ABSTRACT

Title of Dissertation:	UNDERSTANDING LEARNING AND SKETCHING EXPERIENCES OF CHILDREN INVOLVED IN STEM DESIGN
	Ekta Shokeen, Doctor of Philosophy, 2023
Dissertation directed by:	Dr. Caro Williams-Pierce, Assistant Professor, College of Information Studies

Sketching is considered a helpful activity in STEM design and education. Scholars have argued for including children in designing technology as it has been found to improve product design and leads to social and cognitive benefits for children. However, little is known about children's learning and sketching experiences when participating in design activities. How do children sketch during design activities? How do children learn about sketching in design activities? What information do they share via their sketches? What information do they use for sketching? How do they use sketching in the overall design process? How do learning and sketching relate to STEM design? This three-paper dissertation uses empirical and theoretical approaches to address these questions.

The first paper uses an ethnographic case study approach to qualitatively examine information sharing practices and learning opportunities from children's engagement in interest-driven sketching. Findings suggest that sketching can provide multiple learning opportunities to

children. Also, it can be helpful to gather information about the broader contexts of children's lives which can help identify their needs and improve the future design of technologies for children.

The second paper presents a theoretical framework, Radical Constructivist Cooperative Inquiry (RCCI), for understanding children's learning in design activities. Based on the theoretical synthesis of the cooperative inquiry design approach and the radical constructivist perspective of learning, RCCI establishes six pillars of learning in design. Finally, the paper discusses how these six pillars can be utilized in design activities to support children's learning.

The third paper is a secondary analysis of video data of children's learning and sketching experiences in engineering design in their home environments. It focuses on examining the relationship between children's sketching and learning following the RCCI framework with the thematic analysis method. Results suggest that sketching can engage children in learning about STEM skill sets.

These three papers collectively contribute empirically and theoretically to building knowledge about improving and sustaining design cycles by children in STEM learning contexts.

UNDERSTANDING LEARNING AND SKETCHING EXPERIENCES OF CHILDREN INVOLVED IN STEM DESIGN

by

Ekta Shokeen

Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
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Advisory Committee:
Dr. Caro Williams-Pierce, Chair
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Dedication

To my child, Avyanna, who was born during this research.

To my Shokeen and Boeckel family, without their encouragement and support, this dissertation would have never happened.

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Statement of Co-Authorships

Co-Authored publications have contributed to this dissertation:

1) Shokeen, E., Katirci, N., & Williams-Pierce, C., & Bonsignore, E., (2022). *Children Learning to Sketch: Sketching to learn*. *Information and Learning Sciences*, Vol. 123 No. 7/8, pp. 482-499.
2) Shokeen, E., & Williams-Pierce, C. *Radical Constructivist Cooperative Inquiry Framework: Learning within Design.* To be submitted to *International Journal of Child-Computer Interaction* (ijCCI).
3) Shokeen, E., Simpson A., & Williams-Pierce, C. The Relationship between Learning and Sketching in Engineering Design. Venue to be determined.

The dissertation examining committee has determined that Ekta Shokeen has made substantial contributions to the jointly authored work warranting its inclusion in the dissertation.

List of Abbreviations

CCI : Child - Computer Interaction
CI : Cooperative Inquiry
IDC : Interaction Design and Children
RC : Radical Constructivism
RCCI : Radical Constructivism Cooperative Inquiry
SDC : STEM Design Club
STEM : Science, Technology, Engineering, and Mathematics

Chapter 1: Introduction

1.1 Rationale

This dissertation examines children's learning and sketching experiences in Science, Technology, Engineering, and Mathematics (STEM) design activities. Sketching has become an increasing research interest in design and STEM education (Ainsworth & Lewis & Sturdee, 2021; Scheiter, 2021; Sung et al., 2019). The physical act of sketching involves the construction of visual representations that can then be reinterpreted in thinking, learning, and communication (Forbus et al., 2017). In addition, there are a wide variety of benefits associated with the use of sketching in STEM education, including encouraging learners to make explicit spatial relationships between elements, attending to the spatial structure of a problem, and promoting the comprehension of multiple representations through which they develop a better understanding of scientific concepts (Bobek & Tversky, 2016; Gagnier et al., 2016; Stammes et al., 2023).

In design practice, sketching serves multiple social and cognitive functions such as ideation, a short-term memory aid, communicating and documenting structural relations during the product design process, and as a tool to externalize viewpoints in collaborative design work (Cunningham et al., 2018; Quan & Gu, 2018). Sketching is critical to design practices – exploring, explaining, persuading, and analyzing ideas (Lewis & Sturdee, 2021). These properties make sketching a vital topic to be explored in research as it involves aspects of cognition, including visual, spatial, and conceptual knowledge, and how they interact through thinking, reasoning, and learning (Lewis & Sturdee, 2020; Sung et al., 2019). There is a call for broadening the research on sketching in design and STEM education.

1.2 Problem Statement

Sketching is recognized as an essential tool for STEM education and design; however, its affordances are underexplored in the field of design with children. Prior research on children's sketching experiences focuses on scaffolding children's experiences with storyboards and adults who sketch as children verbally describe their design ideas (Hiniker et al., 2017; Mitchell & Nørgaard, 2011;). In particular, the fields of design and STEM education lack a clear understanding of children's sketching experiences. As I investigated how children develop sketching skills for design, I found another gap in the literature on design with children - a lack of a solid theoretical grounding for understanding children's learning when they engage in designing technology (Antle & Hourcade, 2021; DiSalvo et al., 2017; Eriksson et al., 2022).

A recent literature review of children's interaction in technology design highlights that most of the papers from the field of CCI reference learning but "do not provide explicit theoretical grounding for aspects of learning in either the research design or result" (Eriksson et al., 2022, p. 60). Scholars who have rigorously used theories of learning in their analyses of children engaging in design have not synthesized their chosen theory of learning with the theoretical grounding of their chosen design process (Bekker et al., 2015; Giannakos et al., 2022). Therefore, there is a strong need to develop learning theories in the design field (DiSalvo et al., 2017; Eriksson et al., 2022; Giannakos, M., 2022).

The goal of this dissertation is to fulfill the three gaps related to children's experiences in the design process:

1) lack of understanding of children sketching experiences in design;

2) lack of a theoretical grounding for understanding learning in design; and

3) lack of understanding of the relationship between children's sketching and learning experiences in the design process.

I approached these gaps in the literature with the overarching Research Question:

1.2.1 Research Question

How do children learn and sketch in design activities?

This central question consists of multiple minor research questions: How do children sketch during design activities? What information do they share via their sketches? What information do they use for sketching? How do they use sketching in the overall design process? What do children learn through sketching in design activities?

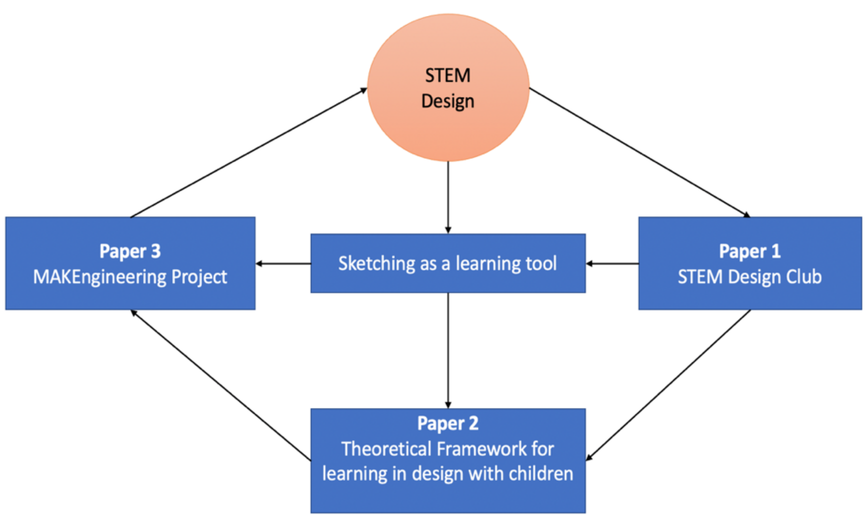

Figure 1. 1: Connections between the three papers

This dissertation addresses these research questions with the findings from these three interrelated papers (See Figure 1.1). Next, I provide the background and framing of each of the three papers.

1.3 Background and Framing of Papers

The three papers take distinct methodological approaches to the fundamental question of - how do children learn to sketch in design activities. The first paper takes an exploratory approach using a qualitative method to understand the sketching and learning experiences. The second paper is a theoretical approach to understanding the moments of learning in design activities. The third paper leverages the findings of Paper 1 and Paper 2 to explore the moments of learning further and sketching in design activities within a different context. Thus, Paper 3 expands on the use of sketching in design activities and examines the moments of learning in sketching activities using the theoretical framework RCCI from Paper 2. These three papers provide insights into children's learning and sketching in design activities. Table 1.1 provides the overview of these three research papers, followed by the details such as objectives, background, and framing of the three papers:

Table 1. 1: Overview of the framing for three papers

Paper Title	**Objective**	**Context**	**Method**
Paper 1 *Children Learning to Sketch - Sketching to Learn*	To identify what information sharing and learning opportunities occur when children engage in sketching	Children sketching experiences in the synchronous virtual STEM Design Club	Ethnographic Case Study
Paper 2 *Radical Constructivist Cooperative*	To consolidate theoretical grounding for examining and supporting	Synthesis of theory of Radical Constructivism with the framework of	Theoretical Synthesis

Inquiry Framework: Learning within Design	children's learning in design activities.	Cooperative Inquiry – Participatory Design	
Paper 3 *Exploring the Relationship between Sketching and Learning in the STEM Design*	To establish the relationship between learning and sketching experiences	Children's sketching for designing pre-determined products with their caretaker in their home environment.	Thematic Analysis Secondary Research

1.3.1 Paper 1: Research Objective

To identify what information sharing and learning opportunities occur with children sketching experiences while they engage in sketching for designing products of their interest.

The first paper is a qualitative study of the children's experiences in the STEM Design Club (SDC), which I planned and conducted in collaboration with a public library. Due to COVID-19 restrictions, the data collection was virtual, weekly virtual synchronous STEM design sessions with five children over four months. During the sessions, children were engaged in individual and collaborative sketching to find technology-based solutions to problems based on their interests. I used an ethnographic case study approach to examine information sharing practices and learning opportunities from children's engagement in interest-driven sketching.

While some educators might have overlooked children's sketches, I was intrigued by the learning I could see when children sketched during design activities. However, due to the lack of an established learning framework in the design literature, I was struggling to examine moments of learning in children's interactions during STEM Club design activities which motivated me to pursue the next chapter of my dissertation and provide a theoretical framework that synthesizes across the field of design and education.

1.3.2 Paper 2: Research Objective

To consolidate a theoretical grounding for examining and supporting children's learning in design activities.

The second paper provides a novel framework - Radical Constructivist Cooperative Inquiry Framework - for establishing a theoretical grounding to understand children's learning during design activities. The development of a theoretical framework like this is timely because the recent literature reviews in the field of technology design with children highlight the lack of a coherent theoretical grounding for learning. This paper also uses examples from the empirical study of STEM Design Club (Paper 1) to illustrate how the framework can help design, support, and examine children's learning moments in design practices.

1.3.3 Paper 3: Research Objective

To establish an understanding of the relationship between children's learning and sketching experiences while they engage in sketching for designing pre-determined products in their home environment.

The third paper is a qualitative study based on a secondary analysis of the data collected from the participants of the MAKEngineering project. This secondary analysis was appropriate for two reasons: 1) to examine the adaptability of the theoretical framework developed in the previous paper into a different context, and 2) to expand the previous sketching research into a context that included building the physical prototype in order to gain insights on children's use of sketching during prototype building. The researcher who collected this data was part of each analysis step. However, the role of that researcher was limited to meeting the guidelines of secondary analysis, as I did the coding and writing.

1.4 Operationalization of Constructs

1.4.1 Sketching

Sketching involves the construction of visual representations that can then be reinterpreted in thinking, learning, and communication (Forbus & Ainsworth, 2017). Sketching has multiple properties, such as generating and communicating new insights and grounding communication while working in a group setting (Wu & Rau, 2018). These properties make sketching an important topic to be explored by researchers as it involves aspects of cognition, including visual, spatial, and conceptual knowledge, and how they interact through thinking, reasoning, and learning (Ainsworth & Scheiter, 2021; Forbus et al., 2017). Some researchers define sketching as an engineering language representing abstract ideas and human cognition (Dym et al., 2005). Due to the diverse use of sketching in the learning and design process, there is a lack of standardized operationalization of sketching. Sketching is often referred to as drawing in the context of children's STEM education. For this dissertation, I conceptualize sketching as *a process that involves the construction of visual representations, the planning and visualization of ideas that happen before and during the construction of a visual representation, and the other forms of representations (verbal, textual) used to consider various ideas before actually making a sketch.*

1.4.2 Learning

The learning construct in this dissertation comes from the theory of Radical Constructivism (RC) proposed by Glasersfeld, built upon Piagetian constructivism (Glasersfeld, 2013). RC promotes the idea that knowledge is the interpretation of individuals' experiences in their environment (Glasersfeld, 2013). Glasersfeld called his model 'radical' in order to distinguish it from more conventional interpretations of constructivism, and described the two fundamental principles (Glasersfeld, 1995; p. 18):

- *knowledge is not passively received but built up by the cognizing subject; and*
- *the function of cognition is adaptive and serves the organization of the experiential world, not the discovery of ontological reality.*

According to RC, learning happens during the process of inventing things to improve our functioning in the environment as a coherent and productive way of thinking that helps to deal with the fundamentally inexplicable world of our experience (Glasersfeld, 2013). Based on the RC principles, the term 'learning' in this dissertation entails my interpretation of what knowledge children were acquiring through their experience of participating in design activities.

1.4.3 STEM Design

STEM is a well-known acronym emphasizing an inclusive approach to the fields of science, technology, engineering, and math. STEM education highlights the need to prepare children for careers in STEM fields and increase 'STEM literacy' for all students (National Research Council, 2014).

The term ‘design’ in this work is derived from Cooperative Inquiry (CI) research approach to design with children, which is rooted in the theories of participatory design, contextual inquiry, activity theory, and situated action (Druin, 1999). This view argued for involving children as equal partners in the design process (Druin, 1999, 2002). However, more recent work of design with children argues for a child as protagonist approach (Iversen et al., 2017), and design by children (Gennari et al., 2022; Gennari et al., 2017) emphasizes making children the leading agent in carrying out the complete design process. This shift promotes the benefits for learning children embedded in the design process (Gennari et al., 2022; Roumelioti et al., 2022). The use of the term ‘design’ in this dissertation captures the latest approach to making children the leaders in the complete design process while adults provide scaffolds.

Additionally, this dissertation’s context is children’s design experiences in *informal learning*. Often informal learning has been defined simply as learning outside of schools; however, my understanding of informal learning from Rogoff et al. (2016) idea of informal learning emphasizes the organization and scaffolding for learning rather than where it occurs. The informal learning experiences discussed in this dissertation are non-didactic, collaborative, embedded in a meaningful activity initiated by the learner’s interest in connection with a larger community, and do not involve assessment external to the activity (Callanan et al., 2011; Rogoff et al., 2016).

The use of the acronym “STEM design” in this dissertation work entails informal design experiences for children to engage in problem-solving, collaboration, creation, testing ideas, and building prototypes with an integrated understanding of STEM concepts.

1.5 Organization of the Dissertation

This dissertation consists of six chapters, as briefly described below:

Chapter 2: Literature Review

Chapter 2 presents a literature review related to the affordances of sketching in the design and STEM education fields. It highlights what we know about using sketching for learning and what gaps exist in the literature.

