both topside and underneath to secure the sticks together, shown in scene 2, a-d. In scene 3a, Ali tested the 3-stick design. She observed that the 3-sticks-long lever did not launch the ball as well as the 1-stick long lever. In scene 3b, without speaking, she notices the sag in the lever arm and puts her finger under it. She then decides to take the lever -arm length down to 2 sticks and double them up to make sure they don't sag. She says, "I don't know how to explain it," but she is committed to a 2-stick-long lever length, indicating through the artifact that she understands that there is less force for the launch across the longer lever length.

6 Dimensions Added One-at-a Time to Mental Model During Activity

Most participants (N=23) added one dimension to their mental model at a time. Kai is unique in that he added all the anticipated dimensions, one-at-a-time to develop a scientific mental model of the cotton ball launcher system, captured in Table 13 below. In scene 1, Kai has the lever on top of and centered across the spool. He uses this to demonstrate that when he uses his hand to apply force to one end of the lever, the other end lifts up. He observed the way the lever came off of the flat surface of the spool as fulcrum. In scene 2, Kai demonstrates an understanding of pivot when he makes a tiny loop out of masking tape to make a tiny fulcrum so that the lever does not use the spool surface. In scene 3, Kai added two spools stacked vertically to increase the height of the lever and demonstrates an understanding of fulcrum height. Kai builds off of his understanding of fulcrum height and pivot to incorporate the dimension of rotation. His addition of rotation is shown in scene 4 when he is able to push the effort arm of the lever down farther and get the load arm to come up more. In scene 5, Kai demonstrates the addition of the dimension of fulcrum position as he extends the load arm and declares that the cotton ball is now very far away (from the fulcrum.) Kai uses what he learned from testing his artifact in scene 5 to increase launch height with the longer load arm in scene 6. Once his artifact is reaching the height he wants, he turns his focus to launch angle. In scene 7, Kai demonstrates the angle at which the cotton ball will exit the launcher reflecting the new dimension of launch angle to his mental model. His final artifact reflects the development of his mental model to include all 8 dimensions.

Table 13. Kai Adds 6 Dimensions

Scene	1	2	3	4	5	6	7	Final
Dimension								
Dimension								
Time	1:26	6:52	17:53	26:46	29:09	38:09	38:47	42:29
								
	With the artifact he demonstrates force and mechanical advantage	In artifact he solves pivot by making a “little lever” is actually a tiny round fulcrum out of a tiny loop of tape	In the artifact he has doubled the height by taping two spools together	in the artifact he solves rotation using fulcrum height & pivot, so he is able to push down farther & get a greater rotation for launch	In the artifact, “cotton ball is pretty far away” he has made the load arm of the lever longer by changing the position of the lever on the fulcrum	In the artifact he uses the fulcrum position to solve for launch height. Gesturing height he says ‘If there’s more wood over here than there is here, this thing is going to go higher”	He uses launch height to solve launch angle and demonstrates with artifact	He wants to capitalize on his new understanding and optimize the artifact, but I had to stop him there for time
	F, MA	**P**	**FH**	**R**	**FP**	**LH**	**LA**	

Key:

Force	Mechanical Advantage	Fulcrum Height	Fulcrum Position	Pivot	Rotation	Launch Height	Launch Angle	Force Distance

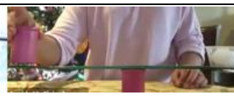
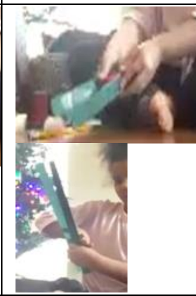
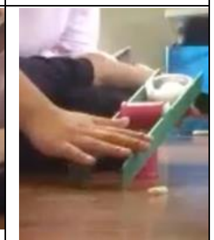
Bold color = complete addition, shaded color = incomplete addition, arrows indicate the dimension was carried into the next iteration

Mental Model Development of Multiple Dimensions in One Design Move

Ser is a unique example of the one participant who was able to add multiple dimensions in one design move.

Table 14 depicts the sequence of her design process and the 3 dimensions she added simultaneously in one design move. Ser's initial design shown in scene 1 reflects her understanding of the dimensions of force and mechanical advantage. In this scene she has one green stick over a vertical pink spool as a fulcrum and shows what happens when she presses down on one end of the lever with another spool. Next, in scene 2, she has turned the spool horizontal and is focusing her attention on the way the stick moves on the spool, indicating that she is thinking about pivot. Then she leaves the dimension of pivot, and in scene 3 she is changing the position of the fulcrum to make one end of the lever longer, and one end up so that there is, as she says, "air under it," and explains, "if you put it [the lever] evenly it won't launch." In her next design she leaves fulcrum position and focuses on fulcrum height and the artifact has two vertical spools stacked up. In scene 4, the stick over each spool is even. At this point in her development, she has stopped working on pivot, fulcrum position, and fulcrum height without having finalized any of these dimensions in her design. In scene 5, Ser picks up two green sticks with a spool sandwiched between them and starts to rotate them in such a way that the sticks rotate up and then down, indicating that the dimension of rotation has entered her mental model. In the next move, Ser puts the sandwiched horizontal spool on top of a vertical spool, simultaneously addressing the 3 dimensions of fulcrum height, pivot, and rotation as shown in scene 6. Her final artifact reflects the coordination of those three dimensions.

Table 14. Solving Multiple Dimensions in One Design

Scene	1	2	3	4	5	6	7
Dimension							
Dimension							
Dimension							
Time	18:52	24:42	27:01	31:37	34:30	36:20	53:24
							
	Artifact reveals her understanding of Force = pushing down with hand & Mech adv= to make other side of lever come up	Trying to figure out pivot-tries it out with fulcrum vertical, and then with fulcrum horizontal	"*I was thinking less weight on the side that we are going to launch because if you put it evenly it won't launch*"	Thinking about fulcrum height	Thinking about rotation	Combine height, pivot, and rotation all together into one design move	Final design
	F, MA					**R, FH, P**	

Key:

Force	Mechanical Advantage	Fulcrum Height	Fulcrum Position	Pivot	Rotation	Launch Height	Launch Angle	<u>Force</u> Distance

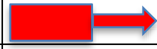
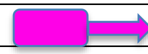
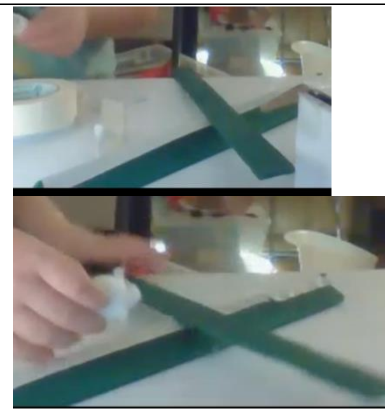
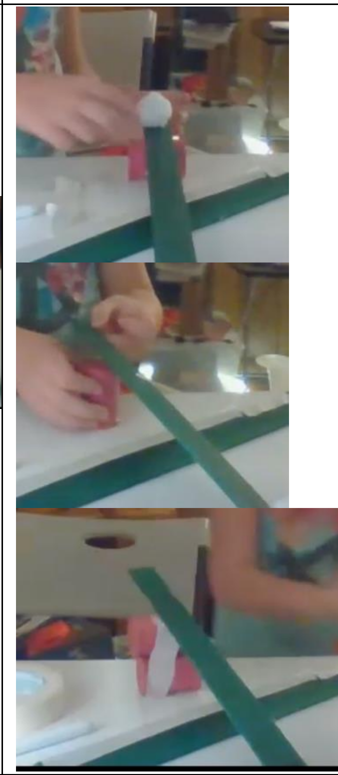
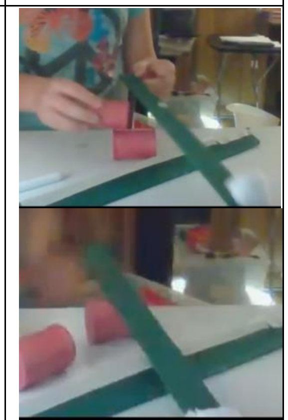
Bold color = complete addition, shaded color = incomplete addition, arrows indicate the dimension was carried into the next iteration

Incomplete Change in Mental Model

Most participants (N=23) were able to make complete changes to their mental models by the end of the design session. However, some participants (N=3) still had incomplete changes at the conclusion of the session. One participant with an incomplete mental model change is Joi. I have chosen to focus on the example of Joi because she had a unique design for the dimension of pivot, was able to add the dimension of fulcrum position, but was then unable to add the dimension of height. This example shows how her mental model development may have been limited by her unique triangular fulcrum design. No other participants used a triangular fulcrum.

Table 15 below captures Joi's incomplete mental model change. Joi's first design, in scene 1, reflects that her initial mental model includes the dimensions of force and mechanical advantage. In 1b, she is experimenting with the way the lever moves on the fulcrum, saying "This [the stick] is a flat base, and this [the spool] is kinda like curved" indicating that the dimension of pivot is entering her mental model. In scene 2, she has started building a triangular fulcrum (made by placing two sticks up against each other, each at 45-degree angle, to make one point of a triangle) for the lever and solves the dimension of pivot. In her next design, scene 3, she lays the lever over the triangular fulcrum so that one lever arm is longer, and one is shorter, indicating that she has added the dimension of fulcrum position. In the next iteration, she is grappling with, "It's not as high as it needs to be now. If I put it like this [two spools] then it's as high as it needs to be. "Maybe height is what I'm missing." She tries to incorporate the dimension of height along with fulcrum position and pivot, but she cannot make the dimensions work together. In scene 4a she adds one spool for height, in 4b she stands the spool vertical for more height and settles in 4c on 2 horizontal spools for height. However, when she tests this, she finds that the spools are serving as the fulcrum and not the triangle. This brings her to iteration 5 where she tries taking some of the height away, but she still cannot get some height to work with her triangular fulcrum. At this point we have to end the design session because it has been an hour, she is getting frustrated, and height is not a complete addition to her mental model. Joi was able to successfully add the dimensions of pivot and fulcrum position to her mental model but did not expand beyond the addition of those two dimensions.