Chapter 3: Children Learning to Sketch: Sketching to Learn

Chapter 3 is the Paper 1 of this dissertation. I used an ethnographic case study method (Merriam, 1998) to examine two research questions – 1) how do children share information via their sketches in a design activity? and 2) what learning opportunities occur when children engage in interest-driven sketching activities? Findings indicate that sketching can be useful for gathering information about the broader contexts of children's lives, which can help identify their needs and improve the design of future technologies for children. Additionally, participating in sketching allows children to develop their sketching skills, a vital multimodal skill set for both design and personal expression.

Chapter 4: Radical Constructivist Cooperative Inquiry Framework: Learning within Design

Chapter 4 is Paper 2 of the dissertation. It provides a theoretical framework, Radical Constructivist Cooperative Inquiry (RCCI), to examine children's learning experiences in design activities. It provides six pillars - Child-centered, Dynamic, Iterative, Collaborative, Representations, and Outcomes - as affordances that may support children's learning in informal design activities. In practice, these pillars intertwine to provide a strong foundation for learning design theory. RCCI is based on the strength and history of radical constructivism (Glasersfeld, 2013) to understand better how children learn to design in cooperative inquiry contexts (Druin, 2002; Iivari et al., 2018). Practical implications discuss how the RCCI framework can help understand, design, implement, and evaluate learning in design experiences.

Chapter 5: Exploring the Relationship between Sketching and Learning in the STEM Design

This chapter is Paper 3 of my dissertation. I used the RCCI framework with the thematic analysis method (Braun & Clarke, 2006) to examine two research questions - 1) how do children sketch during engineering design activities? and 2) how do children participate in learning through sketching activities? Findings indicate that children's sketches depicted a wide variety of details, guiding them to make design considerations for building their prototypes. Regarding learning, children learn to regularly modify, improve, better communicate, and collaborate about their engineering design ideas. Based on these findings, I recommend ways to support the development of children's sketching abilities during design activities. This study contributes to building knowledge about improving and sustaining design cycles by children in informal learning contexts. The context and methodological approach of this paper are different from Paper 1, so this paper serves three purposes - 1) to improve the understanding of children's sketching experiences as the dynamics were very different in this study than the first study, 2) to evaluate the adaptability of the RCCI framework into a different design context, and 3) to provide insight on how children use sketching in the overall design process.

Chapter 6: Synthesis and Conclusion

In this dissertation's final chapter, I draw connections between the three papers and provide the synthesized version of the new knowledge from the three papers of this dissertation about children's design and learning experiences in activities. It also includes implications, recommendations, limitations, and future directions for this dissertation research. Broadly, I argue that children can benefit from integrating learning *in* design and learning *by* design. Design is a powerful tool for engaging children in learning about STEM. Therefore, it needs to be valued, examined, and supported for children during STEM design activities. Regarding learning in design, the RCCI framework can be helpful in weaving learning throughout the planning, execution, and analysis process of design. Finally, I conclude by pointing out that if we engage children in sketching during design activities, they can learn about visualizing, modifying, communicating, and collaborating on design ideas.

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Chapter 2: Literature Review

2.1 Overview

The organization of this literature review is as follows:

- *First*, a literature review on children's drawing experiences in general.
- *Second*, a literature review on sketching in the field of children's design.
- *Third*, I review the role of sketching in learning STEM and synthesize the literature about sketching from the fields of design and STEM education, highlighting the gaps in the literature regarding children's learning and sketching experiences.
- *Fourth*, I describe the methods and theoretical framework used in this work, stating the rationale behind selecting those methodologies to address the gaps in the literature. I include a review of studies on designing with children, particularly the cooperative inquiry framework within participatory design methods, which informed Paper 1 and Paper 2 of this dissertation. Then, I review radical constructivism - a theory of learning within the field of education, which informed Paper 2 and Paper 3. Finally, I review the methodological guidelines for secondary analysis of qualitative data, as used in the analysis for Paper 3.
- *Fifth*, I elucidate the framing of the three papers to address the literature gaps identified, as shown in Figure 2.1.

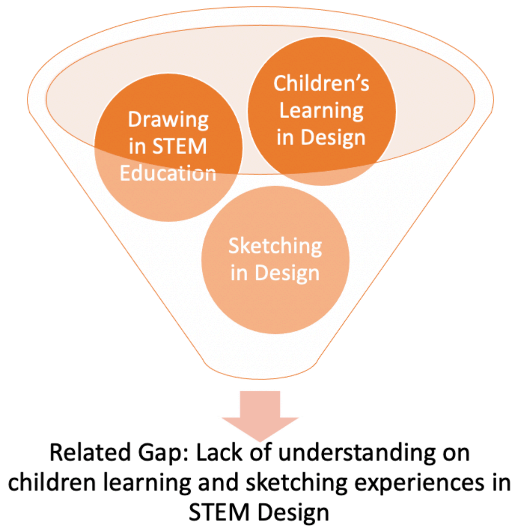

Figure 2. 1: Overview of Literature Review

This review frequently uses two words - 'drawing' and 'sketching' - commonly used interchangeably in STEM design. To avoid confusion, in this dissertation: *drawing* is conceptualized as "*a static visuospatial representation*" with meaning (Ainsworth & Scheiter, 2021, p. 2), whereas I conceptualize *sketching* as

> *a process that involves the construction of visual representations, the planning and visualization of ideas that happens before and during the construction of a visual representation, and the other forms of representations (verbal, textual) used to consider various ideas before actually making a sketch.*

In this dissertation, sketching is considered a subset of drawing done particularly for design purposes. In this review, I stick with the use of the term that researchers referred to in their studies, irrespective of whether their conceptualization was like mine or not.

2.2 Children's Drawing

Drawing is a spontaneous activity for a child that allows them to express their desires and deliverance from their fears (Fineberg & Fineberg, 1998). Adams' Power Drawing project (2002) proposes three critical functions of drawing for youth aged 3-18 years: drawing as perception, communication, and manipulation. Additionally, it is a unique mental development tool for children with which they can visually represent themselves (Brooks, 2005; Matthews, 2003). The meaning behind children's use of certain marks and shapes in their drawings is often in their speech and actions (Matthews, 2003). For instance, Gelmini-Hornsby et al. (2011) argue that making drawings in their stories helped young children enhance their collaborative storytelling.

There are multiple ways in which children can use drawing in their daily lives. For example, sometimes children's drawings can serve as a medium for self-expression, whereas other times, they can be a projection of their social identity. For example, Adams (2002) argues that drawing enables youth to organize and understand their experiences, as well as to shape ideas and communicate their thinking and feelings to others. In contrast, Hawkins (2002) claims that children's drawings reflect the social construction of their identity rather than a free and unfettered act of self-expression. It is hard to determine whether children's drawings are a projection of their social identity depicting what society expects them to be, or a medium to express themselves as they are, free from societal expectations. Maybe it is both, and we need to talk to children to find out what their drawings represent.

Drawing as a visual representation tool has the potential to help children solve problems, but there are limited opportunities provided to young people to see the affordances of drawing (Anning, 2008). For instance, young children enter formal schooling with a repertoire of modes of representation with which they try to make sense of the world, including drawing, modeling, role play, storytelling, emergent literacy, and numeracy (Anning, 2008). As children progress in the education system, they have increasingly limited opportunities to choose the content and style of drawing as it is often perceived as a 'time filler,' a medium to decorate walls, or within art 'lessons' as a one-off directed activity for occupational or recreational purposes (Anning, 2002). In middle school, youth draw realistic drawings representing space, scale, and perspective – though teachers do not model or explain the functions of different genres of drawing within different disciplines (Anning, 2008). Thus, children rarely see drawing as a tool for problem solving or its potential to help them to learn (Anning, 2008).

To summarize, drawing has multiple affordances for children (Anning, 2008; Brooks, 2005; Matthews, 2003). However, this dissertation focuses on children's learning and sketching experiences in STEM contexts. Therefore, next, I present a review of prior literature on sketching in STEM Education.

2.3 Importance of Sketching in Design

Sketching is central to design thinking rather than a byproduct that designers create while designing (Atilola et al., 2016). There are multiple affordances of sketching within design processes, such as exploring, explaining, or persuading another of a design idea (Ranscombe et al., 2019; Rasmussen et al., 2016). These affordances support a re-interpretive cycle in an individual's thinking process, support the re-interpretation of each other's ideas in a group activity, generate a wide variety of ideas, and enhance understanding of earlier ideas (Buxton, 2010).

Studies of design professionals show that they often revise their designs toward better alignment with the content and design constraints (Goldschmidt, 2014). Their designs often shift from abstract to concrete as they relate their drawings to the real world. Most of the prior work on design practices focuses on professionals and expert-level students; it is unclear whether the drawings of novice students also shift from abstract to detailed representations of content (de Vere et al., 2011; Johri et al., 2013).

Greenberg et al. (2011) discussed some strategies for designers to get started with sketching and how sketching can be helpful in problem solving. Kudrowitz et al. (2012) evaluated people's perception of product idea creativity and found that the quality of sketches influences the perception of creativity. Researchers argue that it is unclear to students how and when to apply sketching (Zhao et al., 2020). In addition, there has been a call for developing effective sketching instruction in the engineering and design curriculum (Kudrowitz et al., 2012).

With the arrival of engineering and modeling software, some curricula have reduced the use of freehand drawing in their courses (Quillin & Thomas, 2015; Uziak & Fang, 2017). Oehlberg et al. (2009) examined the sketching behavior of designers and the role of sketching in the design process by analyzing sketches provided by student designers in tangible design journals versus hybrid journals (which contain some digitally produced content). They found that with the use of digital resources (such as CAD), there is an increase in the number of sketches and more annotations on sketches in hybrid journals than tangible ones. Research has suggested that instructors design drawing activities to help students practice rapid and flexible drawing skills (de Vere et al., 2011) or ask them to generate multiple drawings (Cooper et al., 2017). Each drawing helped designers see new structural relations and determine how to refine their designs to solve their design problems (Purcell & Gero, 1998). Analyses of professionals' design processes have shown that designers first search for ideas by constructing rapid, manual drawings and then formalize ideas by interpreting their drawings (Suwa et al., 2001). Thus, designers are required to use freehand sketching before moving to digital sketching tools.

On the other hand, research on sketching in the field of design explores the potential of combining the affordances of 2D (precise, constrained, ergonomic) and 3D (immersive, unconstrained, life-sized) sketching using virtual reality and augmented reality technologies (Arora et al., 2020; Drey et al., 2020; Kent et al., 2021). Virtual Reality and Augmented Reality applications provide promising results for enhancing the perception and understanding of complementary affordances of 3D and 2D interaction for in situ 3D conceptual design (Arora et al., 2020; Drey et al., 2020). However, these studies highlight the challenges of providing appropriate scaffolding or constraints for these interactions (Kent et al., 2021; Drey et al., 2020). Therefore, there is a need to investigate further sketching experiences to find the potential pedagogical implications for supporting the development of sketching skills.

2.4 Sketching in STEM Education

Sketching is a prevalent and vital practice in the STEM disciplines (Brew et al., 2013; National Research Council, 2012). The literature suggests sketching improves learners' efficiency in learning science and extends their cognitive ability (Ainsworth & Scheiter, 2021). It is considered helpful in multiple ways, such as making predictions, observing patterns, constructing representations of content, making sense of complex and abstract content by externalizing thinking, communicating about visual-spatial content and ideas with others, transforming representations, and synthesizing content (Cheng & Gilbert, 2009; Fan, 2015; Quillin & Thomas, 2015). Thus, researchers advocate incorporating drawing activities throughout STEM curricula (Ainsworth et al., 2011; Cooper et al., 2017).

Scientific inquiry uses various representations, such as model-based reasoning and model construction, closely related to drawing (Lehrer & Schauble, 2012). DiSessa (2004) argued that children have a rich "metarepresentational competence" (p. 294). So, involving learners in model-based reasoning and model construction through drawing can facilitate their understanding of scientific representations (Schwarz et al., 2009). It will also help them develop representations for specific purposes (diSessa, 2004; Cooper et al., 2017). Thus, educators argue to involve children in scientific exploration and reasoning via sketching (Cheng & Gilbert, 2009; Evagorou et al., 2015).

Drawing can help direct children's attention to valuable details through which they develop a better understanding of scientific concepts (Nyachwaya et al., 2011; Schmidgall et al., 2019; Schmidgall et al., 2020). For instance, when children draw what they see, they pay closer attention to what they view, enhancing their observational skills, which are essential in scientific practices (Quillin & Thomas, 2015). A recent eye-tracking study showed that drawing activities help students direct their gaze to the conceptually relevant parts of the content presented in text and transition more frequently between the relevant content and their drawing when compared to activities that provide images or ask students to summarize (Hellenbrand et al., 2019). These kinds of constructive activities where children are required to transform their observations into visual-spatial representations can help them to enhance their engagement with the content (Leutner & Schmeck, 2014; Van Meter & Garner, 2005; Danish & Saleh, 2014; Glogger-Frey et al., 2015). Additionally, transforming verbal text into visual-spatial representations via drawing helps children synthesize information across multiple pieces of content (Danish & Saleh, 2014).

Brooks (2009) studied how drawings help children bridge the gap between their perception-bound thinking and more abstract thinking in science learning. Children begin by drawing what they observe from their real life. When they learn about the scientific concepts they are observing, they tend to draw their interpretation of the relationship between various concepts involved in the scientific phenomena (Brooks, 2009). These visual representations of their ideas help to develop their exploration of more complex ideas. Thus, visual representation in children's drawings progresses from concrete to abstract as they develop an understanding of the concepts they are representing in their drawings (Schwartz & Heiser, 2009).

Drawing activities that help students activate their mental models and compare them to the content can further refine them (Cooper et al., 2017; Duit & Treagust, 2008;

Nyachwaya et al., 2011). According to Van Meter and Firetto's (2013) model, learners form their propositional network of content focusing on its elements and relations based on which they create a drawing. This way, learners externalize their understanding of the content, which can help recognize and correct misconceptions in their mental models (Cooper et al., 2017; Nyachwaya et al., 2011).

Providing instructional support to students to encourage them to revisit the relationship between their mental model and the new content can be useful in developing their knowledge of complex ideas (Chi & Wylie, 2014; Cooper et al., 2017; Treagust & Duit, 2008). One of the effective ways to increase student's constructive engagement with STEM content is by asking them to read contextual material and then transform that into a drawing (Cromley et al., 2020; Fiorella & Zhang, 2018; Leutner & Schmeck, 2014; Kunze & Cromley, 2021; Van Meter & Garner, 2005). Additionally, prompting students to synthesize information across multiple pieces of content into drawing (Danish & Saleh, 2014) or asking students to invent new ways of drawing to represent content (Glogger-Frey et al., 2015) can be helpful to increase students' constructive engagement with STEM content.

Prain and Tytler (2012) provide a Representational Construction Affordances framework integrating three perspectives - *semiotic*, *epistemic*, and *epistemological*. This framework helps to explain how and why representational construction supports learning in science. For instance, the semiotic perspective focuses on how students use symbols and tools to make meaning of scientific concepts. The epistemic perspective focuses on the relationship between representation and the broader picture of scientific inquiries, such as knowledge-building and problem solving. The epistemological perspective focuses on how to challenge students to use the available tools for representing causal relationships between specific concepts. This kind of representational construction can help students in building scientific knowledge.

While engaged in STEM drawings, novice students occasionally lack the necessary knowledge to engage in bottom-up and top-down processes when they draw (Suwa et al., 2001; Uttal & O'Doherty, 2008) and may not know which features are relevant nor how to relate them to one another. In such scenarios, students can benefit from instructor feedback focused on their drawings to support them in generating relevant visual cues and making inferences about the concepts (de Koning et al., 2010; diSessa, 2004; Glogger-Frey et al., 2015). Moreover, it is crucial to ensure that students have time to discuss their drawings and give them time to draw them. In addition, giving explicit prompts to help students reflect on and refine their drawings can be useful for them to learn the content and solve the given problems (Backhouse et al., 2017; de Vries, 2006; Wagner et al., 2017).