Table 15. Joi's Incomplete Change in Metal Model

Scene	1	2	3	4	5
Dimension					
Dimension					
Dimension					
Time	37:18	45:13	51:40	54:05	60:00
					

Scene	1	2	3	4	5
	"I could use it like a teeter-totter and shoot it up" Her artifact reflects force mechanical advantage. She is thinking about pivot*:* *"This* (the stick) is *a flat base and this* (the spool) *is kinda like curved"*	She is focused on pivot and builds a triangular fulcrum for the lever	Here she adds fulcrum position as she extends the load arm down to the table and the short effort arm is up	*"It's not as high as it needs to be now. If I put it like this* (two spools) *then it's as high as it needs to be. Maybe height is what I'm missing."*	She cannot resolve how to combine height and pivot. She tries decreasing the height but that does not work. After 1 hour of the design session, she is getting tired, and we decide to end the session.
	F **MA** *P*	**P**	**FP**	*FH*	*FH*

Key:

Force	Mechanical Advantage	Fulcrum Height	Fulcrum Position	Pivot	Rotation	Launch Height	Launch Angle	<u>Force</u> Distance

Bold color = complete addition, shaded color = incomplete addition, arrows indicate the dimension was carried into the next iteration

Summary of Findings

These findings indicate participants' design artifacts reflected the changes in their thinking and that artifacts can serve as externalized mental models. It is the assumption in this study that the addition of each dimension reflects progress toward a complete scientific mental model. In this engineering activity, eight dimensions make up the scientific mental model. We could see in Kai's artifact, showing the move from 2 dimensions in his initial artifact, to 8 dimensions in his concluding artifact that he has developed a scientific model of the cotton ball launcher system. We could see in Joi's artifact, where she resolved the dimension of pivot and she moved to add height, but she could not resolve how to add height along with pivot, that some mental model changes are partial, but that there is still positive change. Therefore, artifacts provide insight into the cognitive changes that happen as children build, test, and improve their designs during the iterative design process. It is evident that the perceptual dimensions of force, mechanical advantage and fulcrum height are foundational to further development of the scientific concepts of force and motion in the cotton ball launcher system.

CHAPTER 5

FINDINGS FOR RESEARCH QUESTIONS 3 & 4

Overview of RQ 3: Capturing Changes to Mental Models with Video-Stimulated Prompted Recall

In the following section I will answer research question 3 which investigates how video-stimulated prompted recall interviews (VSR) captured changes to participants' mental models during the design process. The main purpose of this research question was to gain insight into mental model changes and to verify the researcher's inferences about changes to participants' mental models from design changes made to artifacts during the engineering design process. Recall that VSR interviews consisted of participants watching pre-selected episodes of change from coding the video data of them constructing their design artifacts, and then being asked to recall what their thinking was at the time they made the change. Change was defined as moments in the design process when a child responded to an idea that occurred through observation, conversation, manipulation of the materials (as evidenced by gestures, facial expressions, exclamations) and alteration made by the child to the artifact. Each episode focused on a different moment of artifact construction and communicated change within 1 minute or less, with the average being around 30 seconds. Almost all VSR interviews included 4 VSR episodes.

The data set for the VSR interviews is incomplete (N=19). As a reminder, at the time of the data collection, Zoom was still relatively new to me, the participants, and their families. All the children in the study received schooling at home due to the COVID-19 pandemic face-to-face school shut down. While all the participants were thrilled to engage with the design activity many were also experiencing video call fatigue. Further, not all participants had the optimal conditions for watching the video clips through a Zoom call. In some instances, the technology made it difficult for the child and me to see or hear, and, in other instances, the child did not want to watch the video clips. The data, while incomplete, does provide robust accounts of children's learning during the design activity and detailed examples of how the interviews captured changes to their mental models because it contains many instances of children demonstrating cognizance of the changes in their thinking at the time and being able to articulate it.

The following sections first summarize the overarching results of the analysis of the VSR interviews, identifying three themes of how reflections during VSR captured changes to mental models, followed by an elaboration of the three themes with vignettes of participants.

Three Categories of VSR Captured Change

Data analysis of VSR interview data yielded three categories of changes to children's mental models elucidated through VSR interviews:

1. Change corroborated
2. Change not corroborated
3. Change partially corroborated

Table 16 below provides a view of how VSR episodes were distributed across the 3 categories. Each participant experienced an average of 4 episodes in their VSR interviews, and each episode was categorized individually. Each episode lasted an average of two minutes and the entire VSR interview lasted an average of 10 minutes.

Table 16. Number of VSR Episodes each Participant Spent in Each Category

Participant	Category 1 Change Corroborated	Category 2 Change Not corroborated	Category 3 Change Partially corroborated
Sai	4/4		
Ser	4/4		
Tei	4/4		
Avi	4/4		
Mal	4/4		
Noe	2/4		2/4
Wyn	4/4		
Ras	4/4		
Ara	4/4		
Van	4/4		
Joi	2/4		2/4
Via		1/4	3/4
Che	1/4	1/4	2/4
Ral	2/4		2/4
Sam	1/3		2/3
Dio			4/4
Rae	2/2		
Tru	4/4		
Ash	3/3		

Category 1, “change corroborated”, is defined as: Articulates intentional choice to address a specific dimension in the artifact. This was the most prevalent category of how VSR reflections captured changes to participants' mental models. Of all the VSR episodes (N=72), 53 (74%) were in this category. Over half of the participants (N=10) had all four of their VSR episodes categorized exclusively as category 1. This means that more than half of the young participants in this study were intentionally making design changes to their artifacts and able to confirm their mental model changes with explanatory power. Only two (3%) of the VSR episodes (N=72) were categorized as category 2, “change not corroborated,” defined as: does not articulate an intentional choice to address a specific dimension, yet the artifact indicates that the design change solved a specific dimension. This indicates that it was rare for a participant to make a change without a clear purpose or to be unable to communicate their thinking. Seventeen (23%) of the VSR episodes (N=72) were categorized as category 3 “partially corroborated,” defined as: articulates intentionality but no specific dimension is identified, is unclear, or there is a dissonance regarding solving the dimension. Three (12%) of the participants (N=19) with episodes in this category described a new idea for how to solve a dimension within the VSR interview, indicating that the VSR reflection evoked additional change in participants mental models.

In the following section with examples of each category, almost all images are screenshots taken from the screen- in -screen Zoom view of the recording of the VSR interviews and show moments of what the participants themselves were watching. The only images that are “live” moments during the interview when one participant picked up the materials for demonstration to further explain herself seen in category 3 described below.

Category 1: Change Corroborated

The first category of mental model change, “change corroborated,” indicates that the child has made an intentional choice to address a specific dimension(s) and communicates a clear rationale for why they made that change. To illustrate this category, I describe participant Tru's VSR interview episode one, captured below in Table 17 where she is shown changing the position of the lever on the fulcrum which addresses the dimension of fulcrum position. Tru was chosen as a representative example of how children communicated their intention and rational in child-like language and how her facial expression was used in selecting the change for the VSR episode. The images are from the design session video data that were shown to Tru during the interview. Image 1 shows Tru's initial design drawing. During the VSR episode I showed her this drawing and I remarked that the end of the lever with the cup (in child parlance this is called the *cup side*) is up in the air and this lever arm (LL for load arm) is shorter than the other lever arm (LE for effort arm of the lever). This part of the VSR episode lasted about 25 seconds. Then I showed her about 30 seconds of video of her deciding where to put the fulcrum and lever. This video segment is broken into images 1a-1d in the table. In images 1a she is looking down at the artifact, makes a decision about where she tapes the green stick (lever) onto the spool (fulcrum) and then steps back to look at it. At this point in the interview, I describe how the artifact is different from her drawing. In image 1b, she steps toward the artifact, and touches the LE as if testing something. At this point I describe to her what I see (her making small adjustments to the lever) and ask her what she was thinking as she was touching the lever. She replied, "How it's gonna launch." This response indicated that she was considering how the lever position on the fulcrum would affect the launching of the cotton ball. Then in image 1c, as she looks down, she makes a facial expression that silently conveys "Ooh" as if she has just thought of something, followed by more adjustment to the lever position on the fulcrum. I told her it looked like she had an idea here and asked her about adjusting the stick (lever). She replied that she was moving the position of the lever on the fulcrum so the cotton ball would launch farther. Lastly, in image 1d she has adjusted the stick (lever) length until she is satisfied with it and ready to test it. I asked her how she made her decision to stop adjusting the lever position on the fulcrum. Her reply that she stopped, "when the cup side was starting to get too short," indicates that she visualized the length of the lever load arm and knew how long she wanted it.

Table 17. Tru's VSR Interview Within-Episode Sequence for Episode 1

Image #	1	1a	1b	1c	1d
VSR Time	3:15	4:04	5:05	6:35	7:47
Image					
Researcher's framing of the scene, questions, and Tru's responses	R: *"So the cup side was up and this side (load arm) looks kinda short to me and where you put your hand (effort arm) looks longer"* T: no response	R: *"But then look, now this is the short side (effort arm) and this is the long side (load arm) from your drawing, and the cup is down instead of up."* T: no response	R: *"Here you were touching it and making some little adjustments. What were you thinking about there?"* T: *"How it was gonna launch."*	R: *"It looks like you had an idea here. Did you see how you adjusted the length of the stick?"* T: *"I was adjusting the stick so I can make it go a little bit farther?"*	R: *"What helped you make your decision about when to stop adjusting it (the stick)?"* T: *"I stopped adjusting it when the side (with the cup) was starting to get too short."*
Explanatory Evidence			Clear rationale	Intentional choice and specific dimension	Explanation provided

From watching Tru make the change to a longer load arm during the design session, I inferred that this artifact change indicated that she has developed a better understanding of fulcrum position and added the perceptual dimension of fulcrum position to her mental model. In the VSR interview, Tru was able to explain what she was thinking about. She corroborated the inference that she intentionally adjusted the stick (position on the fulcrum) in order to make it go a little bit farther and that she intentionally stopped at a certain point. She did not elaborate on her decision and was parsimonious with her spoken words, but she articulated that she made the changes intentionally to address a specific dimension with a clear rationale.

Category 2: Change not Corroborated

The second category, "change not corroborated". indicates that in response to questioning about a design change, participants expressed that they did not make an intentional choice or address a specific dimension(s) and did not communicate a clear rationale. Of the 72 interview episodes, only two were placed in this category, with one episode each from two participants: Via's, episode one and Che's episode three.

Table 18 provides images and excerpts from episode 1 with Via. In image 1, she is just starting to build and is shown putting the green stick balanced over the upright spool fulcrum, indicating that she likely understands the dimension of mechanical advantage. In image 1a, Via is shown taping the green stick down to the pink spool so that it will not move, now indicating that she might not have an understanding of mechanical advantage. In image 1b, Via is shown taping the cup to one end of the secured lever and placing the cotton ball on the other end of the lever. With a secured lever that will not move up or down on one end, and no obvious way to launch the cotton ball, I asked her to tell me about her thinking, and she did not remember, simply said she didn't think it would work, and did not provide explanatory evidence, making this change not corroborated for mechanical advantage.

Table 18. Via's Interview Within-Episode Sequence for Episode 1 (4:23-7:43)

Image #	1	1a	1b
Time stamp	5:01	5:42	6:48
Image			
Researcher framing of the scene, questions and Via's responses	R*: "Do you see what you were doing? You were under the table at that point, and you were putting the green stick on the pink spool. Then suddenly you said "Wait, I think I have an idea!" "Do you remember saying that?"* V*: "Yes"*	R*: "So you moved up to the table, and you put the green stick on the spool, and this is kind of where you started building. What were you thinking about there Via? What was your plan?"* V: *"I don't remember."*	R: In the video Via taped the cup to the left end of the green stick and placed the loose cotton ball on the right end of the green stick. *"Tell me about what you were doing there -why you put the cotton ball on the end opposite the end with the cup"* V*: "I didn't think it would work"*
Explanatory evidence	Via remembered saying that but does not indicate intention.	No rationale provided.	The lever across the fulcrum indicated mechanical advantage was solved in the artifact but Via did not explain how the cotton ball would launch with the lever taped down and the cup and cotton ball on opposite ends. Without a clear rationale this episode was deemed not corroborated.

Via remembered saying “wait, I have an idea” but she did not recall what she was thinking about. This finding indicates that Via could recall the episode, but not her thinking at the time of the event. The episode revealed that Via had solved the dimension of mechanical advantage, but she could not corroborate it. This was the first episode, and it is possible that Via needed more time to “warm up in the interview”. It was not possible to determine if she truly did not remember or was shy, or unexperienced with the type of reflecting asked of her in the interview. Her next three episodes were all categorized as “partially corroborated” indicating that at no point in the VSR interview did Via fully corroborate the mental model changes perceived through her artifact design changes.

Category 3: Change Partially Corroborated

The third category of mental model change, “partially corroborated”, describes another way that reflections during VSR interviews captured mental model changes. Table 19 shows the interview video segment, broken into images 2a-2d, from his fourth VSR episode that lasted about two minutes total where Dio watched himself working to address force for launching the cotton ball. This table includes images from the design session as well as images of Dio during the interview. Dio is clearly wearing the same shirt in both the design session and the VSR interview, but the two events did indeed happen on two separate consecutive days and can be distinguished by the piano behind him during the VSR interview.

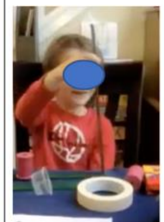
In image 1, Dio is describing in speech and demonstrating how he will press on a spring and to make the artifact launch and making the sound “Zhoop”. I asked him if he remembered having that idea yesterday and he replied that he did. I continued to ask him about this and if he built something where he pulled and released it. He replied that he did. Then I asked him what he pulled on and he said he did not pull on anything.

In image 1a, Dio is demonstrating how he will use a spool and flick up the lever. So, he has gone from a pull to a push. I asked him if he built something that he had to flick up and he said yes. When I asked him why he changed his mind he did not know.

In image 1b, Dio has built a design that looks like alligator jaws. This design is consistent with the idea of pushing down on the upper “jaw” lever to create the force. When I asked about the alligator jaw design he told me what inspired the idea, but he did not explain how that design would launch the cotton ball.

Image 1d captured Dio lifting the lever and pushing it upright to release the cotton ball and declaring the ball launched. When I asked him about the change from his previous ideas, he communicated accurately that the flick was not enough force to move the stick. He also stated that a push down without a spring would not create any power.

Table 19. Dio's VSR Interview Within-Episode Sequence for Episode 4 (7:00- 15:19)

Image #	1	1a	1b	1d
VSR Time	7:09	9:22	11:16	14:12
Image and text of Ben during the design session	 *"Maybe a little spring so I could just go like 'Zhoop' and then I could let go and just like shoot it"* (pulling down)	 *"Instead of a spring I could just and I could just go like 'Zhoop'"* (flicking it upwards)		 "It launched!"
Dialogue from researcher and Ben during interview with responses including speech, gesture, and onomatopoeia	R: Do you remember that idea you had yesterday? B: Yup R: Did you end up building something like that where you pulled and released it?" B: Yup R: So, what did you pull on? B: Well, I don't think I really pulled on anything really.	R: Did you end up building something where you go 'Zhoop'?" (Hit up) B: Yup. R: How come you went from something you were going to hit down to something you were going to hit up? B: I don't know.	R: So, Ben, what was the idea behind the big alligator? B: It reminded me of the greater and less than sign, and you can act like the alligator is going for the bigger number.	R: When you did that you were actually moving the whole green stick with your own hand. Did you see that? B: Yup R: So that was a change from your original idea when you were going to flick it or pull. You were going to pull at first and then you were going to flick it. And then you went to lifting it up and carrying it up and over. What made you change? B: I don't really know. R: How come you ended up lifting it up? B: Because like if I just went like *"doop"*  there wouldn't be that much power. And also if I pushed it down  there wasn't a spring so …"  no power at all.
Explanatory Evidence	Ben does not provide consistency across the question and responses about force	Ben demonstrates dissonance in responses between what he actually did and what he said he did	Ben demonstrated a design consistent with the use of a downward force, but that idea was not reflected in his explanation	Ben demonstrated that he understands force from pushing down, insufficient force upward from a "flick" but he cannot connect these ideas with how he provided force in his artifact

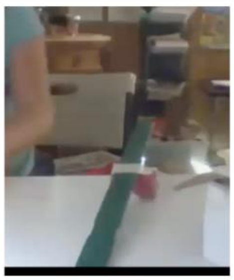
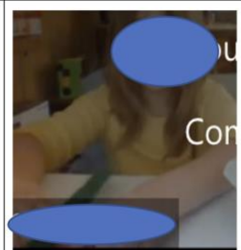
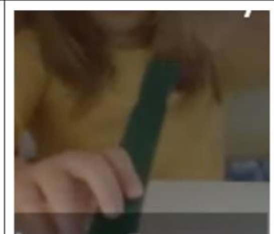
I made an inference that Dio did not develop an understanding of force because he could not resolve force in his artifact and therefore did not add the perceptual dimension of force to his mental model. The VSR interview allowed me to explore Dio's understanding and look for increased explanatory evidence. He was able to use words, gestures, and sounds to communicate his thinking about force but he could not explain how using his hand to lift the lever was his intentional choice. He knew that if he pulled (downward force) he could create force to launch and he knew that a "flick" was not enough upward force, but he could not resolve how to make force work in his artifact, which indicates a dissonance between his thinking and the design. The VSR interview episode confirms that Dio did not add the perceptual dimension of force to his mental model. Dio's "alligator jaws" design approximated a successful design if he just pushed down on the top "jaw" rather than pulling it up. Between his artifact, his spoken words, his gestures, and his use of onomatopoeia, Dio demonstrated that he had some understanding of force but could not resolve it in his artifact and therefore his interview episode demonstrated partially corroborated mental model change.

Subcategory 3a: Change Partially Corroborated and Within VSR Interview a New Idea is Evoked

One of the most interesting results of VSR, highlighted in subcategory 3a, was the unexpected outcome that the VSR prompted reflection afforded participants an opportunity to realize what they wanted to do differently, or do next, to work on their artifacts. Only three participants demonstrated this subcategory, but all the participants were eager to get back to building and testing their artifacts and pick up where they left off the day before, creating an unplanned second design session. It was not the intent of the study to provide a second building session, but I was happy to accommodate participants' interest and motivation. However, video data of the unplanned second design session was not analyzed. At the conclusion of the VSR interview, I asked participant Joi ,"Did it help to watch?" She sums up her experience with VSR best with her reply, "Yes, it did!"

Table 20 provides images and excerpts from VSR interview episode 2 with Joi. Image 1 is an image from the video clip of the design session where she was responding to the question of what worked well. In the video clip she responds that the ball flew but then fell straight down. In the interview episode, I recapped this scene for her, and she exclaimed that now she knew the answer (to the problem). She proceeded to describe how she would move the fulcrum back. In image 1a, Joi is shown live during the interview, manipulating the design artifact to explain how the artifact would function if she moved the fulcrum back (meaning away from the visible table edge). She accompanied the artifact manipulation with a verbal explanation in which she explained that the ball would go to "a lower place" when the fulcrum was in the middle. During the episode, which was focused on Joi's re-positioning of the fulcrum, Joi was able to articulate her intentionality in her change and expresses some understanding of the dimension of fulcrum position. Then in image 1b, also an image that shows Joi live during the VSR, she manipulates the artifact and shows how one end of the lever is "aiming at the sky" when she pushes the fulcrum back. However, in her explanation she talks about moving it (the fulcrum) back and talks about the lever "aiming at the sky" but she had a very unclear explanation of the effect of the change on the cotton ball. This dissonance between the dimension and its effect on the cotton ball launch demonstrated a partial corroboration of the change to her mental model. For Joi to be able to articulate during the VSR reflection the change that she should have made to solve the dimension indicates that the VSR interview process contributed to additional change in her mental model beyond the original design session.

Table 20. Joi's VSR Interview Within-Episode Sequence for Episode 3 (14:11- 16:01)

Image #	1	1a Live in interview	1b Live in interview
Time stamp	14:11	15:09	15:37
Image			
Researcher framing the scene, asking interview questions and Joi's responses	In the video clip I am asking her to reflect on what worked well in her design and Joi is saying "what worked well is when it …" And she demonstrated the movement of the lever and said, "because it flew but then it went down there" "I don't know why it went down there (floor)." So, then I asked: R:*" Did you see what you did? You were demonstrating it worked well when it went up, but then it went straight down."* *J: "I know the answer now to why it went straight down there." "Because I could see that wasn't really like this, but if I put it back it probably would have worked better"*	R:"*Can you tell me more about that*?" J: "*See, if it's like that it would probably go into a lower place, but if it was like this it would probably go higher"*	R:"*Why would it go higher?"* *J: "If it's aiming toward the sky it would probably fly farther."*
Explanatory Evidence	Joi is unclear on how the fulcrum position affects the function but knows that moving it back would help which reveals inconsistency in her understanding.	This explanation is unclear	Increased explanatory evidence as Joi demonstrates that she wants one end of the lever to face up indicating an increased understanding of the dimension of fulcrum position

In the VSR interview, Joi talked about moving the fulcrum position and changing the rotation of the lever, and she demonstrated while she talked. She spoke about what happens when the effort arm is up versus when it is down to start. Image 1 is from the design session but images 1a and 1b are from the screen- in-screen during the VSR because after she watched herself, she then demonstrated live. This means that as a result of the reflection she had a change in her mental model. That change was toward an increased understanding of fulcrum position and rotation. Joi had an incomplete mental model change and was not able to completely resolve rotation. As an outcome of the reflection during VSR, Joi was able to make some change to her mental model evidenced by an increased understanding of fulcrum position.

Summary

In summary, the results of the VSR show that almost all of the participants (89%) (N=19) were able to corroborate changes to their mental model with evidence in the form of intention, rationale, and elaborated explanations for the purpose and outcome of the design change in every episode of their VSR interview. It was exceedingly rare for participants to not corroborate change to their mental models. There were only 2 VSR episodes (N=72) that were categorized as unable to corroborate, with only 1 episode each in 2 participants. Three participants (16%) revealed a new idea to resolve the dimension during VSR interview. This finding indicates that VSR interview reflection may evoke mental model changes. Overall, 7–8-year-old children in this study were able to fully or partially corroborate changes to their mental model as perceived through changes made to their artifacts using spoken words, gestures, and onomatopoeia. These findings help validate the design artifact as an externalized mental model.