Prior research found that children engage with drawings differently when working individually versus collaboratively (Danish & Enyedy, 2007). Further investigating the differences between individual and collective drawing experiences among children, Parnafes and colleagues (2012) found that elementary students can learn about the Moon's phases by individually constructing drawings about what they observe and then collaboratively revising them to understand the underlying concept of reflecting visible sunlight. For example, one study asked children ages 7–15 to create drawings in an informal environment without instructional support and found that older children created more accurate drawings but were less motivated to draw (Van

Joolingen et al., 2015). These studies highlight the scope of further research to understand the influences of factors such as prior knowledge, prior experience with drawing, and motivation on children's ability to engage with drawing.

In engineering practice, sketching serves multiple social and cognitive functions (such as ideation, balancing multiple designs or modeling parameters, and communicating structural relations) during the product design process (de Vere et al., 2011; de Vries, 2006; Nichols et al., 2002; Yang, 2009). Additionally, sketching is a language for engineers to represent mental ideas (de Vere et al., 2011; Dym et al., 2005). Engineers use sketching strategies to translate mental design ideas into graphical displays and create new ideas which may not exist prior to drawing (Goldschmidt, 2014). For engineers, sketching has two primary operations: externalizing and internalizing design ideas (Kelley & Sung, 2017; Tversky et al., 2003). Sketching is essential in crystallizing engineers' amorphous design ideas into visible design artifacts (Sung et al., 2019). Engineering education aims for young learners to teach them how to solve problems like an engineer, so teaching practical sketching skills should be integrated throughout engineering education (Cunningham et al., 2018).

When faced with a problem, individuals instinctively doodle, sketch, and make notes to understand the problem at hand (Goldschmidt, 2014). The human mind and hands are closely connected, so educators need to develop student visualization skills while teaching effective ways to share and develop design ideas in engineering classrooms (Weber & Sansone, 2016). However, sketching instructions in engineering education focus on technical drawing rather than strategic sketching (Sung et al., 2019). For instance, most engineering education textbooks highlight sketching techniques –

precise lines and shapes, symbols, isometric drawing, and parametric modeling – rather than examining why and how designers use sketching practices (Marunic & Glazar, 2013). Additionally, secondary engineering and technology educators focus on technical drawing skills such as CAD with less emphasis on sketching strategies (Kelley & Wicklein, 2009).

Recently, Sung et al. (2019) examined how sketching instructions in engineering design influence the quality of sketching products and students' design cognition. Their experimental study found that providing advanced sketching strategies (such as the strategic use of sketching and 2D layout models) helps students to generate high-quality design sketches with a high emphasis on designing concentration. Their findings imply that sketching can bridge conceptual thoughts and graphical design expressions, alleviating cognitive demands. Finally, they argue that K-12 science and engineering education curricula should incorporate freehand sketching techniques, particularly for younger grade students, to reduce their cognitive load of drawing 3D representations.

Drawing to learn is an active, constructive, and interactive form of engagement (Ainsworth & Scheiter, 2021). Experiments show that students who constructively generate their drawings outperform students who actively trace or copy images (Gagnier et al., 2016; Mason et al., 2013). Wu and Rau (2019) argue that drawing activities are more effective if students use drawings to build knowledge by integrating prior knowledge with externally presented information. Additionally, Fiorella and Kuhlmann (2020) found that encouraging students to coordinate verbal explanations with drawings that they create can enhance their learning. Sketching as a form of visual representation can serve as an anchor for designers to develop common ground for the design of a product. In collaborative design work, discussing sketches helps designers to externalize their knowledge while eliciting peers' viewpoints (Quan & Gu, 2018). Therefore, we should encourage making drawings representing the new concepts they are learning (Ainsworth & Scheiter, 2021).

Research on disciplinary practices suggests that drawing activities can help students engage in specific disciplinary practices used by STEM professionals (Cheng & Gilbert, 2009; Fan, 2015; Quillin & Thomas, 2015; Wu & Rau, 2019). Students gradually learn to depict content in their drawings that conform to the visual language used in specific STEM disciplines (Brooks, 2009; Enyedy, 2005; Prain & Tytler, 2012). Students' initial drawing construction uses innovative and non-conventional features that reflect their naïve and internally robust misunderstandings (Stieff et al., 2011). By reflecting and negotiating their drawing with others, they learn to refine them using appropriate scientific conventions (Greeno & Hall, 1997; Nathan et al., 2007). Thus, learning to construct scientific drawings is iterative, and students gradually learn to make sense of disciplinary conventions and tools for visual representation.

Designing a solution for a disciplinary problem involves a combination of creative ideas with the external constraints of STEM content (such as structural limitations of the materials). Constructing drawings to solve problems can help students throughout the process (de Vries, 2006; Goldschmidt, 2014). First, students construct drawings of their ideas using their cognitive, cultural, and social resources (Prain & Tytler, 2012). Second, they can ask to combine their creative ideas with external constraints related to STEM content (de Vries, 2006). Constructing drawings, combining the ideas, and external constraints help students refine their ideas. Additionally, getting feedback from instructors providing information on how the design can be improved can be beneficial for students learning how to use drawing to solve disciplinary problems (de Vries, 2006). Thus, disciplinary practices should encourage students to use their drawings to transform STEM content and solve disciplinary problems (Wu & Rau, 2019).

STEM professionals often modify and revise their designs as they relate their drawings to the real world by using their drawing expertise, allowing them to transform content for further exploration rapidly (Kothiyal et al., 2016). Case studies of engineers show that they first transform problems into drawings that depict concepts qualitatively or quantitatively and then iteratively evaluate and revise their drawings (Kothiyal et al., 2016). Drawing skills play a crucial role in students' identity as STEM professionals and their ability to contribute to the STEM community by using drawing to solve complex, open-ended problems (Kothiyal et al., 2016). As discussed above, children's drawings move from concrete to abstract representation (Brooks, 2009; Schwarz et al., 2009), whereas professionals in design use sketching to move from an abstract representation of ideas into concrete forms (de Vries, 2006). However, the design field lacks clarity on how and when this shift occurs.

The primary ways students draw for STEM disciplinary practices are scientific modeling and design practices; both involve constructing and refining representations to solve a disciplinary problem (Wu & Rau, 2019). Scientific modeling practices in the mathematics and science disciplines involve shifts from external objects to internal representations (Cooper et al., 2017). Design practices in the engineering and technology disciplines involve shifting from internal representations to external objects (de Vere et al., 2011; de Vries, 2006; Goldschmidt, 2014). These practices should consider the development of students' drawing skills as an essential learning outcome (Wu & Rau, 2019).

To summarize, a STEM professional's ability to draw differs significantly from a novice, as a professional's drawing tends to focus on actual observation, whereas a novice's drawing tends to reproduce the textbook drawing (Hay et al., 2013; Jee et al., 2014). However, it is unclear how STEM students develop these practices as they transition from novices to professionals (Johri et al., 2014; Prain & Tytler, 2012). Even though there is recent interest in STEM research to explore the development of sketching skills among students, there is a call for more research to focus on instructions for students to develop drawing skills like STEM professionals, especially among middle-school students who are preparing to pursue STEM careers (Ainsworth & Scheiter et al., 2021; Cunningham et al., 2018; Sung et al., 2019).

Since this dissertation focuses on children's experiences in the STEM design context, the following section presents the literature review involving children in the design process, which informs the design of Paper 1 and Paper 2.

2.5 Involving Children in Design

Children's dependence on technological tools increases for learning and socialization purposes (Bulger et al., 2021; Ito et al., 2020). To improve the design of these technological tools, researchers argue to involve youth in technology design for children (Bonsignore et al., 2013; Druin, 2002; Guha et al., 2013). Although various ways involve children in the technology design process, including being users, testers, and informants in and for technology design (Druin, 2002), these roles are less involved and in-depth than actual design partners. For example, a child design partner is "...a part of the research and design process throughout the experience" (Druin, 2002, p. 19). The method which involves children as design partners in the design of technology for children are called Cooperative Inquiry (Druin, 1999, 2002).

The Cooperative Inquiry Design method has its roots in Participatory Design (Bødker et al., 2000) and Contextual Design (Beyer & Holtzblatt, 1999). Both Participatory Design and Contextual Design focus on adults as technology users. These methods provide some of the backgrounds for Cooperative Inquiry, which adapts these methods and creates others to enable working with children during the technology design process. Druin (2002) describes Cooperative Inquiry as an intergenerational partnership between children and adults. In this kind of partnership, adults neither teach nor guide children in the traditional sense; instead, adults and children work together as peers in the design process. In other words, children are considered designer partners with particular expertise in being a child. In order to be design partners, however, it takes time and effort to build and sustain relationships (Yip et al., 2017). Therefore, researchers generally work with a small number of children, as opposed to a large group, primarily working with children ages 7-11, as they are old enough to articulate their ideas (Druin, 1999; 2002). The method of Cooperative Inquiry was chosen for the design of Study 1 in this dissertation in order to involve children within the design process as equal partners.

Cooperative Inquiry employs various techniques, including 'bags of stuff,' sticky notes, journals, mixing ideas, and layered elaboration (Druin, 1999; Yip et al., 2013; Walsh et al., 2010; Fails et al., 2013). *Bags of stuff* involve art or low-tech prototyping supplies in a bag (e.g., glue, craft paper, and Styrofoam) that children and adults use together to "sketch" ideas during design sessions. Design partners can use *sticky notes* (post-it notes) to offer specific design suggestions and keep individual *journals* to sketch their ideas and write reflections about design sessions. *Mixing ideas* involves each design partner beginning with a unique idea and progressing stepwise to combine those ideas. Although there is often mention of drawing and sketching within these techniques, there is no exploration or explanation of how drawing and sketching help young designers participate in Cooperative Inquiry or how the use of drawing may affect the design process.

There are some similarities between design processes involving only adults and design processes involving children; for example, adults and children can brainstorm, prototype, or evaluate (Fails et al., 2013). Despite these similarities, some differences are also to be considered, such as developmental differences in cognitive, motor, social, emotional, and communication abilities, which call for a modification in scaffolds to be provided to children during their engagement in design activities (Fails et al., 2013). Prior research separately presents the prevalence of sketching in design practices and children's use of drawing; however, no studies examine children's experiences with sketching in the design processes. Therefore, this dissertation focuses on addressing this gap in the literature.

In recent literature on technology with design, the perspective of involving children as design partners has evolved into letting them take the lead in the design process (Iversen et al., 2017; Kinnula & Iivari et al., 2021). Some approaches suggest involving children in the design process as ‘co-researchers’ and ‘protagonists’ to participate in technology design through mutual learning (Iversen et al., 2017; Van Doorn et al., 2016). Our approach to CI aligns with the child-as-protagonist approach, which emphasizes allowing children to complete the design process (Iversen et al., 2017; Gennari et al., 2022). Children need to be encouraged as the leading agents in driving the design process to develop design skills and reflect on technology’s role in their life (Iversen et al., 2017). Enabling children to make things can empower them with technical skills and a critical stance toward technology (Kanafi et al., 2021; Kinnula & Iivari et al., 2021). Therefore, there is a shift from giving equal voices to children in the design process to promoting design by children in order to emphasize the learning benefits (Gennari et al., 2022; Gennari et al., 2017; Pellegrino et al., 2021; Roumelioti et al., 2022). As two instances of implementing processes that reflect design-by-children, Gennari et al. (2022) and Melonio et al. (2020) began by familiarizing children with innovative technologies and encouraging them to imagine and conceptualize smart technologies for themselves.

Despite these evolving views on children’s participation in the design process, the research is thin on children’s sketching experiences in design, limited to scaffolding children’s drawings with storyboards or adults who sketch as children verbally describe their design ideas (Hiniker et al., 2017; Mitchell & Nørgaard, 2011). Most of the references to sketching in Cooperative Inquiry and drawing in STEM learning emerged almost entirely from co-located in-person sessions (Fails et al., 2013; McNally et al., 2018; Roldan et al., 2020; Yip et al., 2019).

More recently, however, there has been an emerging need to develop online Cooperative Inquiry practices for children (Constantin et al., 2021; Fails et al., 2022; Lee et al., 2021). Paper 1 of this dissertation was conducted fully online via Zoom due to COVID-19 and consequently contributes to filling this recently emerged gap in the field related to online synchronous design sessions with children. Next, I present the literature review focusing on online Cooperative Inquiry with children.

Engaging children in an online Cooperative Inquiry environment has become increasingly important due to external factors, such as the COVID-19 pandemic and the diversification and inclusion of children from diverse backgrounds (Korte et al., 2021; Lee et al., 2021). There are benefits and challenges in conducting online Cooperative Inquiry design sessions with children (Constantin et al., 2021; Fails et al., 2022). Online Cooperative Inquiry sessions give children more independence, privacy, and autonomy. For instance, they can choose whether they want to turn on their cameras or not (Constantin et al., 2021; Fails et al., 2022). On the other hand, during technological issues (e.g., connectivity, interaction challenges), unexpected power imbalances may emerge as children seek help from adults (e.g., parents, facilitators) to resolve the issues.

Due to unforeseeable technological disruptions that may require sudden attention, a low child-to-adult ratio is recommended more in online sessions than in in-person Cooperative Inquiry sessions (Constantin et al., 2021). Moreover, the lack of physical co-presence makes collaborating harder (e.g., sharing physical arts and crafts supplies; digital slides to draw digital artifacts) (Fails et al., 2022). It is hard for facilitators to gauge children's attention when their cameras are off (Fails et al., 2022). Despite these challenges, one of the benefits of online Cooperative Inquiry sessions is the increased inclusion of children participants as it allows participation of children who are unable to participate in in-person sessions due to health issues, transportation limitations, and time constraints of adult caregivers (Lee et al., 2021; Prabhakar et al., 2017).

Online, there are different models of conducting Cooperative Inquiry design: synchronous (Fails et al., 2022; Lee et al., 2021) and asynchronous (MacLeod et al., 2016; Prabhakar et al., 2017; Walsh et al., 2012). The asynchronous model of online Cooperative Inquiry requires assisting children in the absence of a facilitator in developing the understanding of design tools; however, it gives children the freedom to work at their own pace during the time of their convenience (Prabhakar et al., 2017; Walsh et al., 2016; Walsh et al., 2015). In contrast, synchronous virtual sessions support in-the-moment interactions with their peers and facilitators; however, these can also be disrupted by numerous external and internal factors because sessions occur in real-time (Fails et al., 2022). Recently, Lee et al. (2021) provided a conceptual framework for conducting synchronous online sessions where children describe their ideas for arriving at a solution and an adult sketches their ideas and designs. These conceptual frameworks provide practical understanding for conducting virtual and face-to-face cooperative inquiry design sessions with children; however, they are limited to understanding children's learning through sketching experiences in design sessions.

Thus, there is still a gap in the literature regarding understanding children's sketching in design environments.

Next, I discuss the literature review on the theoretical framing of learning in the design sessions with children.

2.6 Theoretical Framing of Learning in Design

Multiple recent frameworks in design reference learning briefly but need to focus on it thoroughly (e.g., Zhao et al., 2020; Gero & Milovanovic, 2020; Meyer et al., 2020). A recent literation review on the role of learning theory in the field of Child-Computer Interaction (CCI) argues that the theoretical positioning of learning in design with children is grounded in four positions: (1) Constructivist Theories, (2) Cognitive Theories (3) Socio-cognitive Theories, (4) Constructionism (Eriksson et al., 2022). The Piagetian view of child development – Constructivism – dominates the field in these theoretical positions. However, the review highlighted that the field's understanding of these theoretical positions is scattered (Antle & Hourcade, 2021; Eriksson et al., 2022). In particular, the nuances between Piaget's Constructivism, Papert's Constructivism, and Vygotsky's Socio-cognitive theory remain vague in the field (Eriksson et al., 2022). This review concludes by highlighting two gaps in the field of child-computer interaction, "lack of solid theoretical grounding for learning and a lack of CCI-specific literature to which researchers can refer" to ground their work (Eriksson et al., 2022, p. 60).