Overview Of RQ 4: In What Ways Do Children Articulate Differences Between Their Mental Models and The Artifact

In the following section I will answer research question 4, which investigated the ways children articulated differences between their mental models and the artifacts they created. This research question attempted to separate the physical and conceptual aspects of the engineering design activity. To answer the question, I used two different contexts: First, I analyzed how students responded when provided with opportunities to communicate challenges or difficulties with manipulating the physical materials during the design session. Secondly, I analyzed the VSR interviews for instances where participants said they were trying to do something but were not able to do it or where they showed signs of frustration or changed the course of their work. Results showed that some participants' initial mental models (as indicated by their drawings) could not be realized because of material constraints, but after realizing these constraints, all participants (N=26) were able to make a design artifact that could do what they wanted it to do. Even Dio was satisfied with his design and its ability to launch (see Table 19). The analysis revealed differences between the children's interaction with the materials.

I will begin by describing the distinction between conceptual and physical limitations as pertains to this research question. I will then detail the ways in which participants did or did not articulate differences between their mental model and what they were able to create in each of the following opportunities: when the participant discussed success of their drawing and artifact design, when I probed if there was any material they wished they could have used, when participants provided stepwise instructions for building their design artifact, when I probed if there was any material they wished they could use, anything they would change, and any advice they would give a friend.

Conceptual, Not Physical Limitations

Recall that the purpose of this research question was to separate physical limitations of the task and materials from the conceptual limitations in moving toward a more comprehensive scientific mental model. Therefore, it is important to clarify the distinctions made between the two in this study. A physical limitation refers to an impediment to a child's ability to physically manipulate the materials in order to create the design that is in their mind. A conceptual limitation refers to an impediment to the child understanding why the artifact behaves a certain way. Detailed below are the ways in which participants demonstrated conceptual limitations rather than physical which include differences between what was possible with the materials available in the kits and what material participants wished they had in their kits.

Differences Based on What Was Possible with Available Materials

Four participants (15%) demonstrated a difference between their initial mental models and what it was possible for them to create using the existing material. One participant, Dio, who wished for an unavailable material, is discussed below. Two participants, Ash and Van, expressed an initial mental model, through their words and initial design drawings, that required an airpower, button-type mechanism to push the cotton ball to launch it. Two other participants, Sai and Mal, expressed initial mental models, through words and design drawings, that required a ram-rod style mechanism to push the cotton ball to launch it.

Both Ash and Van attempted to create a button out of the small plastic cup, but both moved away from this model as they developed new ideas about the force required for launching the cotton ball. Both participants were entirely satisfied with their artifacts upon conclusion of the design session.

The following vignette captures dialogue between the researcher and Ash at the end of the design session. Ash tried four different designs over 42 minutes before making an artifact that successfully launched the cotton ball.

> Researcher: *So do you like the idea that you ended up with or do you wish it had been different?*
> Ash: *I'm very happy with it!*
> Researcher: *Even though you had to give up on the idea with the button it's ok?*
> Ash: *Ya!*

Ash did not struggle with the materials as he made his four different designs, but he did struggle to find a successful launching mechanism. He never appeared to lack perseverance, but by the time he came up with his final design he had been designing, testing and revising for a full hour and his success also came with some relief and a great deal of excitement.

Sai and Mal both expressed initial mental models that required a ram-rod style mechanism to push the cotton ball to launch it. Both were able to develop an increased understanding of the force and required to launch the cotton ball and implement force through a new design.

The following vignette captures the dialogue between the researcher and Mal at 40 minutes into the design session. Mal worked on her design iterations for about 30 minutes before she changed her approach to solving for the dimension of force in the artifact. She changed her approach and was able to successfully launch the cotton ball without the ram-rod approach. She expressed that she was satisfied with the design.

> Mal: *I have another idea.*
> Researcher: *You do?*
> Mal: *I press on that there* (one end of the lever). *Wait, maybe if I give it a whack.*
> Researcher: Wow, *how was that*?
> Mal: *It went far and high.*
> Researcher: *Good. Now what?*
> Mal: *It was much farther!* (Lots of giggling and excitement)
> Mal: *Oh my God it completely changed. It's like a see-saw machine now. I knew it was gonna change a little, but I didn't think it was gonna change a lot!*

After Mal revised her initial mental model and solved the dimension of force, she expanded her mental model to include four more dimensions, including mechanical advantage, fulcrum position, launch height and rotation, indicating that she advanced far beyond her original conceptual limitation and was never limited by the physical components.

Perplexing Performance

Two participants, Tru and Dav, made design changes based on their current understanding, but then found the performance of their artifacts perplexing, indicating a conceptual limitation of their mental models, but not a difference between their mental models and the artifacts. After discovering that doubling the length of the lever arms of their artifacts improved the launch performance, both Tru and Dav decided to make the lever arms even longer by taping 3 paint sticks together. At the new triple-lever length, both participants observed a decrease in effectiveness of the artifact. This was, of course, a direct result of the decrease in the force over distance, which was beyond the expected scope of conceptual development for 7-and 8-year-old children.

The following vignette shows dialogue between the researcher and Tru that took place 25 minutes into the 50 minutes design session, after she has tested her design. Recall that after each test of a design, participants were asked to state what worked well and what did not work as well as they hoped. It illustrates the conceptual limitation in Tru's understanding of the performance of her artifact, where she expresses that she has made the artifact the way she wanted to but has trouble articulating why the artifact is not performing as she hoped it would.

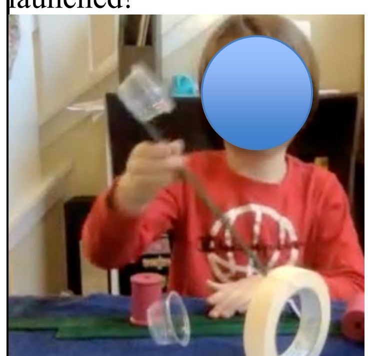
> Researcher: *What worked well?*
> Tru: *The cotton ball went about ten inches farther*.
> Researcher: Why do you think that is?
> Tru: *Because it* (the lever arm) *was farther back.*
> Researcher: "*Now that was pretty good, right. Do you think there is anything else you can do to make it go even farther?*
> Tru:(got another stick out of the box) *We could make the stick longer, so it goes farther*.
> Researcher: Why would a longer stick help?
> Tru: *So that you have more space to put your hand on and the ball is going to go more farther*.
> Tru:(tests the artifact) *The bad news is it wasn't pressed on a lot, so it didn't go very far*.
> Researcher: *Why do you think it wasn't pressed on a lot?*
> Tru: *Because it's more heavy, and it was kind of wobbly, and it didn't want to press on the ball a lot.*

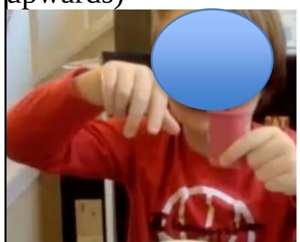
It is evident that Tru attributed the distance of the launch to the lever arm length. She knew that the ball launched farther when she increased the length of the load arm, so she thinks that making it even longer will launch the ball even farther. She added a second green stick to double the length of the load arm. She observed that the double length lever does not launch the ball farther and that it does not perform well. When she said "It did not press on the ball a lot" she indicated that she has some understanding that there is a problem with force over the increased distance, which reveals a conceptual limitation and not a physical limitation in building the artifact as she wanted.

Differences Based on Wishing for an Unavailable Material

Only one participant (4%), Dio, expressed an initial mental model, through his words and initial drawing, that required a material that was not available in the engineering design kit. In Table 21 the images show Dio trying to move away from his initial design idea that required a spring. In image 1, he looks discouraged when looking at the materials he can use. In image 1a, he shows his drawing with "alligator jaws" and where he can put the spool in between the jaws, instead of a spring. He explains he will flick it up. Then in image 1b, Dio declared that the machine launched but he was holding the lever in his hand and the spool evidently had no role in powering the launch.

Table 21. Sequence of Dio Working Through Materials Constraints During Design

Image #	1	1a	1b
Time stamp	5:00	13:13	24:41
Image of Dio during the design session description of scene	 Dio took out all the materials he could use, and he looked a little discouraged	Dio holds up his drawing and shows a design that looks like "alligator jaws" 	"It launched!" 

Researcher framing the scene, asking interview questions, and Dio's responses	I explained all the things that he could use to make his artifact and then the rule. R*: "So what do you think? Do you have an idea in your mind?"* B: *"Maybe something so there's a little more power."* Then, because he looked discouraged, I asked*:* R: *"Are you thinking of something that you wish you had to work with?"* *B: "Maybe a little spring*	R*: "Can you look at what you have right in front of you?* B: *"Instead of a spring I could just use this* (the spool*) and I could just go like 'Zhoop'"* (flicking it upwards) 	R*: "What will power it"* B*: "My hand, I'm just gonna go like* *"Zhoop"*  As he talked, he flicked his hand in an upward motion
Explanatory Evidence	Dio wants to use a spring and had trouble thinking of a new way to power his artifact without the spring.	Dio has decided a spool can take the place of a spring and he can flick upwards rather than pull down. His drawing shows the spool between the jaws. He thinks he will flick up to power it but based on this design he would need to press down on the upper jaw. This shows a partial change in his mental model.	Dio used his whole hand to lift and move the upper "jaw" lever. The spool was not used at all for power. He demonstrated a design consistent with the use of a downward force, but that idea was not reflected in his explanation or his demonstration. He has adapted to the materials constraints but only partially moved away from his initial mental model.

Dio adapted to the materials constraints and continued to build his design and expressed that he believed that he successfully launched the cotton ball. However, used a spool where he had hoped to use a spring and ultimately the spool played no part in powering the launching of the cotton ball. This indicates that there was a change in use of materials, there was not a complete change in Dio's mental model resulting in a conceptual limitation and not a physical limitation with the materials.

Instructions for How to Build Their Artifacts

An element of my interview protocol was to ask the participants to tell me the instructions for how to build an artifact like theirs at the conclusion of the design session. It was my assumption that the process of stating how to build an artifact might open the door to conversation about any changes they would want to make or would suggest to someone just starting to build. Without fail, every child's response was instructions to build the artifact exactly as it appeared without change.

Probe: "If a Friend Wanted to Build a Cotton Ball Launcher What Advice Would You Give Them?"

Another probe I used to elucidate any differences between mental model and physical model was to ask participants, "If a friend of yours wanted to build a machine to launch a cotton ball, what are the big ideas you would tell them?" Again, my assumption was that this question would be a gateway to understanding the physical limitations of what the participants could build and not the conceptual limitations. Overall, all participants had a clear understanding of what contributed to the success of their design and did not share anything about what they were not able to do.

In one clear example to this probe, Ash responded “I would tell them it would have to be high up. And they would have to have something long that is a flat surface to hold something. I would tell them that the stick is the power.” In this example, Ash focuses on the conceptual aspects of design. He is clear about the key physical features of a successful artifact and does not use the opportunity to describe any difficulties or concerns with physical limitations of artifact construction.

Probe: “Is There Anything You Would Change About Your Artifact?”

Another way I attempted to uncover participants' differences between their mental models and their artifacts was to ask the question:” What would you change?” All but the one participant, Dio, were satisfied with and proud of their designs. Early in the design activity, Ash struggled to move past his initial idea of creating a button mechanism to propel the cotton ball. After the button mechanism he went on to a swing-arm mechanism which was also unsuccessful. On his third design, Ash constructed a lever-based contraption that he was very satisfied with. At the end of the design session, I asked him if there was anything he wished he could have done differently. He responded, “No, this is actually perfect!” Seven-year-old Avi expressed a similar perspective when she exclaimed, “I wouldn't change anything!” In fact, she was so satisfied with her design that she said it “would have blasted even farther if I sat on it,” which indicates that the design was not in doubt in her mind, but she would like to add more and more weight to power it.

Summary

In summary, there were no identified physical limitations with the materials or the task that created a division between what the child attempted to do and what the child was able to do in this study. I provided multiple direct and indirect opportunities for participants to express dissatisfaction with what they were able to build versus what they wanted to build. None of those opportunities yielded a participant's experience of physical limitations with the artifact design and construction, indicating that both the activity and the materials were age appropriate.

CHAPTER 6

DISCUSSION AND IMPLICATIONS

Overview of the Chapter

In this Chapter I will first summarize the major findings from Chapters 4 and 5. I will then discuss how those findings relate to those of other studies. Following the discussion, I will set forth implications of this research and suggest further topics of study to build on my findings. The findings were in response to the four research questions:

1. What mental models of the targeted science concepts do participants develop during design artifact construction?
2. To what extent do participant's mental models change from initial to target scientific mental models?
3. How do reflections during VSR capture changes to participants' mental models?
4. In what ways do participants articulate differences between their mental models and the artifact?

Summary of Findings

Mental Model Types

Mental model types were characterized by the number of dimensions included in the concluding mental model. My findings indicate participants needed two specific dimensions, force and mechanical advantage, in order to build on their models, that initial number of dimensions didn't correlate with final number of dimensions, and that starting number of dimensions was highly variable.

.

Extent of Change

My findings indicate that 88% of participants developed a concluding mental model with more dimensions than their initial mental model, but the extent of change varied from an increase of one dimension (19%) to an increase of six dimensions (4%) with most participants increasing by two dimensions (27%).

Reflections Capture Change

VSR provided insight into incremental changes in children's mental models that accrued during artifact design. VSR allowed young children to verify the inferences made by the researcher and did not require the use of traditional written instruments. With the participant as the unit of analysis, findings revealed three categories of how VSR reflections captured change: (1) change corroborated, (2) change not corroborated, and (3) change partially corroborated.

Differences Between Mental Models and Artifact

The most frequent difference between participants' mental models and their artifacts occurred at the initial mental model stage but this was resolved in all but one participant by the end of the design session, once participants became familiar with the constraints of the task. Based on the lack of differences between participants' mental models and artifacts, it can be concluded that both the engineering design activity and the materials were age appropriate for the participants and any differences between artifact and mental model were conceptual not physical.

Discussion

Perceptual Dimensions was a Meaningful Way to Evaluate Mental Models

One of the biggest challenges with understanding conceptual development, specifically of the concepts of force and motion, is having a way to visualize the process of that development. Building off of Vosniadou's (1994) framework for looking at conceptual development through mental models, in combination with Dankenbring & Capobianco's (2016) framework of mental model category features, allowed me to use the mental model for examining young children's conceptual development. Because a mental model cannot be seen, the means of evaluation of the mental model needed to be visualizable in a physical representation—in this case the design artifact. By using eight perceptual dimensions, which had not been previously identified in the literature, as the feasible aspects of a cotton ball launcher system that a young child could attend to both physically and cognitively, I coordinated the mental model with the physical artifact. Thus, I was able to look at conceptual development through the physical model as an externalized mental model.

The full complement of eight perceptual dimensions was considered to be the targeted scientific mental model of force and motion as relating to the cotton ball launcher system. Progress from initial to target mental model was measured by the addition of dimensions, meaning each added dimension was evidence of a more complex mental model and therefore indicative of conceptual development. Using perceptual dimensions allowed me to designate a separation between each part of the system, by identifying the specific aspect the participant was attending and focused on in a moment of making a change to the artifact. Because the launcher itself is a system made of separate parts (the green sticks, the pink spools, plastic cup, and tape) that works as a whole, it is nearly impossible to change one part without effecting change in the whole.

Thus, perceptual dimensions were important for examining a participant’s intentionality of a design change. The artifact of design was found to be a valuable mental model proxy. Since no one representation can fully capture a mental model, other proxies used in the study, including participants’ drawings, gestures, and speech, served to corroborate evidence of conceptual development found in the artifact. Prior research on children’s learning outcomes using engineering design (King & English, 2016; Portsmore, 2113; Wendell, Andrews, Paugh, 2019) revealed gains in science conceptual development. However, this line of research examined static representations of group constructed knowledge, seen in digital design notebooks, posters and drawings created by teams of students. Though my research builds on the use of drawings (static representation), it goes further using design artifacts as dynamic representation of students’ conceptual development. Conceptual development is evidenced in the design changes taking place in response to in-the-moment changes in the mental model. Because individual design artifacts, created in a one-on-one context, have not previously been considered to demonstrate conceptual development, this study provides unique insight into cognitive outcomes as instantiated in design artifacts.

It is not surprising that the design artifact yielded useful insight into participants' mental models because there is a reciprocity between the mental model and the external physical model—the artifact. Mental models are useful to children for making predictions, for testing implicit physical knowledge, and for revising current thinking, particularly in the moment of problem solving (Vosniadou, 2002). Salient information from the external source (the artifact) is processed and represented internally as part of model-based reasoning (Nercessian, 2008). With the artifact as a physical representation of participants' mental models, participants themselves were able to test their own thinking and derive useful feedback which in turn promoted their mental model in the reciprocal system of internal and external representation.

Conceptual Development of Force and Motion

One of the most substantive, yet not unexpected, findings of this study was that almost all the young children in the study developed more complex mental models of the concepts of force and motion through designing and testing a cotton ball launcher. This finding is consistent with other studies who found engineering design to be an effective method for promoting science concept development in older children (Capobianco & Nyquist, 2016; Roth, 2001; Schnittka & Bell, 2011; Wendell, Andrews, Paugh, 2019). However, my study adds to the existing body of literature that engineering design promotes the development of science concepts with early elementary children, an age group that hasn’t been considered in previous research. Furthermore, my finding demonstrate that engineering design activities can be integrated into early elementary classroom science teaching practices, rather than as add-ons to science curricula or implemented only after science instruction has occurred (Roth, 2001), which may be of special importance for foundational concepts such as force and motion.

Another important contribution of my study to the understanding of conceptual development is the finding that the dimension of force is critical to mental model development. For the participants of this study, it was evident that no dimensions were added to their mental model without an intuitive understanding of force. Dio was the only participant without the dimension of force, and he was not able to develop his mental model beyond his initial dimensions. Furthermore, force was not a dimension added to any participant's final mental model. In the cotton ball launcher challenge, mechanical advantage was related to force in the application of a simple machine and related to the motion as a product of opposite force. Participants with the dimensions of force, mechanical advantage, and fulcrum height in their initial mental models were able to add the most dimensions to their mental model. This indicates that these are likely to be foundational concepts which promote increased understanding of the overarching concepts of force and motion. Participants who did not have the dimension of force in their initial mental model were “stuck” trying to grapple with operationalizing force in their artifact design before they could add on. Force is a complex concept and may be best understood through activities, like the one used in this study, that explicitly focus on force prior to activities that combine force with other concepts.

The concept of force is also an important component of science education. It appears in the NGSS in al grade bands, from K-2 to high school (NGSS, 2013), and remains a difficult concept for adults, even after advanced science instruction (Tao & Gunstone, 1997; McCloskey,1983; Clement,1982). Because force and motion are difficult and complex concepts, some participants needed a longer time than other participants to gain an understanding of force and of mechanical advantage. The design-based activity of creating a machine to launch a cotton ball afforded participants to grapple with these dimensions at their own pace and understand the limitations of their initial conceptions of force and motion, and ultimately advance their understanding.

Artifact Design Supports Conceptual Development

The creation of a design artifact did more than externalize children’s mental models, it supported mental model development toward a more scientific mental model of the concepts of force and motion, consistent with model-based reasoning (Nercessian, 2008) and the idea that children's design artifacts are "objects to think with" (Roth, 1996, p.33). Constructing the cotton ball launcher was an iterative physical process that served as a generative process for conceptual development seen as mental model changes. It required children to apply their existing science knowledge to the work of solving a pragmatic problem. Design-based problem solving is an external condition that provides the physical sensorimotor experience that supports concept development (Hadzigeorgiou, 2009) and the internal processes of mental modeling, revision, and reflection, which are mechanisms for conceptual change (Vosniadou, 1994).

The majority of participants were able to expand their mental models through the design activity because as soon as they began the physical work of constructing a cotton ball launcher, they immediately engaged in a motor activity that provided sensory input, that is known to precede and promote representational thought (Piaget & Inhelder, 1967). The cotton-ball launcher itself began to provide immediate feedback on their initial ideas, becoming its own problem space with internal and external resources (Nercessian, 2008).

Reciprocity between the two types of models—the mental model and the physical model—was evident in the sequence in which participants added dimensions to their mental models. This was especially evident in Kai's sequence; Kai added six dimensions, one-at-a-time to arrive at the full complement of eight dimensions. The physical model supplied the physical stimuli through the salient features that help constrain the phenomenon (Prain & Tytler, 2012).

The cotton ball launcher provided a context in which the science concepts work together in a system, making the relations between concepts more salient, and thereby supported mental modeling, a known mechanism of conceptual development. Mental modeling is a process of using existing conceptual resources to examine a problem while undergoing a restructuring of concepts and the relations between them (Carey, 2006). In this way the learning reflected in and promoted by the design activity was like a conversation with the artifact (Ackermann, 2007) and the conversation took place at different speeds for different children. Once built, the artifact becomes the lens for interpreting and organizing new understanding (Ackermann, 1996). While constructing their artifacts, children "conversed" with their artifacts, then encountered the limits or inadequacies of their current understanding, which is critical to revision of one's conceptual framework (Amsel et al., 1996). Consequently, the new revised artifact revealed a new framework with greater explanatory power. A deeper understanding of children's differences in ability to hold some features of an object and conserve them in spite of modification to other features requires additional research.