There is one theoretical view of learning that aligns with the design with children framework but was not included in Eriksson and colleagues' review (2022) or the field of design in general (Antle & Hourcade, 2021). Glasersfeld proposed Radical

Constructivism (RC) in the late 1970s as an expansion upon Piagetian Constructivism, in part as a response to the prevalent misuse of Piaget's works on Constructivism. In particular, Glasersfeld noticed that researchers accepted the idea that learners construct knowledge as they learn, as proposed by Piaget but ignored that the very definition of 'knowledge' had also changed (Glasersfeld, 2013).

RC differs from the conventional views of cognitive constructivism, social constructivism, and constructivism because it does not emphasize knowledge lying 'inside' an individual, dictated by cognitive stages, or present outside in the community to be discovered by the learners; instead, it promotes the idea that knowledge is the interpretation of individuals' experiences in their environment. Glasersfeld called his model 'radical' in order to distinguish it from more conventional interpretations of constructivism, and described the two fundamental principles (Glasersfeld, 1995; p. 18):

- *knowledge is not passively received but built up by the cognizing subject; and*
- *the function of cognition is adaptive and serves the organization of the experiential world, not the discovery of ontological reality.*

Based on these principles, RC entails a radical rebuilding of knowledge, truth, communication, and understanding; it cannot assimilate into any traditional epistemology (Glasersfeld, 2014; Glasersfeld, 2013). It replaces the notion of 'truth' (and seeking a 'true' representation of an independent reality) with the notion of 'viability' within the subjects' experiential world. Consequently, it refuses all metaphysical commitments to only one possible thinking model about our world together. Instead, it replaces it with a conceptualization of the world *we* construct as living subjects. RC suggests that there is no ultimate truth or reality to be discovered by the learners as it is impossible to verify knowledge beyond one's interpretation of their experience.

According to the RC perspective, learning happens while inventing things to improve our functioning in the environment as a coherent and productive way of thinking that helps to deal with the fundamentally inexplicable world of our experience. In the 1970s, RC provided a new methodology to scholars in the United States to understand children's ways of learning and knowing: the teaching experiment (Steffe & Thompson, 2000; Glasersfeld, 2013). Steffe and Thompson's (2000) foundational article, published decades later, outlines the development, purpose, and protocol for conducting teaching experiments (TEs). They define TEs as a sequence of episodes, including a teacher/facilitator, one or more students, a 'witness' to challenge or corroborate the teacher/facilitator's understandings, and a record of each episode. These records are both teaching aids for the teacher/facilitator and witness to prepare for the following episodes in the TE's sequence, and memory support to analyze the overall arc of the completed TE.

A key component of TEs is that the researchers (e.g., the teacher/facilitator and witness) formulate hypotheses to test during and between each episode, using the students' language and actions as evidence for or against the hypotheses – and adapting the TE accordingly. In such a way, the students guide the course of the individual episodes and the TE through their engagement and learning while the researchers seek to be responsive to the directions indicated by the students. This approach requires researchers not to hold fast to a specific path of learning but to remain open to unforeseen directions and responses by and between the students. TEs involve long-term interactions between the researcher(s) and a child or group of children through a series of teaching episodes and occasional clinical interviews (anywhere between 6 weeks to 2 years) as an observational technique (Cobb & Steffe, 2011). Lastly, TEs are not a prescribed methodology but guidelines organized around RC to understand how students learn and reason, much as CI organizes the design process to understand how children design and interact with designs. The theoretical foundations of CI and RC are further synthesized in Paper 2 of this document to address the gap and inconsistencies in various theoretical positioning of learning in design and provide a novel theoretical framework to which further researchers in design can refer.

2.7 Secondary Analysis of Qualitative Data

Secondary data analysis involves investigating the data collected for a previous study - either by the same researcher(s) or different researcher(s) – to explore new questions or use different analysis strategies that were not a part of the primary analysis (Szabo & Strang, 1997). Secondary data analysis is widespread due to its "cost-effective approach in maximizing the usefulness of the collected data" (Hinds et al., 1997, p. 408). However, it is more common in quantitative studies than in qualitative studies. Scholars have started arguing for the effectiveness of sharing data in qualitative research, and to address its rigor and ethics concerns, they have established guidelines (Heaton, 2008; Ruggiano & Perry, 2019). Below is the list of these methodological guidelines:

- Specify how the original purpose and focus of the research are similar/different to the focus of the secondary analysis
- Specifying the source and mode of data sharing between the primary and secondary analysis researchers.
- Explaining how ethical concerns are maintained for secondary analysis
- Describe how the confidentiality of data will be maintained
- Describe the nature of data collected for secondary analysis
- Describe the rigor of secondary analysis
- Identifying limitations

I followed the above-stated guidelines for the secondary analysis of qualitative data for Paper 3 (Heaton, 2008; Ruggiano & Perry, 2019). Additionally, I involved the researcher who collected the data throughout the data analysis process to ensure correct accounting for its secondary nature.

The main reasons for using the secondary data for Paper 3 are:

(i) It engages children in sketching during engineering design, which aligns with the topic of interest for this dissertation.

(ii) The secondary data is from the targeted age group of children (7-11 years).

(iii) The primary data collector of the MAKEngineering project was not planning to analyze their data with a focus on children sketching, so I collaborated with them, taking the lead in analyzing data from a perspective that would otherwise not be done.

(iv) It includes more stages in the design process than the SDC in Paper 1, especially the development of low-fidelity prototypes and testing of prototypes by youth.

(v) It provides a new context to evaluate the adaptability of the framework I developed in Paper 2.

(vi) To run an entire project similar to the MAKEngineering project would need many resources beyond the scope of a doctoral student.

2.8 Building Cohesion Across Representations

According to RC, one of the pedagogical recommendations for creating learning environments is that teachers should provide for and encourage multiple perspectives and representations of content (Glasersfeld, 1995). Prior work on STEM integration emphasizes the need to build cohesion across various forms of representations as it can support and deepen students' knowledge of STEM content (Nathan et al., 2013; Nathan et al., 2017). Given the multimodal nature of STEM environments, students require translation across different representations, including symbolic, concrete, gesture, and speech representations, in order to solve problems (e.g., Alibali et al., 2012; Simpson et al., 2021). Prior work found that verbal interactions with children add meaning to their drawings (Hiniker et al., 2017). Therefore, I analyze different representations children use during sketching captured in the video data, including their language (verbal & written), sketches (visual), and gestures to interpret their sketching experiences. I further expand on the role of representations for learning and sketching in Paper 2 and Paper 3.

2.9 Synthesis of Literature Gaps

Over the past years, research on sketching and learning has increased in separate fields- design, STEM, and children. This literature review synthesizes these lines of research to understand when, how, and why sketching is effective (or ineffective) for children's learning in STEM design. Collectively, the prior literature from these fields suggests that children are spontaneous at sketching, which can support their STEM learning. However, there is a lack of understanding of children's experiences in STEM design, especially in informal learning environments. Most of the research on children's STEM learning is from the context of formal education; we know little about children's experiences in informal STEM design activities. Based on this literature review, no prior research primarily focuses on children's learning experiences in informal STEM design environments. Moreover, there has not been an investigation into how sketching and learning relate to the disciplines of design, children, and STEM education. This literature review highlights three gaps:

1) Sketching is prevalent and useful in STEM design, but the field needs a better understanding of children sketching experiences in STEM design.
2) Sketching is a learning tool to support children in developing an understanding of STEM concepts; however, the field needs instructions and scaffolding support for educators to support the development of sketching skills among children.
3) Learning is an area of interest in designing technologies with children; however, there is a gap in CCI on a clear theoretical position to which future researchers can refer to provide to support children learning in design.

This dissertation addresses these literature gaps theoretically and empirically with three interrelated papers.

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Chapter 3: Children Learning to Sketch: Sketching to Learn

Abstract

Purpose: To understand children's sketching behavior while they engage in interest-driven design activities, we examine their information sharing practices and the learning opportunities that may occur when they engage in a sketching activity.

Methodology: We used a participatory design approach with children, *Cooperative Inquiry*, for data collection. For analysis, we used the ethnographic case study approach to consider the particularity and complexity of sketching and its affordances within each design activity.

Findings: We found that children share information about their expectations, experiences, beliefs, and knowledge via their sketches. Additionally, they were engaged in multiple learning opportunities, including how to label sketches, build on ideas, sketch in collaboration, and innovate on ideas.

Implications: Sketching can be useful for gathering information about the broader contexts of children's lives, identifying their needs, and improving the design of future technologies for children. Additionally, participating in sketching allows children to develop their sketching skills, a valuable multimodal skill set for design and personal expression.

Originality: This empirical research is original in its context of focusing on children's sketching experiences in an interest-driven design environment occurring virtually in the informal setting of a library.

Keywords: sketching, drawing, design, children, information, learning, STEM

3.1 Introduction

Today's children depend on technological tools for learning and socialization (Bulger et al., 2021; Ito et al., 2020). Research indicates that when children are involved in a technology design process, their involvement can enhance the designed technology (Druin, 2002) and develop our understanding of ways in which they use technology across the contexts of their daily lives (Bonsignore et al., 2013; Clegg et al., 2014). Sketching is a crucial component of the design process (Goldschmidt & Smolkov, 2006; Oehlberg et al., 2009); designers use sketching techniques extensively when generating ideas and prototypes (Ainsworth et al., 2011; Buxton, 2010; J. Self, 2019). Prior research on children's sketching experiences for technology design is limited to small-scale exploratory studies, most of which scaffolded children's drawings with storyboards or adults who sketch as children verbally describe their design ideas (e.g., Hemmert et al., 2010; Hiniker et al., 2017; Mitchell & Nørgaard, 2011). Related studies have focused on sketching instruction in formal learning environments (e.g., Kelley & Sung, 2017; Sung et al., 2019). In contrast, our study focuses on engaging children in interest-driven sketching to understand how their needs and interests can enhance the design process and development of products.

Broadly drawing involves making meaningful marks on the paper, and different drawing styles have different functions (Adams, 2002). For this study, we consider sketching as *a particular kind of drawing that involves constructing visual representations to design technology*. Specifically, we investigate the following research questions:

RQ1: How do children share information via their sketches in a design activity?

RQ2: What learning opportunities occur when children engage in interest-driven sketching activities?

To answer these questions, we examine data collected from a series of STEM Design Club sessions held in a virtual public library. This exploratory project aimed to understand children's interests and issues by involving them in interest-driven technology design activities. However, this paper focuses on examining children's sketching behaviors. Our findings suggest that children's sketches offer insights into their *expectations*, *experiences*, *beliefs*, and *knowledge*. We also observed that sketching promoted children's efforts to engage in multiple learning opportunities, including *labeling sketches*, *building on ideas*, *collaboratively sketching*, and *developing innovative ideas*. These findings extend our understanding of children's sketching experiences during design processes. The contribution of this study is a better understanding of children's sketching to strengthen future design processes with children and prepare researchers to support children's sketching abilities. Moreover, understanding children's sketching can inform the creation of future sketching software by providing insights into what children do, how they do it, and their needs while they engage in sketching.

3.2 Related Work

3.2.1 Sketching in Design

Sketching is critical to design (Buxton, 2010; van der Lugt, 2002;) as it is helpful in analysis, communication, and documentation (Ainsworth et al., 2011; Atilola et al., 2016). During the design process, sketching evolves in three stages: explorative, explanative, and persuasive (Olofsson & Sjolen, 2005), and can support reinterpretations of individual thinking, collaborative thinking, and access to earlier ideas (van der Lugt, 2002). Thus, sketching is not merely a byproduct of design; it is central to design thinking (Atilola et al., 2016; Buxton, 2010). Although widely used, sketching is an aspect of design that is the least taught and practiced (Ainsworth & Scheiter, 2021; Sung et al., 2019). There is limited guidance for supporting sketching instruction or explaining how and when to apply sketching knowledge (Ainsworth et al., 2011; Kelley & Sung, 2017; Sung et al., 2019; Zhao et al., 2020). Prior work has identified a few strategies for sketching, but detailed examples of how sketching can be helpful to problem solving are limited (Greenberg et al., 2011). There are calls for sketching instructions in the engineering and design curriculum (Ainsworth & Scheiter, 2021; Greenberg et al., 2011; Kudrowitz et al., 2012). Prior studies have examined sketching in design; however, few studies have focused on how children create and use sketches in design activities. So, we ground our study more broadly in prior research on children and drawing.

3.2.2 Drawing and Children

Drawing is a unique mental development tool for children (Brooks, 2005; Matthews, 2003) that empowers them to represent their desires and fears visually (Fineberg & Fineberg, 1998). Children's speech and actions can help adults understand the meaning behind using certain marks and shapes in their drawings (Matthews, 2003). Adams (2002) proposes three critical functions of drawing for children between the ages of 3-18 years: perception (understanding their experiences), communication (communicating their thinking and feelings to others), and manipulation (shaping ideas). In contrast, Hawkins (2002) found that children's drawings reflect the social construction of their identity rather than a free and unfettered act of self-expression. It is unclear what children's drawings represent unless we talk to the children themselves about their intent (Matthews, 2003). Young children enter formal schooling with a repertoire of modes of representation, including drawing, with which they try to make sense of the world. However, as they progress in the school system, their opportunities to choose the content and style of drawing become limited (Anning, 2008). In young children's lives, drawing is perceived as a 'time filler' (Anning, 2002). Later, teachers expect middle school children to draw realistic drawings representing space, scale, and perspective without teachers' modeling and explaining the functions of different genres of drawing within different disciplines (Anning, 2008). Thus, children rarely see drawing as a problem solving tool and consequently miss its potential for helping them learn (Anning, 2008).

Prior studies show that drawing activities can increase students' constructive engagement with content by prompting them to transform the verbal text into visual-spatial representations (Leutner & Schmeck, 2014; Van Meter & Garner, 2005) and synthesizing information across multiple pieces of content (Danish & Saleh, 2014). Prain and Tytler (2012) provide a Representational Construction Affordances (RCA) framework integrating three perspectives - semiotic, epistemic, and epistemological - to explain how and why representational construction supports learning. For example, drawing helps direct learners' attention to the conceptually relevant parts of the content (Hellenbrand et al., 2019). More recently, Ainsworth and Scheiter (2021) argue that learners should draw visual representations for themselves as it is an active, constructive, and interactive form of engagement and promotes learning. Next, we discuss how drawing connects with STEM before introducing how STEM and sketching connect.

3.2.3 Connecting drawing and STEM

STEM disciplines involve constructing and interpreting visual representations, including drawing (Brew et al., 2013). For STEM professionals, drawing is a valuable tool when translating scientific texts, representing complex phenomena, enhancing observation, externalizing thinking, and making interferences for discoveries (Ainsworth et al., 2011; Arcavi, 2003; Quillin & Thomas, 2015). Prior research found that engaging in drawing activities can help children to learn about STEM (Schleinschok et al., 2017; Van Meter et al., 2006; Wu & Rau, 2018). For instance, Cooper et al. (2017) showed that constructing and interpreting sketches is crucial to student learning in modern chemistry. In particular, research shows that students often struggle to interpret spatial relations conveyed in STEM visual representations (Rapp et al., 2007; Stull et al., 2012), which can be a barrier to their success in STEM - but generating sketches can improve students' ability to understand these spatial relationships (Gagnier et al., 2017; Scheiter et al., 2017).