Moving participants beyond the age/grade expectations

The dimension of force over distance added to the mental models of three participants was unanticipated and demonstrates that engineering design activities may promote conceptual development beyond the typical progression. The integration of force and distance is considered intermediate level and difficult for 8-year-olds (Leuchter & Naber, 2017). The cotton-ball launcher activity used in this study provided context and feedback for learning the application of force over distance. Structured manipulation is considered a scaffold that helps children learn to focus on distance and force (Leuchter & Naber, 2017). Starting at 8-years-of-age, children begin to show an understanding of force amplification but are not able to explain why (Leuchter & Naber, 2017). Tru, Dav, and Ali were all able to express some understanding of the problem with increasing the distance of their lever load-arms in their artifacts, but not able to explain it in spoken words.

It is possible, and perhaps even likely, that other factors that I did not account for played into participants' abilities to consider multiple dimensions. For example, Sam and Ral both struggled with the dimension of rotation and tried to use more and more force. Although both struggled, I conjecture that there are different underlying reasons for this struggle and the resulting outcome. Recall that Sam was very focused on the concern of the launcher breaking apart rather than on the launcher's ability to launch the cotton ball. Possible reasons could be a fear of failure or not having outside experiences that could contribute to new ideas. In contrast, Ral appeared be more perseverant than Sam. Even though she initially struggled she persisted in trying new ways to solve the problem (rotation) and eventually noticed that the position of the fulcrum was an important aspect to the function of the launcher.

Some participants spent a substantial portion of the engineering session 2 working through the concept of force. Having time to persist may have been a gateway to further conceptual development, and without that time they may have stopped short of the same amount of learning. Therefore, the time to concentrate and not be rushed may have been an important factor. Multiple participants wanted to have more time, but I had to stop because of scheduling constraints. Would they have experienced further conceptual development if time wasn't somewhat constrained? Classroom-based learning commonly has strict schedules that may underestimate the attention span and engagement of young children. The results of my study calls for giving young children the time they need to become deeply engaged in activities and be allowed to keep working when they are deeply engaged.

Participants acknowledged that they learn from their peers and by watching their peers. Because the study took place during a time of learning from home for all participants, they may have been lonely and overestimated the added value of working with peers. Household members were otherwise engaged while children participated. I had only a small view through Zoom, and I could not see everyone in the space the children were in. However, participants were very transparent and unable to not look at or address others who were present in the space. I also could hear background noise and see the foot traffic pass by. I often engaged with siblings, parents, grandparents, and even pets who were in earshot. This may have been because it was still novel at the time of the study to interact through Zoom or because the kit full of materials was compelling or even just the general loneliness of people in a pandemic while we were all experiencing some degree of physical isolation from people outside of our immediate families. Thus, it is possible that factors I did not anticipate, and therefore did not measure, were critical to participants' successes and challenges.

VSR method and reflection

This study has demonstrated that one potential way to promote reflection is using video-stimulated recall interviews (VSR). VSR interviews provided additional opportunities for children to reflect on their designs. Recall that during the VSR interviews, children were shown an average of four video episodes of changes, approximately one-minute in length each, and asked to recall their thinking in those moments. The episodes were watched in chronological order; thus, participants were actually able to watch their own design process, even in the very brief episodes. Watching their process sparked new ideas and new ways to solve a design problem, that they had not thought of before, indicating that there was mental model revision on-the-spot. Mental models were not further evaluated after the VSR interviews, yet the “aha moments” during the interview were clear indicators that reflection has a role in further conceptual development.

Through VSR, participants were able to see things from a “birds-eye view”, and because I had assembled the video segments in chronological order, I was essentially assembling a view of what they already learned and understood, that offered them an opportunity to see what the next steps should be. Reflective learning in this way may be more consistent with the practices of engineering as it allows the designer to revisit the thinking, not just the prototypes.

VSR interviews were largely successful with the young children in this study because children typically like to watch themselves, a known aid in promoting children’s self-reflection (Foley & Green, 2015) and because of the purposeful design of the VSR interviews. The video segments were very brief (typically between 30 seconds and one-minute in length) and children were typically shown only four video clips. Though, some children were already experiencing video call fatigue from their school-based experiences and were impatient to continue building, the majority of children were active listeners, viewers, and responders during the VSR interviews.

Another pivotal aspect to the successful employment of VSR in this study was the flexibility of the interview questions. Children are quick to figure out that the easiest path in a VSR interview is to say, “I don’t remember.” However, they did usually remember substantial details about their thinking and their process, but they needed to be made to want to answer and to elaborate. As the interviewer, it was critical to proceed gently after the initial "I don't remember" and try the again with a question that was far less direct. Interview prompts such as, "If a friend of yours wanted to build a machine to launch a cotton ball, what are the big ideas you would tell them?" were useful to get the conversation started. Once a child felt engaged in the conversation it was much easier to draw out more detailed responses in the VSR.

Perhaps the most important consideration in employing VSR for assessing student's understanding is episode selection because episodes that did not vividly capture a significant change or significant moment of reasoning were not productive. Some children in the study needed to have the episodes book-ended to show the beginning and the end of the change in question, rather than just the change itself.

VSR was a child-friendly, reflection-based methodology that provided an important departure from the pencil and paper tests. While other research-based instruction approaches, such as Ambitious Science Teaching (Windshitl, Braaten & Thompson, 2018) and 5E Model (Bybee & Landes, 1990), include reflection and modeling, they are often implemented with students in groups. VSR-based reflection affords individualized reflection experiences and allows individuals insight into their own conceptual development progression. Understanding conceptual change in young children as it is happening is a significant step toward understanding how engineering design can be implemented as part of an integrated STEM learning approach.

It is a common perception that children are just tinkering when they are working on design activities, that they are not making intentional changes, and that learning is incidental. My VSR approach to understanding mental model changes in young children revealed that children in this study are indeed deliberate, they make intentional changes, they are cognizant of the changes in their thinking, and that these changes look like micro-changes instead of one big change. Furthermore, because children are usually aware of the changes in their thinking but sometimes cannot articulate them in spoken words and they need to rely on modalities other than speech, it is even more important to have ways of understanding and gaining insight into these cognitive changes. VSR interviewing holds promise for accessing conceptual development in multiple modalities of representation which, in turn, can foster more equitable educational practices of evaluation as an alternative to typical one modality evaluation that leaves some children unable to express their full understanding.

Limitations

Although data revealed science concept development through mental model changes, conclusions are limited by four important factors. First, the study did not take place inside a classroom environment. While it lacks this ecological validity, it did offer insight that could not be gained if this same study was conducted in a classroom setting. I was able to closely observe each participant and hear each individual share their thinking and view learning in the moment it was happening. Lending some ecological validity, while some participants enjoyed the peace and quiet of their own rooms, most were experiencing the activities from inside very chaotic and noisy households without discrete workspace for their projects which is more like a classroom environment. Second, the results of this study cannot tell us the durability of the mental model changes.

While this approach afforded insight into the mental model changes that occurred during the design session, it does not afford insight into how long the mental model changes will endure. Durable cognitive change requires concepts to be moved from working memory to long term storage with multiple pathways for retrieval. An engineering design activity that employs the perceptual and motor systems may have great potential for retrieval. Third, data was not analyzed for a finer-grained analysis of the continuum of dimension development, and a dimension was evaluated as added or not added to the mental model. Lastly, the data cannot speak to the generalizability of the conceptual development and its potential to transfer to other design activities. The principles of kinematics and projectile motion require very flexible conceptual knowledge. The results indicate only the conceptual development as related to this specific design activity.

Curricular and Instructional Implications

School science often involves finding a "right" answer, but engineering design does not have one right answer, and the use of iterative design allows students a chance to try out multiple ideas, thus going beyond their initial ideas and developing a more robust understanding of the problem (i.e., using more dimensions).

Early elementary classrooms often run on a rigid schedule with little time for science. Students do an activity once, the teacher tells the students why they did it, and then they move on. Giving children the time to explore relationships between parts of a system, try multiple ideas, and develop an increased understanding of causal influences within the activity, is important. The takeaway from this would be yes, it takes more time, but the payoff is crucial, especially it is clear which dimensions students need to have a solid understanding of before they can advance.

Since a goal of science education at the elementary level is to build off children's prior knowledge, young science learners may need more time and support, through structured reflection, to develop metacognitive awareness and become aware of, and therefore able to, question their naive theories to pave the way for conceptual development. Classroom-based science learning with engineering design would benefit from structured time for reflection. Two simple questions, like those used in this study: (1) What worked well in your design? and (2) What did not work as well as you hoped it help children evaluate their results and provide the opportunity for metacognitive awareness that promotes science concept development.

Future Directions

Further studies are necessary to understand how durable the observed mental model changes were. It would be interesting to find out if the children in this study still remember what they learned and how they would apply the same concepts to a new context.

The surprising outcome of "revelations" during VSR reflections suggests that VSR could promote further conceptual development. To explore the potential of VSR reflection as well as exploring its functionality in the elementary classroom, I would partner with a second-grade classroom teacher. I would use the same cotton-ball launcher activity but have children use iPads /Chromebooks to video record themselves building the launcher. Then children working in pairs would watch each other's videos and respond to each other's questions, "VSR interview style." The child-child interviews would also be video-recorded. After their interviews children would continue working on their designs and continue video recording their work (post-VSR artifact designs). Such a design allows evaluating the conceptual development as represented in individual artifact designs both before and after the VSR. Clearly before working in pairs, children would first have to learn when and what type of questions to ask during the VSR interviews. A possible way of learning this is through learning by model. I would show them the video of a child's design session (from a different activity and different class), stopping at key moments similar to the VSR episodes of this study, and ask children to respond to questions such as "Why do you think, I stopped the video?" What made me think of stopping the video," and "Why do you think she made that change?"

Conclusion

Previous research left open the question of how design artifacts instantiate science concept development in young children. This research makes three new contributions to the field of elementary science education. First, a design artifact both instantiates a child's existing mental model and promotes changes to the existing mental model. Second, the engineering design process, currently taught as one big circle, is better represented as a series of recursive small circles, where each small circle represents one design. Artifact design is initiated using the existing mental model, then, through design testing, an artifact yields new information that promotes changes to the child's mental model, which is then instantiated in the next design. The series of circles reflects the way children hold information in their minds from design to test to new mental model instantiation in the subsequent design. In the new, linear engineering design model I propose, the small circles are interlocking, representing the way the ideas connect and build. This is different from the dominant engineering design process which suggests that the design stages work individually, in one direction and must be repeated for each engineering design task. Third, VSR is promising for understanding learning outcomes in young children beyond what can be understood with traditional interview methods alone. Furthermore, findings suggest that reflection during VSR interviews can aid in the construction of knowledge. Therefore, VSR holds promise for adding to the understanding of how design-based learning experience contributes to science knowledge construction in all learners across K-12 education.