Research on mental model integration suggests that drawing can help students to recognize and correct misconceptions (Cooper et al., 2017; Nyachwaya et al., 2011). In such scenarios, students can benefit from instructional support that encourages them to focus on the relations between their mental models and new content (Treagust &

Duit, 2008). However, recommendations for effectively designing drawing activities for children still need to be studied (Wu & Rau, 2019).

Clearly, sketching (drawing) is already an integral practice in STEM, design, and learning. Prior research calls for instructions on sketching activities to support children's learning, thinking, reasoning, and sketching skills. To our knowledge, no prior empirical research examines children's sketching experiences in an interest-driven design environment. For this reason, we examine children's sketching in design, where they were interested in the things they were sketching. This study also offers a better understanding of children's sketches during design, which can help researchers working with children to strengthen their sketching instructions during the design process. Finally, attending to children's sketching can improve the design and development of future technologies by highlighting what to expect from children's sketches and identifying where children may need specific support.

3.3 Methodology

We use the ethnographic case study approach (Merriam, 1998), focusing on how children participate in an informal learning setting. We investigated children's sketching within the practice of an interest-driven, design-based, virtual informal learning environment. The use of an ethnographic case study approach allowed us to consider the particularity and complexity of sketching and its affordances within different design activities. We use pseudonyms for participants.

3.3.1 Overview of the STEM Club Design

The primary aim of the STEM Design Club was to engage children in their interest-driven design activities. It followed a Cooperative Inquiry (CI) approach, where the children participated in a technology design process as full design partners (Druin, 1999, 2002; Druin et al., 2009). The duration of each session was 90 minutes (but sometimes ran over), structured as follows: (1) Social/Snack Time (5-10 min); (2) Question of the day (5 min); (3) Recap of previous session & Overview of the current session (5 min); (4) Game Time (5-10 min); (5) Group Brainstorming on the topic of the session (10-15 min); (6) Individual/Team activity (20 min); (7) Presentation of individual/Teamwork (20 min); and (8) Wrap up (5 min).

The club consisted of eight members, including five young members – Anna (age 9, Female), Bella (11, Female), Nora (10, Female), Aaron (10, Male), Ryan (9, Male), two researchers, and one librarian. This age group (ages 9-11) for the study was selected due to the similarity in their cognitive abilities to reflect, understand, and share their thinking with the group (Druin, 1999). The first author led the sessions, and the second author assisted in the small group activities when children were moved into separate Zoom rooms to work in pairs/triplets. The librarian's role was limited to providing technical support if needed and overseeing the program. The club members met for 11, 90+ minute weekly sessions over three months. The three adult members (two researchers and one librarian) attended all the sessions, and the number of children who participated ranged from 3-5.

Table 3. 1: Brief about the STEM Design Club activities

Session	**Topic** (First author planned decided these topics based on the previous session)	**Sub-topics** (*Italicized texts are the sub-topics that emerged from children's responses and discussion*)	**No. of children who attended the session**	**Was sketching involved**
1	Introduction to activities and tools to be used in design sessions	What is design? Who designs? How do products get designed? Children Interests, Introduction to Jamboard, Brainstorming, Sticky Notes, Sketching.	5	Yes (individual)
2	Problems faced by today's Children	*Being on screen for too long; lack of confidence; Shyness, stage fever, breaking rules among school campus, disobeying traffic rules; bully in schools; cyberbullying*	5	Yes (individual)
3	Potential technology-based solution to children's problems	*Search engines; search for design apps*; *Social time within and after school hours; collectables for reducing anxiety (e.g., stress ball)*; *Security cameras on school campus and roads*; *game as product; personalized-device; smart pocket-fits*	5	Yes (individual)
4	Games as products	*Process of Game Design; Different kind of games; Game mechanics*	5	No
5	Card Games	Observing game mechanics while playing game of SETS, *Re-mixing SETS mechanics by adding more cards and shapes*, *testing the re-mix version of SET*	5	No
6	Digital Games	*Game elements - objective; constraints; surprise; strategy; fun*	5	No
7	STEM Day	STEM influence in daily life of children; *Self-cleaning version of photocopier/printer; Smart backpack with voice control; Smart curtains*	4	Yes (collaborative)
8	STEM Design Toolkit	*Measurement toolkit; Do It Yourself (DIY) Metal Box; Math Toolbox*	4	Yes (collaborative)
9	Mental Models	*Computer; Trash Can; Cerebrum; Satellites*	5	Yes (collaborative)
10	Tools for Connectedness	*Smart eyeglasses; app to connect people who speak different languages*	4	Yes (collaborative)
11	Presentation and Reflection	*Games; designing technology based products; toolkits*	3	No

Although the first author led each session with specific topics and prompts as part of the partnership, each week's topics were developed to follow the previous week's activities. Sub-topics of the session were often based on children's discussions during that session. Table 3.1 presents the overview of each session, listing the topic, sub-topics, the number of children who participated in that session, and whether the sketching was part of the activity.

Recruitment

This study was in partnership with a public library, and the library staff helped recruit participants by posting the project on their official website. Interested patrons registered online via their library authorization. Once consent and assent forms were collected, the librarian shared the signed forms with the personal contact details of the participants with the researchers.

3.3.2 Data Collection

All sessions were online via the Zoom (https://zoom.us) and Jamboard (https://jamboard.com) platforms. Engaging children in an online CI environment has become increasingly important due to external factors such as the COVID-19 pandemic and the diversification and inclusion of children from diverse backgrounds (Lee et al., 2021; Korte et al., 2021). There are benefits and challenges in conducting online CI sessions with children (Constantin et al., 2021; Fails et al., 2022). For instance, research recommends no more than two children per adult in the online CI sessions due to unforeseeable disruptions that may require sudden attention (Constantin et al., 2021). As a result, our number of 5 children with 3 adults made it easier to navigate the online dynamics and technical issues. Additionally, the children participating in this study were familiar with the Zoom and Jamboard features because of their online schooling experiences. Limiting the platforms to those familiar to the children helped researchers focus on the design activities instead of scaffolding the use of novel digital applications.

In addition to video recordings of sessions, observation notes and artifacts developed during the session were collected. Members did brainstorming and ideation via shared Jamboard slides; they also supported data collection of discussion notes and sketches. The first author created a new Jamboard for each session and shared it with the club members at the beginning so everyone could add their input simultaneously during the session. After each session, the first author converted these Jamboard into PDFs for the data records.

3.3.3 Data Analysis

All session data was transcribed, combining the Jamboard PDFs with video recordings. Then transcripts were imported into the qualitative analysis software MAXQDA with respective video recordings for coding purposes, allowing easier video reference in case of lack of clarity. The study team comprises four researchers with expertise in design, STEM, and formal and informal learning contexts. To leverage the expertise of different researchers, the first author met weekly with team members throughout the program planning, data collection, and analysis processes. During these weekly meetings, the team would review the plan for the next session, examine raw or coded data, and resolve differences in interpretation by revisiting examples from the data. Although data are coded solely by the first author, the study team reviewed the approaches to collecting and analyzing the data weekly. These reviews and discussions increased the reliability and transferability of results.

The first author did a round of open coding on the data to get familiarized and sensitized to the data and shared different threads emerging from the data with the study team. Then, the team collectively decided to focus on the sketching experiences of children in the program. The first author selected excerpts of data focused on sketching experiences and shared the snippets with the study team. The study team discussions and background knowledge of the literature on children drawing and sketching in design activities guided the first author through a second round of coding on the data, during which several themes emerged, including 'labeling while sketching,' 'learning while sharing,' and 'experience sharing via sketches.' These emerging codes formed the basis of the codebook developed by the study team to answer the study's research questions. Then, the first author applied focused coding using the codebook developed by the study team. Next, axial thematic coding was applied, addressing two main themes: 1) *Information that resides in children's sketches* and 2) *Learning opportunities while engaging in sketching activity*.

<u>3.4 Findings</u>

Our findings are organized by themes and sub-themes that emerged from the data in response to our research questions. We define each (sub)theme and provide a corresponding illustrative example.

3.4.1 Information sharing via sketches

How do children share information via their sketches in a design activity? We found that children's sketches contain information about their *expectations, experiences*, *beliefs*, and *knowledge* about their topic of interest.

Expectations Sharing

Children share information about their expectations via their sketches. *Expectation sharing* refers to incidences where children, via their sketches, share what they expect will or should happen. For instance, in session 3, children were prompted to individually sketch a potential solution to one of the problems discussed in session 2 (Table 3.1). In Nora's (age 10) potential solution to overcome shyness problems among children, she drew two sketches illustrating different scenarios which reflected her expectations. In her first sketch, she wrote, "teacher telling students to try to play together" with illustration, and her second sketch showed children from different houses meeting after school. Nora drew these sketches on sticky notes, which she shared via email with the researcher to upload on the Jamboard shared with the team. When she presented her sketches to the team, she explained that children need adults' encouragement and support to overcome shy behavior. This information suggests Nora expects adults to be directly involved in supporting shy children in encouraging them to interact with others. This example demonstrates how information from children's sketches can be helpful for understanding their needs in the broader contexts of their lives, which can sometimes be challenging to gather via direct communication, especially if children are shy.

Experience Sharing

We found that children share information about their personal experiences via their sketches. *Experience sharing* refers to information where children share personal experiences from their daily lives in their sketches or while presenting their sketch by referencing how their sketch relates to their experiences. For example, Anna's (9) sketched a stress ball as her potential solution for overcoming shyness. While presenting her sketch, she shared that a stress ball might help shy children during social interactions, as she personally found it helpful in such scenarios. She added, "*when I squeeze down the stress ball it feels like I'm just squeezing out like all my worries*." Anna's description suggests that her personal experience inspired her sketches, and she was able to share her personal experience with the group through her sketch. This example illuminates how children's descriptions situate their sketches in the broader contexts of their lives. It also clarifies how children's sketches can empower them to reflect on and resolve their past experiences – a useful strategy for better understanding and designing with or for children.

Belief Sharing

We found that children share information about their beliefs via sketches. *Belief sharing* refers to incidents where children's sketches reflect their personal beliefs. For example, during session 3, Bella (11) drew a sketch illustrating a signpost next to a child on a crosswalk crossing the road in her potential solution to the problem of children breaking the traffic rules. Her signpost said, "*Look out for cars, or you can explain yourself in court*." While presenting her sketch to the group, she emphasized that the signpost was critical to her solution. She added, "*Usually, threatening people make them listen best. I've noticed that a lot. Like in the news threatening people is what helps them like that's technically what laws are*." Bella's sketch and presentation reflect her belief that threatening people can help them to follow the rules. Also, her explanation indicates that her beliefs are formed based on her broader life experiences, such as watching the news. This example suggests that children's sketches reflect information about their beliefs, and their descriptions of the sketches may reveal information about the sources from which their beliefs are forming. Such data highlights can be useful for researchers to understand the broader contexts of youth lives and how they shape beliefs in interaction with various tools, such as news in the media.

Knowledge Sharing

Children also shared knowledge with the group via their sketches. *Knowledge sharing* refers to children sharing information about how they think certain things work. For example, during session 9, children were prompted to sketch the mental model of their favorite STEM product, illustrating their understanding of how it works. During this sketching activity, each child sketched individually. The products children decided to draw were considerably diverse - Computer, Satellite, Cerebrum (part of the brain), and Trash Can – and children included annotations about these products' mechanisms and functionality. During their presentation of these sketches, children shared their knowledge of what they knew about these products and asked each other questions about what they knew or felt about them. This example demonstrates that sketches of children's mental models contain information about what they think about how certain things work, which can be a good starting point for researchers to get children's input on the design of products within their interest. Additionally, these forms of information can help encourage them to explore more details about these products and build their knowledge within their interest areas, which can help them develop design skills such as inquiry and observation.

3.4.2 Learning while sketching

What learning opportunities occur when children engage in interest-driven sketching activities? We found that during the sessions, children were engaged in multiple learning opportunities about sketching, such as *labeling sketches*, *building on ideas while designing, sketching in collaboration*, and *innovating ideas collaboratively*, all of which helped them develop their designer skillset. These learning opportunities are discussed in this section with respective examples.

Labeling Sketches

We found that while engaged in a sketching activity, children began to recognize that labeling in sketching is important. *Labeling sketches* refers to the label given to different components of sketches by children. For example: during session 1, children were asked to sketch their favorite technology-based product using the tools in Jamboard. Their initial drawings did not include any labels (See Figure 3.1). The children drew sketches simultaneously on a Jamboard page shared with the design team. Later, they presented their sketches to the team. While Nora (10) presented her sketch, Anna (9) asked her what a particular 'dot' represented. The researcher used this opportunity to suggest the importance of labeling sketches, after which all children started to label their sketches (See Figure 3.1).

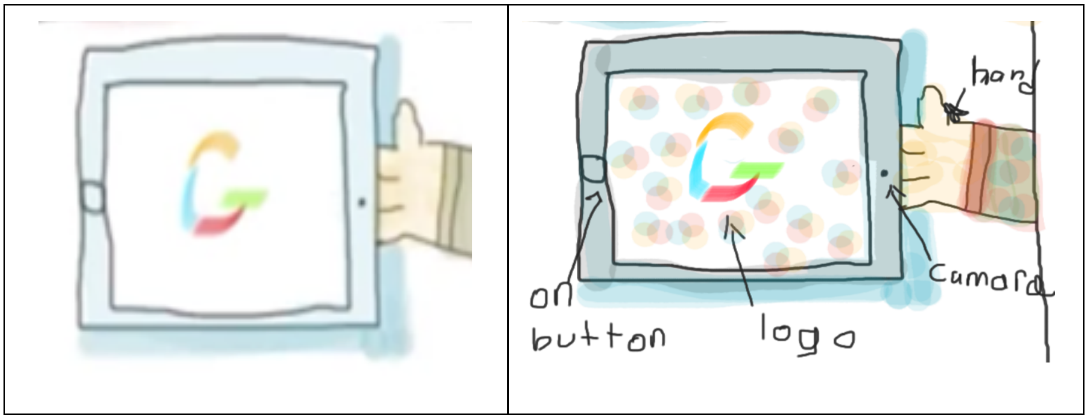

Figure 3. 1: Unlabeled (Left) and Labeled (Right) version of Nora's Sketches

The transitions from unlabeled sketches to labeled ones occurred quickly – within the first session – and children continued this practice in later sessions. We found labeling helped them communicate their ideas and made sketching easier for them. For instance, without labels, drawing a stress ball that looks different from other kinds of balls is difficult. However, drawing a circle and t writing *a stress ball* allowed Anna to convey her idea easily. This example suggests labeling helps children to express design ideas that are difficult to express via sketching alone. The use of labels by children can be useful information for researchers to better scaffold children's sketching experiences in design contexts and highlight the affordance of sketching to communicate and preserve ideas.

Building on Ideas

We found that sketches provide a situated artifact for children to build on each other's ideas. *Building on ideas* refers to moments in sketching activities when children offer ideas related to the sketch or connect multiple ideas to advance the idea represented in the sketch. We observed this affordance of sketching, particularly during the sketch presentation and follow-up discussion. Children used the sticky notes feature of Jamboard to annotate and build on ideas represented in sketches all at once (See Figure 3.2 for an annotated version of Nora's sketch, described in a previous section). Once everyone added their ideas using sticky notes on the sketch, they took turns verbally explaining the connection of their ideas with what already existed in the sketch. For example, after Nora's (10) sketch presentation, the group annotated her sketch. First, Bella (11) added the idea of an 'icebreaker game,' and Anna (9) added 'shared habits' (See Figure 3.2). Then, Bella connected these ideas by suggesting that shared habits could be a part of the icebreaker games.

Extending on Bella's suggestion, Anna said that in some ice-breaking games, people asked about standard stuff to get to know each other likeness, and to capture this idea, she added a sticky note stating, '20 questions common stuff' (See Figure 3.2). This example demonstrates that the sticky notes feature of Jamboard afforded children to elaborate upon each other's ideas during sketch-based discussions. This insight into children's sketching and use of sticky notes to elaborate upon each other's sketches builds upon prior CI techniques such as layered elaboration (Walsh, 2010). Annotated sketching techniques like this can scaffold children's sketching experiences in design contexts where the focus is to develop a product that includes multiple features to address different needs.

Figure 3. 2: Use of Sticky Notes by Children on Nora's Sketch

Sketching in Collaboration

We found children engaged in sketching together and asked questions of each other; these peer questions encouraged children to think deeper about their sketches. *Sketching in collaboration* refers to when two or more children members work together to draw a sketch. We observed that sketching in collaboration requires team members to brainstorm before beginning the sketches and explicitly discuss how to represent specific ideas visually. Through these discussions, children learned to resolve their conflicts and reach a consensus after exploring different options. For example, during session 7, children worked in pairs to improve the design of a low-tech product of their choice by incorporating technology into the design. Each pair was sent to its own Zoom room, and each group of children was facilitated by a researcher whose role was to observe the children’s interaction, address any questions children may have, and occasionally prompt children if they needed support on how to proceed.

Aaron (10) and Ryan (9) were paired together for this activity, and they began by verbally brainstorming different ideas for over 15 minutes. During their discussion, they were observed using many hand gestures to represent their thinking and come to a shared understanding visually. They discussed the pros and cons of different ideas before they decided to update the design of regular curtains by making smart curtains with a voice command feature. Before beginning their drawing, they deliberated about different curtain styles before selecting one that opens from the center outward.

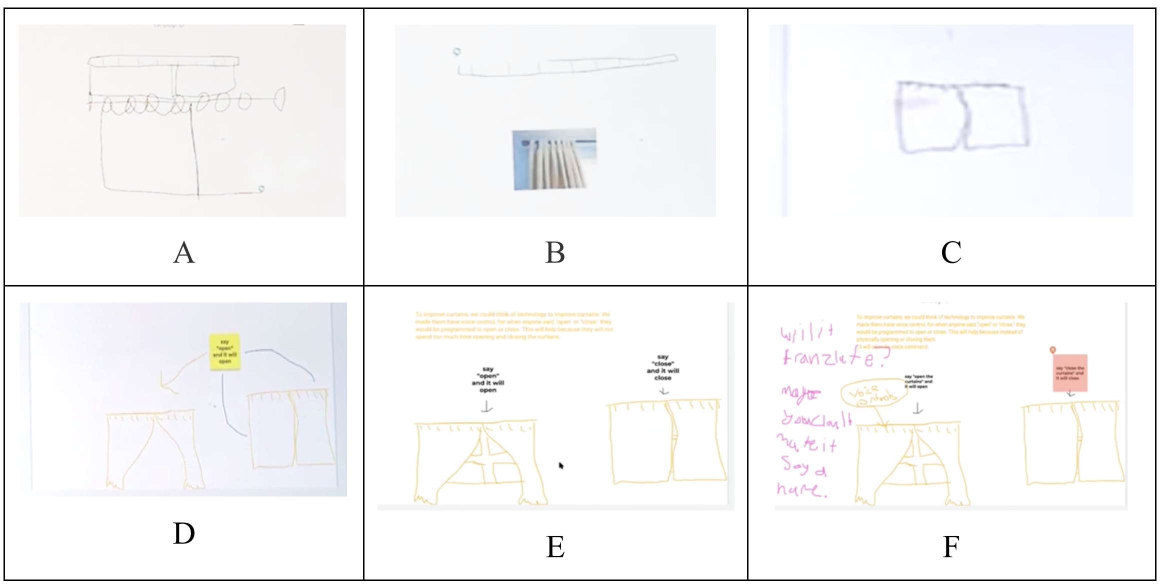

Figure 3. 3: Stages of Collaborative Sketching of Curtains

Figure 3.3 shows Aaron and Ryan’s different drawings during the sketching process. They both started drawing curtains separately, then they negotiated on the style of curtains, as their initial curtain designs were different: Ryan drew curtains with circular loops connecting them to a curtain rod, whereas Aaron drew curtain loops indicated via a smaller line in the rod (See Figure 3.3-A). To reach a shared consensus, Aaron downloaded an image from an Internet search and added it to their Jamboard (See Figure 3.3-B) to show how curtain loops look in the images. Based on the image, they illustrated loops as small lines instead of circles (See Figure 3.3-C). Then they decided to show two drawings: one with an open curtain and the other with a closed curtain (See Figure 3.3-D).

To add more details and make it realistic, they added a window visible when the curtains are opened (See Figure 3.3-E) and also added labels and descriptions. While they were presenting their sketch during suggestion time, Anna annotated their sketch with questions and suggestions (See Figure 3.3-F), which helped Aaron and Ryan to think in new ways. This example illustrates how collaborative sketching among children encourages them to think through different scenarios to reach a common consensus. Engaging in collaborative sketching is a crucial design skill for designers to learn - how to negotiate and reach a consensus based on discussing the pros and cons of different ideas. This example suggests that sketching helps develop such necessary collaborative design skills.

Innovating Ideas

We found that it was not easy in the beginning for children to sketch something they had never seen before, but throughout the SDC, they learned to represent their new ideas via sketches. Innovative ideas refer to the incidences where we observed children presenting novel ideas via sketches; they began to draw sketches of things they had not seen before but wanted to develop. We observed that throughout the club sessions, children moved from sketching existing products to designing new-to-them and often innovative products. For instance, during session 10, children were prompted to develop a product in their team related to the theme of connectedness. When the second time, children were involved in collaborative sketching using Jamboard and were well-versed in how to proceed.

As a team, Aaron (10) and Ryan (9) came up with the idea of Jarvis, smart glasses which allow people to make video calls (See Figure 3.4). When they started sketching the glasses, they discussed the functionality and mechanism of the video call feature. As their sketch demonstrates, “the top left side of the glasses shows a video of the person you are talking to, while the top right side has a video camera to capture what you are doing” (See Figure 3.4). This example illustrates that making sketches encourages children to think deeper about the functionality and mechanism of the products they are designing. This insight can be helpful for researchers to leverage the affordances of sketching in a design session, particularly for developing novel products based on children’s interests.

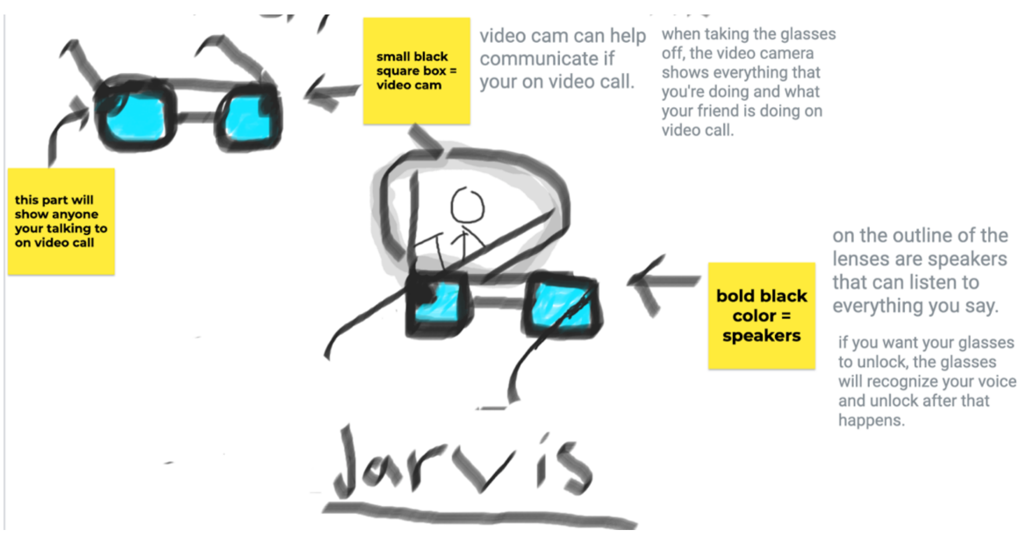

Figure 3. 4: Aaron and Ryan’s Sketch of Smart glasses

3.5 Discussion

Our findings suggest that children share information via sketches about their *expectations, experiences, beliefs*, and *knowledge* while participating in interest-driven design activities. Additionally, as children progressed through various sketching activities, we found them engaged in learning opportunities related to sketching, design, and collaboration, such as *labeling sketches, building on ideas, sketching in collaboration,* and *innovating ideas.*

Some of our findings reinforce claims made in prior literature about drawing as a unique mental development tool for children with which they can visually represent themselves (Brooks, 2005; Matthews, 2003). Our findings build upon this to suggest that attention to children's sketches can help us learn about topics of interest and contexts in their daily lives. Like Matthews' (2003) claim that the meaning behind children's use of certain marks and shapes in their drawings can only be understood through their speech and actions, we found that children's verbal commentary gives insights into the meaning of their sketches. For instance, when presenting their sketches to their peers, children share the source of information and inspiration for their sketches, highlighting the everyday contexts in which children participate and situating their sketches within their personal experiences and interests. In particular, children include different kinds of information via their sketches, including expectations (what they expect to happen), experiences (how it relates to their daily life experiences), beliefs (scenarios they consider true), and knowledge (what they know about how specific things work). Such representational depth requires that children talk about their sketches so we can understand how they are representing their contexts and experiences.

Anning (2008) claimed that children find it challenging to see drawing as a tool for problem solving and its potential to help them to learn. Similarly, we observed that, early on, children found it challenging to see drawing as a tool to think about the solution to specific design problems. However, as the design sessions progressed, we found that children started to believe in the power of sketching to represent their ideas and solutions, which suggests that providing instructional support can help children use sketching as a problem-solving tool. Additionally, modeling and explaining the functions of different genres of drawing within different disciplines can help children understand the potential of drawing in learning (Anning, 2008). As described above, children adapted labeling into their sketching quickly with very little instructional support during the first sketching session. In some sketches, children included long and detailed text-based descriptions. We anticipate that such longer descriptions could be due to 1) children considering their visual representation as not sufficient to communicate the details of their idea; and 2) children struggling to represent the functionality of a thing using sketches (e.g., representing the movement of an object or user over time can be difficult).

Research on mental model integration suggests that drawing activities can help students to recognize and correct their misconceptions (Cooper et al., 2017; Nyachwaya et al., 2011). In a similar vein, we found children comparing their sketches with similar online images because they wanted their sketches to be more realistic. Later, researchers took the opportunity to encourage children to think about the differences beyond aesthetics by emphasizing the structural and functional aspects of sketching and design. This motivated children to understand the differences between their sketches and the images of products on a structural level, which suggests that providing instructional support to focus on the relations between their mental models and new content can benefit students (Cooper et al., 2017; Treagust & Duit, 2008). With instructional support and practice, children can use sketching to innovate ideas, just as we found children represent their innovative ideas via sketching.

Like prior research in design about sketching (Ainsworth et al., 2011; Buxton, 2010; Self, 2019; van der Lugt, 2002), we also observed in our design activities that sketching was vitally important for children to communicate and document their ideas. Specifically, in the exploration and idea generation phase of designing, it supported an efficient generation of various ideas, suggesting that children can benefit by using sketching to generate ideas. We found some similarities with prior work on practical strategies while engaged in CI with kids, such as Layered Elaboration (Walsh, 2010), similar to children annotating each other's sketches using sticky notes to ask questions and give suggestions to the sketcher. Although our findings show some similar results to prior research done on CI with children, the focus of our research on sketching in interest-driven CI makes it valuable for educators and designers interested in working with children to design technologies based on the topics of their interest.

As discussed above, our findings extend prior research from children's drawings to a more specific focus on sketching in design activities. Also, one of the unique contributions of our findings is that they are based on children's engagement in an online design environment focused on their interest-driven technological products.

Finally, we call upon the field to further research in this context and find whether children's sketching behaviors differ across sketching and design modalities.

3.5.1 Implications

Our findings suggest that children share different forms of information via their sketches, including expectations, experiences, beliefs, and knowledge. These findings mean that researchers can use children's sketch-based information to elucidate and discover their interest-driven topics within the broader context of their lives and use this knowledge to design better child-oriented technology. These insights can also help improve children sketching experiences during design.

Moreover, we found that engaging in interest-driven sketching activities can provide multiple learning opportunities for children. They develop their sketching skills, such as the visual representation of observation and ideas, which are crucial for designers. Providing instructional support can help children improve their sketching skills by, for example, adding labels to their sketches to increase the communicative value of sketches. Labeling can be incorporated simply by reminding children to label their sketches during design activities.

Furthermore, we found that children learn essential skills about design and sketching, such as building on ideas and innovation. Engaging in sketching accomplishes multiple goals, such as giving children a medium to represent their ideas and a tool to build on ideas and innovate. We found that children improved their sketching and collaborative skills through sketch-based discussions. Since sketching is a crucial design activity, expanding our understanding of how children experience and improve in sketching supports our ability to scaffold their engagement in design activities. Sketching has tantalizing implications for design education efforts with children and youth who may consider futures in design.

3.5.2 Limitations

We did not design the SDC project to investigate sketching development among children explicitly; participants may have drawn from experiences outside the SDC that are not reflected in our analysis. Nevertheless, our data paint a rich picture of the various sketches drawn by participants and the conversations about sketches that emerged in and across different design sessions making this study's findings viable. In addition, although we verbally asked children to share their name, age, gender, and interest with the group, we chose not to collect other demographic information (e.g., race/ethnicity) from participants to avoid asking invasive questions that may have prevented us from building rapport with the children. Finally, our exploratory study represents a small sample size, which limits the generalizability of the findings, even though the qualitative richness of the data collected and our findings are limited to online contexts. Further studies should address these limitations.

3.6 Conclusion

Our study provides insights into the information children share via sketching their contexts, including expectations, experiences, biases, beliefs, and knowledge. It also offers insights into how sketching helps children engage in multiple learning opportunities within an interest-driven design environment. Our findings suggest that sketching activities provide learning opportunities for children that help develop their design and collaboration skills. In particular, we recommend that designers examine children's sketches during CI, as it can give important insights into children's experiences. Finally, sketching is a powerful tool for researchers to learn about the broader contexts of their lives and support the design of new technological products for children.

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Chapter 4: Radical Constructivist Cooperative Inquiry Framework: Learning within Design

Abstract

The paper presents the Radical Constructivist Cooperative Inquiry (RCCI), a novel theoretical framework bringing together the foundations of Collaborative Inquiry and Radical Constructivism to understand and support children's learning in design activities. RCCI framework consists of six pillars - Child-centered, Dynamic, Iterative, Collaborative, Representation, and Outcomes. Based on RCCI, we suggest implications for scaffolding children's learning and provide illustrative examples from an empirical study. This theoretical paper contributes to the CCI field by providing theoretical grounding that designers and educators can use to improve children's learning in design experiences.

4.1 *Introduction and Motivation*

Learning is valuable in the field of Child-Computer Interaction (CCI) where children are engaged in technology design, but it needs more clarity and consistency (Christensen & West, 2018; DiSalvo, 2016; Eriksson et al., 2022). Most papers in CCI that reference learning "do not provide explicit theoretical grounding for aspects of learning in either the research design or result" (Eriksson et al., 2022, p. 60). A recent review of CCI literature highlighted two gaps in the field related to the theoretical framing of learning, "lack of solid theoretical grounding for learning and a lack of CCI-specific literature to which researchers can refer" to ground their design work with children (Eriksson et al., 2022, p. 60). On the other hand, the education field has rich theories of learning that can help researchers identify critical environmental choices (e.g., peers, tools, adult guidance) that support productive learning and identify powerful learning moments during the design process (DiSalvo, 2016). Therefore, the CCI research leverages the theories of learning from the field of education (Eriksson et al., 2022). In CCI literature, the theoretical positioning of learning in design with children is grounded in four positions: (1) Constructivist Theories, (2) Cognitive Theories, (3) Socio-cognitive Theories, and (4) Constructionism (Eriksson et al., 2022).