While no one representation can embody all of a child's understanding, it is clear from the children in this study that constructing design artifacts can reflect and promote conceptual development of the concepts of force and motion. Participants demonstrated changes in their mental models towards a more scientific mental model through accretion of dimensions, and mental model changes were constructed on-the-spot, consistent with Vosniadou's (2002) perspective on mental model change. The designing, testing, and constructing of the artifact was a continuous source of problem solving that proved fertile ground for conceptual development. This contrasts with how the engineering design process is actually taught (Capobianco & Nyquist, 2016). It moves away from the simple engineering process as one big circle, and instead frames it as a series of smaller circles of micro-changes. This becomes a way to capture the process of change and not just the beginning and end models. In turn, the externalization of child learning in the design artifact provides opportunities for more authentic and equitable assessment of all children.

Elementary science education has consistently recommended starting where the child starts and building on prior knowledge, which in young children is typically acquired through everyday experiences (NRC, 2012). In an engineering design activity, a child must start with their initial mental model which represents their prior conceptual understanding. The initial mental model provides the springboard for concept revision while the artifact under development constrains the child's focus which aids concept development. Activities such as the cotton ball launcher may be especially important for helping children develop deeper understanding of the many aspects of force and motion, such as mechanical advantage (Hadzigeorgiou, et a., 2009) that paved the way for increased mental model development. Engineering design should be moved away from its position as an add-on to science curricula and move it to a pedagogical approach to support science learning in early elementary grades.

The VSR interviews provided insight into incremental changes in children's mental models that accrued during artifact design. VSR allowed young children to verify the inferences made by the researcher and did not require the use of traditional written instruments. The three categories of responses to VSR described indicate that there is variability in the effectiveness of video episodes in eliciting recall about the event, as well as variability between an adult's point of view and a child's point of view on the same event. Thus, VSR provided an advantage over other research methods that privilege the researcher's interpretation of events over the child's interpretation. Furthermore, by participating in VSR interviews, children were able to reflect on their thinking, and were inspired to continue working on their cotton ball launchers. This indicates that reflection has a key role in conceptual development, providing an opportunity to make tacit knowledge explicit and available for development (Matthew & Sternberg, 2009). However, it remains unrealized in early elementary science education as current classroom practices do not provide young children sufficient opportunity to reflect on their own work nor the opportunity to return to it after reflection. To accomplish this in a classroom, children would need the opportunity to return to an activity on sequential days, moving engineering activities away from the one-and-done approach completed in one day,

My VSR approach to understanding mental model changes in young children in this study has revealed that children are indeed deliberate, make intentional changes, and are aware of their mental model changes. Furthermore, because children are most frequently aware of their mental model changes but sometimes cannot articulate them in spoken words, they rely on modalities other than speech. Therefore, it is even more important to have ways of understanding and gaining insight into these cognitive changes.

Data collection with young children is a challenging endeavor that requires children to feel comfortable in the research context, comfortable expressing themselves, and be willing to engage with the content. Therefore, it is no surprise that there is insufficient data on young children's science concept development when learning with engineering design activities. This study provides valuable evidence that 7–8-year-old children can experience science concept development through engineering design activities. Further, artifacts of design can represent changes in young children's understanding of underpinning science concepts and provide a much-needed additional modality for classroom evaluation of science learning. Preliminary data reveals that the reflection opportunity granted during the VSR prompted interviews stimulated further conceptual development. This means that young children are able to reflect on their learning, and opportunities for such reflection need to be incorporated into elementary science education. Research on engineering design as a mechanism of conceptual change is complex because design change can happen quickly and appear unintentional, as if children are simply manipulating materials without a plan. This study has demonstrated that using video-stimulated recall interviews (VSR) helps position children as intentional and competent knowers and doers of some of the practices of science and engineering. Education must advance its understanding of the myriad ways science learning is represented by young children and develop more robust strategies, such as VSR, to capture children's own view of their learning.

APPENDICES

APPENDIX A

IRB APPROVAL

UMassAmherst

Human Research Protection Office

Mass Venture Center
100 Venture Way, Suite 116
Hadley, MA 01035
Telephone: 413-545-3428

University Institutional Review Board (IRB)
Certification of IRB Approval

Date: October 28, 2020

To: Professor Martina Nieswandt and Christine McGrail, College of Education

From: Professor Lynnette Leidy Sievert, Chair, University of Massachusetts Amherst IRB

Protocol Title: *Promoting Conceptual Development with Engineering Design in Elementary Science*
Protocol ID: 518
Review Type: Expedited
Submission Type: Amendment
Approval Date: 10/28/2020
Expiration Date: **02/28/2021**
OGCA #:

This study has been reviewed and approved by the University of Massachusetts Amherst IRB, Federal Wide Assurance # 00003909. Approval is granted with the understanding that investigator(s) are responsible for:

Revisions - All changes to the study (e.g. protocol, recruitment materials, consent form, additional key personnel), must be submitted for approval in e-protocol before instituting the changes. New personnel must have completed CITI training.

Renewals - All renewals need to be submitted at least 2 weeks prior to the expiration date listed on this approval letter.

Final Reports - Notify the IRB when your study is complete by submitting a Close Request Form in the electronic protocol system.

Consent forms - A copy of the approved consent form (with the IRB stamp) must be used for each participant (Please note: Online consent forms will not be stamped). Investigators must retain copies of signed consent forms for six (6) years after close of the grant, or three (3) years if unfunded.

Use only IRB-approved study materials (e.g., questionnaires, letters, advertisements, flyers, scripts, etc.) in your research.

Unanticipated problems involving risks to participants or others - All such events must be reported in e-protocol as soon as possible, but no later than five (5) working days.

Please contact the Human Research Protection Office if you have any further questions. Best wishes for a successful project.

APPENDIX B

RECRUITMENT FLYER

Free STEM Enrichment!

Problem-solving Skills!

Fun and Engaging Engineering Design Activities!

Creativity!

A Kit to Keep!

SEEKING ELEMENTARY STUDENT ENGINEERS

Research Study through the UMass Amherst College of Education

Students entering 2^{nd} or 3^{rd} grade are invited to participate in engineering design projects over Zoom. This study is intended to investigate science instruction and assessment.

Time commitment is a total of 2 hours. Participant information and data will be kept confidential.

All materials will be provided, and you can keep the kit after the activities have been completed.

For more information or to have your child participate, please contact the researcher, Chris McGrail, by email or by phone.

CHRIS MCGRAIL
PhD Candidate

cmcgrail@umass.edu

(508)523-5296

APPENDIX C

CONNECTIONS TO THE FRAMEWORK FOR K-12 SCIENCE EDUCATION

Engineering Design Activity*:*

Pop Fly, https://pbskids.org/designsquad/build/

Connections to the Frameworks for Science Education

PS2. Motion and Stability: Forces and interactions

Core Idea PS2: Motion and Stability: Forces and Interactions, and its component ideas of PS2.A: Forces and Motion,

PS2.B: Types of Interactions, and PS2.C: Stability and Instability in Physical Systems. The core and component ideas emphasize explaining and predicting interactions between objects and within systems of objects

K-PS2-1. Compare the effects of different strengths or different directions of pushes and pulls on the motion of an object.

ETS1. Engineering Design

1.K-2-ETS1-1. Ask questions, make observations, and gather information about a situation people want to change that can be solved by developing or improving an object or tool.

1.K-2-ETS1-2. Generate multiple solutions to a design problem and make a drawing (plan) to represent one or more of the solutions.

APPENDIX D

SCRIPT FOR INTRODUCING THE STUDY

Hi, my is Chris. What’s your name? It’s very nice to meet you. I am excited that we get to do some science and engineering activities today and maybe tomorrow and the next day too if you would like to. What grade are you going into this year? What is your favorite thing to learn about? I love science and engineering -how about you? Do you remember any fun projects you have done at home or when you were at school? Well, we will get to do a fun project today and over the next few days if you want. Would you like to work on a project today? Your (adult who provided consent) thought you would like to, so I sent you a kit with some objects inside that you get to build with. We will use all those things over the next few days, so you have to hang onto them and keep them in the box until we are done with them. And then you get to keep them. Does that sound ok to you? Do you have any questions for me?

Let’s look at the kit and open it together. Can you name the colors of the things you see in the kit? Will you tell me the names of the things in the kit? Is there anything in the kit that you’ve never seen before or don’t know the names of? (If yes) Well, we can just talk about it by saying its color then. (If no) Great, then I will call them by their names and their colors when I talk about them.

APPENDIX E

SESSION 1 PROTOCOL

1) Have you ever been on a teeter-totter (also known as a seesaw)?
2) Where did you sit on the teeter-totter?
3) Can you go on a teeter-totter alone?
4) Please draw me a picture a teeter-totter.
5) Please tell me or show me where one person can sit on the teeter-totter. What about another person who goes on it with you- where might that person to sit? Can the people on it sit anywhere?
6) Please build a teeter-totter with the green stick and pink spool.
7) What is your teeter-totter doing now?
8) Do you know what balance means? Will you please make your teeter-totter balance?
9) Let’s get out the orange people. What do you notice about them?
10) What do you think will happen when you put one orange person on? Now try it. Now try two orange people.
11) In one try, can you get the teeter-totter to balance with the two orange people?
12) Let’s get out the blue person. What do you notice about them?
13) What do you think if you put a blue person on with the two orange people already on the teeter-totter? Now try it.
14) In one try, can you get the teeter-totter to balance with the two orange people and the blue person?
15) What’s the best part about being on a teeter-totter? (Anticipated answers: go up, go down, or make the other person go)

16) In one try, can you do that to any of the people?

BIBLIOGRAPHY

Ackermann, E. (2007) Experiences of Artifacts: People's Appropriations / Objects' Affordances': Chapter in book. Keyworks in radical constructivism. Ernst von Lagerfeld (M. Larochelle, Ed). Rotterdam, Taipei. Sense Publishers. pp. 249-259.

Ackermann, E. (1996). Perspective-Taking and object Construction. In Constructionism in Practice: Designing, Thinking, and Learning in a Digital World (Kafai, Y., and Resnick, M., Eds.). Mahwah, New Jersey: Lawrence Erlbaum Associates. Part 1, Chap. 2. pp. 25-37

Ahi, B. (2017). The effect of talking drawings on five-year-old Turkish children's mental models of the water cycle. Journal of Environmental & Science Education, 12(3):349-367.

Ahi, B. (2106) Flying, feathery, and beaked objects: Children's mental models about birds. International Electronic Journal of Environmental Education, 6(1):1-16.

Alghamdi, A.H. & Li, L. (2013). Adapting design-based research as a research methodology in educational settings. International Journal of Education and Research, 1(10): 1-12.

Amsel, E., Goodman, G., Savoie, D., & Clark, M. (1996). The development of reasoning about causal and noncausal influences on levers. *Child development*, *67*(4), 1624-1646.