The relations between learning theories, models, and frameworks are scattered in the CCI literature. Therefore, there is a strong need to develop current learning theories to understand how to plan, execute, and evaluate learning through design activities with children (Antle & Hourcade, 2021; Eriksson et al., 2022). One theoretical view of learning aligns with CCI research approaches to design with children. However, it has yet to be explored in the field, i.e., Radical Constructivism (RC) proposed by Glasersfeld in the late 1970s. Therefore, in this paper, we focus on the synthesis of the evolution of Cooperative Inquiry (CI) (Druin, 1999) with the learning theory of Radical Constructivism (RC) (Glasersfeld, 1995).

To our knowledge, a framework based on a synthesis of learning theory with a design approach is not present in CCI literature, but it is timely as the increased use of the design approach in education is leading to the development of many new learning opportunities (DiSalvo, 2016; Eriksson et al., 2022). Consequently, we offer the

Radical Constructivist Cooperative Inquiry (RCCI) framework, which provides a novel theoretical grounding for understanding children learning experiences in design.

In the RCCI framework, we identify six pillars that manifest as equally important in both CI and RC, synthesize across those manifestations to develop a coherent alignment of approaches and describe the final version of each pillar within the RCCI framework. Based on our theoretical synthesis, we argue that children learn through design activities when it involves six pillars: Child-centered; Dynamic; Iterative; Collaborative; Representations; and Outcomes.

We illustrate each pillar of the RCCI with data from a design case study conducted with children aged 7–12 years. In collaboration with a public library, we conducted a series of STEM Design Club (SDC) episodes for four months to explore how children learn design practices while participating in design activities. For example, we observed that when sketching during their design work, children engaged in multiple learning opportunities, such as labeling sketches, building on ideas, sketching in collaboration, and innovating ideas (Paper 1, *this document*). This work motivated us to examine further children's learning to sketch within design activities using an established theory of learning, which led us to discover there is not yet an appropriate synthesis, despite the need for such a framework given the increased use of design in education (Eriksson et al., 2022).

This paper also considers how children learn while engaging in Distributed Co-Design (Walsh, 2012). Due to physical distancing restrictions imposed by the COVID-19 pandemic, there is a need realized to develop at-a-distance design approaches in the field of technology design by children (Kinnula & Iivari, 2021; Roumelioti et al., 2022).

Conducting at-a-distance design imposes extra layers of complexity, but it can also offer further opportunities (Constantin et al., 2021; Fails et al., 2022). Also, this paper examines children's learning in designing their interest-based things in a virtual SDC context. Thus, our RCCI framework supports learning in the distributed co-design process.

This paper contributes to the CCI field in three ways – 1) it establishes a theoretical understanding of children's learning experiences that occurs during design interaction from an RC perspective; 2) it provides an update to the conventional use of CI, which focuses on having children as equal partners in the main propose of designing better technologies for children to shift the use of design by children with the primary goal being children learning technical skills and having a critical stance toward technology; and 3) by utilizing RC, this paper provides legitimacy to CI activities in educational contexts that increasingly demand learning theories and frameworks. Broader adoption of CI in educational contexts may therefore benefit from this paper. The RCCI framework provides a valuable foundation for future researchers and instructional designers to support children's learning through design interactions.

4.2 Background Research

There is growing interest in CCI research examining learning benefits to children with their engagement in design (Eriksson et al., 2022; Giannakos et al., 2022; Korte et al., 2022). From the beginning of involving children throughout the design process in the development of technology intended for children, there was a strong desire to understand the learning benefits to participating children (Soloway et al., 1994). While establishing foundations of CI with children, Druin (1999) discussed design-centered learning benefits for children:

1. Improved understanding of the technology design process
2. Developed mutual respect among adults and children as equal partners in the designing process
3. Communication and collaboration as a team member
4. Improved technology skills and content knowledge

Expanding on Druin's work on CI, there is an emphasis on the social and emotional benefits to children with their participation in CI (Guha et al., 2010; McNally et al., 2017; Yip et al., 2013).

Design is manifest as a mutual learning process between children and adult designers (Simonsen & Robertson, 2013), and scholars have used various learning theories as analytical lenses to analyze children's interaction in design activities. For instance, Guha et al. (2010) used a sociocultural perspective, Bekker et al. (2015) used a constructivist learning approach to analyze children's learning within design processes, and Johnson et al. (Johnson et al., 2016) used a constructionist perspective to examine how to teach computing technology to children. Related work shows that engaging children in CI design activities helps to improve the design of technologies and has social, emotional, and cognitive benefits for children (Guha et al., 2010; McNally et al., 2017). Examining children's learning in the design processes is done by evaluating children's responses in questionnaires before and after design workshops (Kang et al., 2019; Pellegrino et al., 2021; Roumelioti et al., 2022). However, there is a distinct lack of frameworks that can identify learning during the design process without the use of external assessment tools (e.g., questionnaires), which further motivated us to propose this synthesized framework.

More recently, design has become an important element of the means (the process) and the end (the product) while working with children (Bekker et al., 2015; Christensen & West, 2018). Several researchers in technology-enhanced learning moved from design with children to design by children to emphasize the learning benefits or empowerment opportunities for children (Iversen et al., 2018; Kinnula & Iivari, 2021; Södergren & Mechelen, 2019). While the focus of design with children was on making children equal partners in the design process, the design by children tends to focus on children's interests, authentic tasks, and informal virtual environments. Design by children includes the integration of design with making, digital fabrication, and computational thinking to support them in developing reflexivity toward the role of technology in their lives and society at large (Eriksson et al., 2019; Iivari & Kinnula, 2018; Iversen et al., 2018). So far, the focus of design by children is on assessing engagement and learning programming skills in the design of smart technologies (Cunningham et al., 2021; Roumelioti et al., 2022). Also, gaining an understanding of the value of technology for society at an early age is expected to help attract younger generations to Science, Technology, Engineering, and Mathematics (STEM) subjects in their future education and career choices, a goal of increasing importance worldwide (Ardies et al., 2021; Sheehan et al., 2018).

There are calls to provide a theoretical grounding for learning in both the research design and results in the field of CCI (Antle & Hourcade, 2021; DiSalvo, 2016; Eriksson et al., 2022; Giannakos, 2022). These calls motivated us to develop a comprehensive framework for understanding children's learning during design activities, using CI and RC as the guiding foundations of the RCCI framework. The following related work discusses our rationale for choosing CI and RC before presenting and illustrating our synthesized pillars.

4.2.1 Foundations of Cooperative Inquiry

Druin (1999) developed cooperative inquiry (CI), a research approach that enables children to participate in the research and design process throughout the experience. While CI is unique in many aspects due to child involvement, its roots are grounded in HCI research with theories of participatory design, contextual inquiry, activity theory, and situated action (Druin, 1999). A combination of multiple techniques forms the methodology of CI, such as contextual inquiry (observation), participatory design (collaboration, prototyping), technology immersion, and team reflections (Druin, 1999; Druin, 2002). Children participate in the CI design process as equal partners, and their participation supports the learning of various 21st-century skills among children, such as enhanced collaboration, problem solving, creativity, and critical thinking (Druin, 1999; Guha et al., 2013; Yip et al., 2013).

Over the last two decades, CI has evolved in CCI literature. Scholars emphasize the importance of supporting children to actively participate in technology design through a mutual learning process (Iversen et al., 2017). Some approaches suggest involving the children throughout the design process as 'co-researcher' and 'protagonist' (Iversen et al., 2017; Van Doorn et al., 2016). Our approach to CI aligns with the child-as-protagonist approach, which emphasizes allowing children to complete the design process (Iversen et al., 2017). Providing children with the leading agent role in driving the design process can support them in developing design skills and reflecting on the technology's role in their life (Iversen et al., 2017).

Enabling children to make things can empower them with technical skills and a critical stance toward technology (Kanafi et al., 2021; Kinnula & Iivari et al., 2021). Therefore, there is a shift from giving equal voices to children in the design process to promoting design by children to emphasize the learning benefits of design environments (Gennari et al., 2022; Gennari et al., 2017; Pellegrino et al., 2021; Roumelioti et al., 2022). As two instances of implementing processes that reflect design-by-children, Gennari et al. (2022) and Melonio et al. (2020) began by familiarizing children with smart technologies and encouraging them to imagine and conceptualize their technologies.

To summarize, we begin our theoretical exploration of design with children from the foundational work of CI by Druin (1999), which was the first call to involve children in the technology design process as equal partners and traced its evolution in the form of children as lead agents in design which emphasize the use of design to engage children in learning technical skills and having a critical stance toward technology.

4.2.2 Foundations of Radical Constructivism

Radical constructivism (RC) is a theory of learning proposed by Glasersfeld that was built upon Piagetian constructivism, in part as a response to widespread misuse of Piaget's works - in particular, researchers accepted the idea that learners construct knowledge as they learn but ignored the fact that the very definition of 'knowledge' had changed as well (Glasersfeld, 2013). RC differs from the conventional views of cognitive constructivism, social constructivism, and constructivism because it does not emphasize knowledge lying inside an individual's cognitive stages or outside in the community to be discovered by the learners; instead, it promotes the idea that knowledge is the interpretation of individuals' experiences in their environment. Glasersfeld called his model 'radical' in order to distinguish it from more conventional interpretations of constructivism, and described the two fundamental principles (Glasersfeld, 1995; p. 18):

- *knowledge is not passively received but built up by the cognizing subject; and*
- *the function of cognition is adaptive and serves the organization of the experiential world, not the discovery of ontological reality.*

Based on these principles, RC entails a radical rebuilding of knowledge, truth, communication, and understanding; it is impossible to assimilate into any traditional epistemology (Glasersfeld, 2014; Glasersfeld, 2013). Instead, it replaces the notion of 'truth' (and seeking a 'true' representation of an independent reality) with the notion of 'viability' within the subjects' experiential world. Consequently, it refuses all metaphysical commitments to only one possible thinking model about our world together. Instead, it replaces it with the conceptualization of the world we construct as living subjects. RC suggests that there is no ultimate truth or reality to be discovered by the learners as it is impossible to verify knowledge beyond one's interpretation of their experience. According to the RC perspective, learning happens while inventing things to improve our functioning in the environment as a coherent and productive way of thinking that helps to deal with the fundamentally inexplicable world of our experience.

As RC was being developed in the late 1970s, a new methodology was being adopted by scholars in the United States to understand children's ways of learning and knowing: the teaching experiment (Steffe & Thompson, 2000; Glasersfeld, 2013). Steffe and Thompson's (2000) foundational article, published decades later, outlines the development, purpose, and protocol for conducting teaching experiments (TEs). They define TEs as a sequence of episodes, including a teacher/facilitator, one or more students, a 'witness' to challenge or corroborate the teacher/facilitator's understandings, and a record of each episode. These records are used by the teacher/facilitator and witness to prepare for the following episodes in the TE's sequence and analyze the overall arc of the completed TE.

A key component of TEs is that the researchers (e.g., the teacher/facilitator and witness) formulate hypotheses to test during and between each episode, using the students' language and actions as evidence for or against the hypotheses – and adapting the TE accordingly. In such a way, the students guide the course of the individual episodes and the TE through their engagement and learning while the researchers seek to be responsive to the directions indicated by the students. This approach requires researchers not to hold fast to a specific way of learning or knowing but remain open to unforeseen directions and responses by and between the students. TEs involve long-term interactions between the researcher(s) and a child or group of children through a series of teaching episodes and occasional clinical interviews (anywhere between 6 weeks to 2 years) as an observational technique (Cobb & Steffe, 2011). Lastly, TEs are not a prescribed methodology but rather guidelines organized around RC to best understand how students learn and reason, much as CI is organized around the design process to understand how children's involvement in the design process.

4.3 Data Context: STEM Design Club

To explore children's interest-driven STEM design experiences in an informal learning context, a team of researchers from the University of Maryland organized the STEM Design Club [SDC] in collaboration with the Clifton Park-Halfmoon Public Library – New York. The SDC aimed to engage children in interest-driven design activities and increase their understanding of the societal relevance of designing modern technologies, aiming to increase their interests in STEM subjects and careers. The episodes of SDC were organized based on an integrated view of CI (Druin, 1999; Druin, 2002) and RC (Glasersfeld, 2013) perspectives and a series of 11 design episodes over four months.

Table 4. 1: An overview of SDC Design Episodes

Episode	Topic	Sub-topics
1	Introduction to activities and tools	What is design?; Who designs?; How do products get designed?; Children Interests; Jamboard; Brainstorming; Sticky Notes
2	Problems faced by children	Being on screen for too long; Lack of confidence; Shyness; Stage fever; Nervousness; Breaking rules; Bully in schools; Cyberbullying
3	Potential technology-based solution to children's problems	Social time within and after school hours; Collectables for reducing anxiety; Security cameras on school campus and roads; Game; Personalized device
4	Games as products	Process of Game Design; Different kind of games; Game mechanics
5	Card games	Observing game mechanics while playing game of SETS; Re-mixing SETS mechanics by adding more cards and shapes; Testing the re-mix version of SET
6	Digital Games	Game elements - Objective; Constraints; Surprise; Strategy; Fun
7	STEM Day	STEM influence in daily life of children; Self-cleaning version of photo-copier/printer; Smart backpack with voice control; Smart curtains
8	STEM Design Toolkit	Measurement toolkit; Do It Yourself (DIY) Metal Box; Math Toolbox
9	Mental Models	Computer; Trash Can; Cerebrum; Satellites

10	Technology Tools	Smart eyeglasses; App to connect people who speak different languages
11	Presentation and Reflection	Games; Designing technology based products; Toolkits

The first author acted as the primary facilitator and led each episode with specific topics, prompts, and ill-structured, meaningful, and novel tasks in the club (Iversen et al., 2017). Each week's plan was developed specifically to follow the previous week's activities (for more details, see Paper 1, *this document*). The research team continuously developed, evaluated, and refined the episodes based on interpreting children's experiences (Iversen et al., 2017). Table 1 shows a brief overview of each episode. The first author planned the topics based on the children's responses in the prior week, while the sub-topics emerged from children's responses and actions during the episode.

Two other adults – one librarian and one researcher – assisted the lead researcher in organizing the episodes and attended throughout as witnesses and occasional participants. The duration of each episode was 90 min (but sometimes ran over because children were excited to share or present their work with the group). The children were new to the designing process and additionally limited to experiencing this process in the virtual design environment.

4.3.1 Participants

The library staff recruited participants by posting the SDC project on their official website. Interested patrons registered online via their library authorization. Once consent and assent forms were collected, the librarian shared the signed forms with the personal contact details of the participants with the researchers.

The SDC project was a collaboration between a public library and a research team examining children's learning experiences in an informal STEM design environment. Following CI, participation of up to 10 children ages 7-12 years. The research team created details of the project with library staff. After approval from the University of Maryland IRB, the library advertised the project on its website, and the library staff coordinated the recruitment of children via their website. Although ten children were registered, only 5 attended the SDC episodes; others opted out due to time conflicts. Five children – Anna (age 9, Female), Bella (11, Female), Nora (10, Female), Aaron (10, Male), and Ryan (9, Male), participated in the episodes over the four-month study.

After getting consent and assent forms signed by the enrolled participants, the librarian shared the basic demographic details (Age & Gender) and signed consent forms of the five participants. No incentives were offered to participants due to the library policies.

4.4 Methodology

This study derives from the SDC research project developed as a Research through Design approach (Zimmerman & Forlizzi, 2014). Previously, we presented a thorough account of the SDC and described how multiple learning opportunities might occur when children sketch during the designing process (Paper 1, *this document*). Here, we use the SDC case study to illustrate how the RCCI framework supports children's learning in informal design contexts and how it can be utilized in learning about design.