Baillargeon, R. (2002). The acquisition of physical knowledge in infancy: A summary in eight lessons. *Blackwell handbook of childhood cognitive development*, *1*(46-83)

Baillargeon, R. (2004). Infants' reasoning about hidden objects: evidence for event-general and event-specific expectations. *Developmental science*, *7*(4), 391-414.

Baillargeon, R., & Carey, S. (2012). Core cognition and beyond: The acquisition of physical and numerical knowledge.

Bybee, R. W., and Landes, N. M. (1990). "Science for Life & Living: An Elementary School Science Program from Biological Sciences Curriculum Study." *The American Biology Teacher 52*(2): 92-98.

Capobianco, B., Nyquist, C., & Tyrie, N. (2013). Shedding light on engineering design. Science and Children, 50(5):58-64.

Carey, S. (1992). The origin and evolution of everyday concepts. *Cognitive models of science, 15*, 89-128.

Carey, S. (2000). The origin of concepts. *Journal of Cognition and Development*, *1*(1), 37-41.

Carey, S. (2000). Science education as conceptual change. *Journal of Applied Developmental Psychology*, *21*(1), 13-19.

Carey, S. (2004). Bootstrapping & the origin of concepts. *Daedalus*, *133*(1), 59-68.

Carey, S. (2009). Where our number concepts come from. *The Journal of philosophy*, *106*(4), 220.

Carey, S., Zaitchik, D., & Bascandziev, I. (2015). Theories of development: In dialog with Jean Piaget. *Developmental Review*, *38*, 36-54.

Chiou, G. L., & Anderson, O. R. (2010). A study of undergraduate physics students' understanding of heat conduction based on mental model theory and an ontology–process analysis. *Science Education*, *94*(5), 825-854.

Clayson, J. (2018) Artifacts, visual modeling and constructionism: to look more closely to watch what happens. Problemos, 8(23): 8-22.

Clement, J. (2008). The role of explanatory models in teaching for conceptual change. In S. Vosniadou (Ed.), International handbook of research on conceptual change. Amsterdam, Routledge.

Clement, J. (1982). Students' preconceptions in introductory mechanics. *American Journal of physics*, *50*(1), 66-71.

Cox, R. (1999) Representation construction, externalized cognition and individual differences. Learning and Instruction, 9:343–363.

Dankenbring, C. & Capobianco, B. (2016). Examining elementary school students' mental models of sun-earth relationships as a result of engaging in engineering design. International Journal of Science and Mathematics Education,14(5):825–845

DeWitt, J. & Osborne, J. (2010) Recollections of Exhibits: Stimulated-recall interviews with primary school children about science centre visits, International Journal of Science Education, 32:10, 1365-1388

Driver, R., Asoko, H., Leach, J., Scott, P., & Mortimer, E. (1994). Constructing scientific knowledge in the classroom. *Educational researcher*, *23*(7), 5-12.

Foley, J., & Green, J. (2015). Supporting Children's Reflection with Phones and Tablets. *Teaching Young Children*, *8*(5), 21-23.

Fortus, D., Dershimer, R.C., Krajcik, J., Marx, R. & Mamlok-Naaman, R. (2004) Design-Based Science and Student Learning. Journal of Research in Science Teaching, 41(10), 1081–1110.

Frigg, R. & Nguyen, J. (2017) Models and Representation. In L. Magnani and T. Bertolotti (Eds.): Springer Handbook of Model-Based Science, Berlin and New York.

Gopnik, A., Meltzoff, A. N., & Kuhl, P. K. (1999). *The scientist in the crib: Minds, brains, and how children learn*. William Morrow & Co.

Gravel, B., Tucker-Raymond, E., Wagh, A., A., Klimczak, S., & Wilson, N. (2021) More Than Mechanisms: Shifting Ideologies for Asset-Based Learning in Engineering Education. Journal of Pre-College Engineering Education Research, 11(1):276-297.

Hadzigeorgiou, Y., Anastasiou, L., Konsolas, M., & Prevezanou, B. (2009). A study of the effect of preschool children's participation in sensorimotor activities on their understanding of the mechanical equilibrium of a balance beam. *Research in Science Education*, *39*(1), 39-55.

King, D. & English, L. (2016). Engineering design in the primary school: applying stem concepts to build an optical instrument. International Journal of Science Education, 38(18): 2762-2794.

Kolodner, J. L., Camp, P. J., Crismond, D., Fasse, B., Gray, J., Holbrook, J., ... & Ryan, M. (2003). Problem-based learning meets case-based reasoning in the middle-school science classroom: Putting learning by design (tm) into practice. *The journal of the learning sciences*, *12*(4), 495-547.

Krippendorff, K. (1989). Content analysis.

Leuchter, M., & Naber, B. (2019). Studying children's knowledge base of one-sided levers as force amplifiers. *Journal of Research in Science Teaching*, *56*(1), 91-112.

Lyle, J. (2002) Stimulated Recall: a report on its use in naturalistic research. British Education Research Journal, 29:6. 861-.

Matthew, C. T., & Sternberg, R. J. (2009). Developing experience-based (tacit) knowledge through reflection. *Learning and individual differences*, *19*(4), 530-540.

McGinn, M. K., & Roth, W. M. (1998). Assessing students' understanding about levers: Better test instruments are not enough. *International Journal of Science Education*, *20*(7), 813-832.

McCloskey, M. (1983). Intuitive physics. *Scientific American*, *248*(4), 122-131.

Meier, A. & Vogt, F. (2015). The potential of stimulated recall for investigating self-regulation processes in inquiry learning with primary school students. Perspectives in Science, 5:45-53.

National Academy of Engineering and National Research Council (NRC) (2009). Engineering in K-12 Education: Understanding the Status and Improving the Prospects. Washington, DC: The National Academies Press.

National Research Council (NRC) (2012). A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas. Washington, DC: The National Academies Press.

Nercessian, N. (1999). Model-Based Reasoning in Conceptual Change in L. Magnani, N.J. Nercessian, and P. Thagard (Ed.). *Model-Based Reasoning in Scientific Discovery* (pp. 5-22). New York, New York: Kluwer Academic/Plenum Publishers, New York Reasoning

Nercessian, N. (2008). Model-based reasoning in scientific practice. In R.A. Duschl and R.E. Grandy (Eds.), Teaching Scientific Inquiry: Recommendations for Research and Implementation (pp. 57-79). Rotterdam, the Netherlands: Sense.

NGSS Lead States. 2013. *Next Generation Science Standards: For States*, *By State*s. Washington, DC: The National Academies Press.

Osborne, R., & Freyberg, P. (1985). *Learning in Science. The Implications of Children's Science*. Heinemann Educational Books, Inc., 70 Court Street, Portsmouth, NH.

Paas, F., & van Merriënboer, J. J. (2020). Cognitive-load theory: Methods to manage working memory load in the learning of complex tasks. *Current Directions in Psychological Science*, *29*(4), 394-398.

Patton, M. Q. (2002). *Qualitative research & evaluation methods*. sage.

Pasco, D. & Ennis, C. (2015). Third grade students' mental models of energy expenditure during exercise. Physical Education and Sports Psychology, 20(2):131-143.

Papert, S. & Harel, I. (1991). Situating Constructionism http://web.media.mit.edu/~calla/web_comunidad/ReadingEn/situating_constructionism.pdf

Pop-Fly. https://pbskids.org/designsquad/build/pop-fly/

Penner, D., Lehrer, R. & Schauble, L. (1998). From physical models to biomechanics: A design-based modeling approach. Journal of the Learning Sciences, 7(3-4):429-449.

Piaget, J. & Inhelder, B. (1967) In The child's conception of space. The coordination of perspectives, Cahp. 8. pp.209-246. New York: Norton & Co

Portsmore, M. (2013). Exploring 1st-grade students' drawings and artifact construction in the engineering design process. *Show Me What You Know, Exploring Student Representations Across STEM Disciplines*, 208-222.

Prain, V. & Tytler, R. (2012) Learning through constructing representations in science: A framework for representational construction affordances. International Journal of Science Education, 34(17):2751-2773.

Pradhan, A. K., Pai, G., Radadiya, J., Knodler Jr, M. A., Fitzpatrick, C., & Horrey, W. J. (2020). Proposed framework for identifying and predicting operator errors when using advanced vehicle technologies. *Transportation research record*, *2674*(10), 105-113.

Pulaski, M. A. S. (1971). Understanding Piaget: An introduction to children's cognitive development.

Rogers, C., & Portsmore, M. (2004). Bringing engineering to elementary school. *Journal of STEM Education: innovations and research*, *5*(3).

Roth, W. M. (2001). Learning science through technological design. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*, *38*(7), 768-790.

Roth, W. M. (1996). Art and artifact of children's designing: A situated cognition perspective. *The Journal of the Learning Sciences*, *5*(2), 129-166.

Sadler, P., Coyle, H. & Schwartz, M. (2000). Engineering competitions in the middle school classroom: Key elements in developing effective design challenges. Journal of the Learning Science, 9(3):299-327.

Sandoval, W. (2014) Conjecture mapping: An approach to systematic educational design research, Journal of the Learning Sciences, 23(1):18-36.

Schnittka, C. & Bell, R. (2011) Engineering design and conceptual change in science: Addressing thermal energy and heat transfer in eighth grade. International Journal of Science Education, 33:13, 1861-1887.

Spelke, E. S., & Kinzler, K. D. (2007). Core knowledge. *Developmental science, 10*(1), 89-96.

Tao, P. & Gunstone, R. (1997) The Process of Conceptual Change in Force and Motion.

Vosniadou, S. (1994) Capturing and modeling the process of conceptual change. Learning and Instruction, 4:45-69.

Vosniadou, S. (2002) Mental Models in Conceptual Development. Model-Based Reasoning: Science, Technology, Values, edited by L. Magnami and N.J. Nercessian, Kluwer Academic/Plenum Publishers, New York, 2002, 351-368.

Vosniadou, S. & Brewer, W. (1994) Mental Models of the Day/Night Cycle. Cognitive Science, 18, 123-183.

Vosniadou, S. & Skopeliti, I. (2014) Science and Education 23:1427-1445

Wendell, K., Connolly, K., Wright, C., Jarvin, L., & Rogers, C. (2010). Children learning science through engineering: An investigation of four engineering-design-based curriculum modules. ICLS 2010

Wendell, K. (2013) Children's design constructions as representations of science ideas. *Show Me What You Know, Exploring Student Representations Across STEM Disciplines*, 189-207.

Wiggins, G. (1998). *Educative Assessment. Designing Assessments To Inform and Improve Student Performance*. Jossey-Bass Publishers, 350 Sansome Street, San Francisco, CA 94104.

Windschitl, M., Thompson, J., & Braaten, M. (2020). *Ambitious science teaching*. Harvard Education Press.

Zirbel, E. L. (2004). Framework for conceptual change. *Astronomy Education Review*, *3*(1), 62-76.