4.4.1 Empirical Data Collection and Analysis

Episodes were conducted and recorded online using Zoom (https://zoom.us) (due to COVID restrictions), and Jamboard (https://jamboard.com) was used to conduct brainstorming and ideation. Our data consisted of video recordings (almost 17 hours), observation notes taken by researchers, Jamboard data, and all the artifacts (e.g., sketches) developed by children during the episodes. During the planning, data collection, and empirical analysis of the SDC project, the first author met weekly with team members throughout the program. During these weekly meetings, the research team would go through the plan for the next episode together, examine raw or coded data and resolve differences in interpretation by revisiting examples from the data. The results of the empirical analysis are further described in the article, Children Learning to Sketch: Sketching to Learn (Paper 1, *this document*). The focus of this paper is to provide a theoretical grounding of learning in design, synthesizing the foundations of CI and RC. Therefore, we provided limited details about the structure and organization of the SDC study (for more details, refer to Paper 1, *this document*).

4.4.2 Theoretical Synthesis

During the empirical analysis, we discovered a desire and need for a framework that could better reveal the process of learning design in each episode. Consequently, we undertook six-month weekly meetings to develop the RCCI framework. This synthesis process occurred through revisiting the foundational literature on RC and CI and tracing its evolution to and interpretation in the present literature. We found six pillars vital to each SDC session, although often instantiated differently (See Table 4.2). For instance, the pillar 'Iterative' was developed to emphasize the iterative nature of children's learning in RC (Glasersfeld, 2013) and the iterative nature of the design process in CI (Druin, 2002). Here, we describe each pillar in more detail, with specific examples from the SDC data.

Table 4. 2: Pillars of the RCCI with corresponding information from CI & RC.

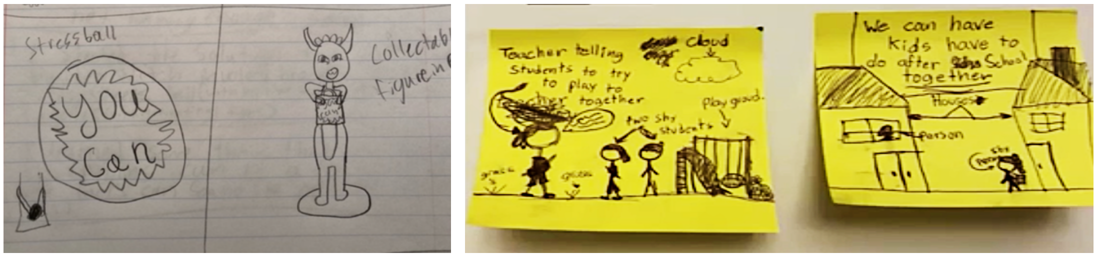
Pillars (RCCI)	Cooperative Inquiry (CI)	Radical Constructivism (RC)
Child-centered	Children are decision-makers about what they do (Druin, 1999). The process is arranged primarily to help children develop their design competence and ability to reflect on the role of technology (Iversen et al., 2017).	Situations presented to the children contain problems they might have encountered in school (Glasersfeld, 2013). The children's untutored individual approach to solving problems is more important than the solution (Glasersfeld, 2013).
Iterative	Iterative low-tech prototyping offers a concrete way for children to discuss ideas (Druin, 1999). Iterations occur within and between each of the activities (Iversen et al., 2017).	Learning is an iterative process (Cobb & Steffe, 2011). Learning is a process that must be viewed as a kind of ideal state that is never achieved (Glasersfeld, 2014).
Collaborative	Members with diverse ages, disciplines, and experience collaborate among teams (Druin, 1999). Collaborations promote opportunities for team members to reflect on their actions during the process (Druin, 1999).	The function of cognition is adaptive and serves the organization of the experiential world (Glasersfeld, 2013). After every episode, adult team members review what happened until they can agree on an interpretation (Cobb & Steffe, 2011).
Dynamic	Adults scaffold the process of design for children by asking questions to inspire and guide them for reflection (Druin, 1999). Group dynamics among the children (Mechelen et al., 2019).	The process of passage from one state of knowledge to another is dynamic (Cobb & Steffe, 2011). The episode does not proceed along a fixed and preconceived plan, but the investigator has to invent it step by step according to what the child says or does (Glasersfeld, 2013).
Representations	Prototyping offers a concrete way to discuss ideas. Documentation and representation of ideas. (Druin, 1999).	The dual use of the term representation; internal representations located in students' heads and external representations located in the environment (Cobb et al., 1992). Materials help students to explicitly negotiate their differing interpretations (Cobb et al., 1992).
Outcomes	The development of technology and learning of team members from their engagement in the designing process is critical (Druin, 1999). Children's insights into design and reflective stance toward digital technology in their life (Iversen et al., 2017).	The conceptual progress made by the small number of children who participated in it (Cobb & Steffe, 2011). Building theoretical models for understanding children's conceptual development (Cobb & Steffe, 2011).

4.5 Findings

In this section, we share examples of each pillar as they manifested explicitly in the SDC, highlighting the connections between our data and the six pillars. We then follow that by describing RCCI at a more theoretical level and how each pillar is more broadly composed of RC and CI.

4.5.1 Child-centered

Child-centered is the most prominent component of all the SDC episodes, as listed in Table 4.1. Each episode topic was planned based on children's responses in the previous episode (except episode 1, which was introductory, and episode 7, which was STEM Day), and the sub-topics were determined by the children's ongoing design and reactions. For instance, episode 2 involved brainstorming on problems faced by children – Anna shared her problem of "nervousness" and "lack of confidence," and Nora shared her problem of "being shy." During episode 3, children were encouraged to develop solutions for their problem – Anna proposed multiple solutions, including using a stress ball and collectable figures. Nora proposed the solution of organized social time within and after school hours as illustrated in their sketches (See Figure 4.1). Likewise, all the episodes centered on children's interests, needs, problems, and solutions.



Anna's Sketch **Nora's Sketch**

Figure 4. 1: Children's Sketches from the SDC Episode 3

4.5.2 Dynamic

Dynamic entails a variety of interactions, such as child-child, child-adult, and child-resources, and occurs at multiple scales. While the teacher/facilitator proposed each topic by asking an open question at the beginning of each episode, the children decided on the sub-topics – such as what design problem they wanted to work on and how to solve it. In other words, the children guide the broader dynamic nature of the overall activities in the episodes. At a smaller grain size, dynamic interactions were guided by the team values mapped out during the first episode by the participating children – which included kindness, empathy, patience, helping each other, working as a team, and trying. Within these guidelines, other smaller moments of dynamic contributions regularly occurred.

Adults also contributed to the dynamism of each episode by structuring the activity and occasionally asking children questions to probe their thinking and reasoning. However, adults did not indicate 'correctness' or explicitly encourage any design idea or paired solution offered by the children but instead merely encouraged certain design practices. For example, as discussed earlier, Anna proposed a potential solution to use a stress ball to overcome her nervousness problem. While presenting her solution, she shared that a stress ball might help shy children during social interactions, as she found it helpful in such scenarios (See Figure 4.1). She added, “when I squeeze down the stress ball it feels like I’m just squeezing out like all my worries.” Her solution contributes to the dynamic nature of the episode, as it provides the grounding for other children’s responses sharing how they manage their nervousness and contributing to the ongoing dynamism.

4.5.3 Iterative

Iterative stands for the iterative nature of design and the learning process. The researchers iteratively designed SDC episodes based on the student’s responses between and within each episode. Also, the activities in the episodes involved engaging the students in iterative nature of design, such as brainstorming a topic, defining the problems, discovering solutions, presenting solutions to the group, incorporating feedback, and developing ideas. The episodes involved teaching children the benefits of reflecting and revisiting the design ideas individually and collaboratively to develop the solutions. For example, the children’s sketches were a situated artifact for children to reflect on, use to communicate, and build on each other’s design ideas.

Jamboard to annotate while discussing sketches, as children offered to connect multiple ideas to advance the ideas represented in the sketch (Paper 1, *this document*). For example, after Nora presented her sketch about including shy children in organized social activities, the group provided feedback discussing why and how her solution might be improved. Bella said, “I like it, because it’s like people collaborating together…it might not work during COVID”. Adding to the discussion, Anna said, “I really think the first idea [within school hours] would be nice. I like the first idea better than the second idea [after school] because I'm usually most like students are too busy after school to sign up for anything… the teacher could just give them a game to play....like they could play like icebreaker games…see if they have stuff in common". Likewise, other children shared their feedback. Finally, they annotated Nora's sketch with sticky notes (See Figure 4.2), engaging in the form of what CI terms layered elaboration (Walsh et al., 2012).

Figure 4. 2: Annotated version of Nora's sketch

4.5.4 Collaborative

The Collaborative pillar captures the collaboration among children during the SDC episodes, as each episode entailed some individual and some collaboration activities. Children were encouraged to collaborate to brainstorm, discuss, evaluate, and develop solutions to their problems. We found that these collaborative activities helped children think about their ideas from different dimensions, improving their overall designed solutions. For instance, the example discussed in the previous section

– feedback and annotation on Nora's sketch - presents a moment of the collaborative efforts to improve Nora's proposed solutions (See Figure 4.2).

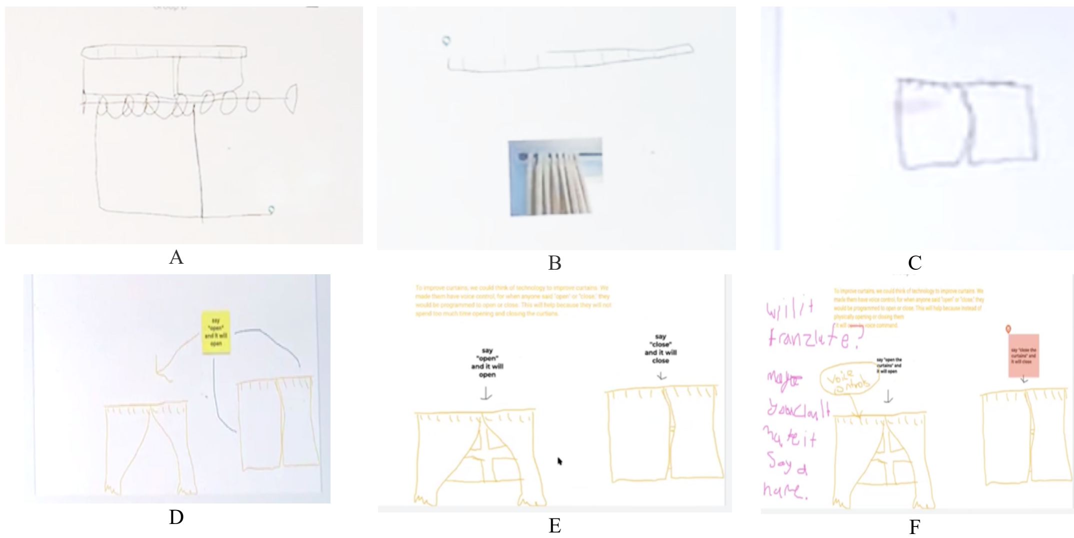


Figure 4. 3: Stages of Collaborative Sketching

Additionally, we found children asking questions of each other while collaborating, with these questions encouraging their peers to think deeper as well as explicitly discuss specific ideas. During such scenarios, children learned to resolve their conflicts and reach a consensus after exploring different options (Paper 1, *this document*). For instance, during Episode 7, Aaron and Ryan were paired to improve the tool's design using technology. They began by brainstorming different ideas for over 15 minutes and evaluating the pros and cons of different ideas. For instance, Aaron proposed the idea of an automated tissue box, "the one that brings tissues to you as you sneeze," and Ryan responded, "What if tissue box is near TV and someone in the TV sneezes that will be a problematic design." In the end, they decided to improve the curtains' design by adding the voice command feature. Then, when they presented their sketch, Anna asked them, "Will it translate voice commands in different languages?"

(See Figure 4.3-F), contributing to Aaron and Ryan's overall design process and product.

4.5.5 Representations

Representation entails the different modalities used to communicate information. By attending to multiple external representations used by children - such as verbal communication during formation and discussion, gestures used by children during the formation and discussion of sketches, and symbols used by children within sketches, we found that using such different representations helped children to communicate their ideas and feedback to each other effectively. For example, sometimes, children struggled to communicate their ideas verbally while collaborating and used hand gestures to illustrate them. They also regularly discussed using visual representations to understand each other's designs.

For instance, during the design of the smart curtains, Aaron and Ryan realized they were using different visual representations. Aaron drew spirals on the rod to represent loops in the curtains, while Ryan used a straight line (See Figure 4.3-A). Aaron downloaded an image from an Internet search to reach a shared consensus on curtain representation and determine a critical physical component of their design. He added it to their Jamboard (See Figure 4.3-B). Based on the image, they illustrated loops as small lines instead of circles (See Figure 4.3-C). They used this representation in both drawings: one representing an open curtain and the other with a closed curtain (See Figure 4.3-D). Then, for additional realism, they added a window visible when the curtains are opened (See Figure 4.3-E). In other words, Aaron and Ryan used visual representations as a critical part of their collaborative design process, indicating the different states of their final product (such as open or closed).

4.5.6 Outcomes

Outcomes entail the results and consequences of engaging in an experience, one of which was the growth and learning experienced by adults and children participating in the SDC. The researchers developed a richer understanding of children's experiences and expectations with technologies (e.g., children are facing problems of shyness and nervousness), identified diverse areas of interest among children (e.g., functioning of brain, satellite), and how to improve current practices of CI (e.g., how to support children in improving design skills such as sketching). In addition, the children learned about the design process (e.g., brainstorming, sketching), engaged in collaboration and communication in teams (e.g., using labeling in sketches), and developed more reflective stances towards technology in their life.

The SDC episodes provided multiple learning opportunities for children, including how to label sketches, build on ideas, sketch in collaboration, and innovate on ideas. These opportunities influenced the ongoing SDC and contributed to the individual children's outcomes. For example, during episode 1, children were asked to sketch their favorite technology-based product using the tools in Jamboard. In their initial drawings, they did not include any labels. The children drew sketches simultaneously on a Jamboard slide shared with the entire design team and then presented their sketches to the team. While Nora was presenting her sketch, Anna asked what a particular 'dot' represented. The researcher mentioned that labeling could be used in sketches, after which all the children started to label their sketches. The transitions from unlabeled sketches to labeled ones occurred quickly – within the first episode – and children continued this practice in later episodes. Labeling helped them communicate their ideas with each other and made sketching easier – for instance, without labels, a stress ball may look just like other kinds of balls. However, drawing a circle and writing a 'stress ball' allowed Anna to convey her idea more quickly and precisely (See Figure 4.1), and learning to label sketches during the design process became an outcome for the children.

4.6 Discussion: RCCI Framework

Here, we present the theoretical underpinnings that epitomize CI and RC and synthesize them into the RCCI framework. In order to avoid considerable repetition, we kept our earlier reviews of RC and CI brief. Finally, we expanded on both details by describing the similarities across the pillars.

Pillar 1: Child-centered

Based on RC, TEs are conducted with the focus on formulating an understanding of children's learning (Cobb & Steffe, 2011; Glasersfeld, 2013). During TEs, researchers present situations or problems for children to work on that they have or will encounter in school. During these interactions, the focus is on understanding children's untutored approaches to solving the problem. Following RC, researchers focus more on how children construct meaning rather than what meaning they construct (Cobb & Steffe, 2011). In particular, the technique of clinical interviewing supports the researcher in investigating the sequence of steps and structural patterns taken by children while constructing a concept.

During CI, children are decision-makers about what they do (Druin, 1999; Druin, 2002). The focus is on capturing children's exploratory experiences, as these experiences offer insights into what children want to do instead of what adults expect. There is an emphasis on observing children and hearing from children directly what they have to say by engaging with them on the development of 'low tech' prototypes. Although CI began with advocating the need to design with children for children, more recent work on a design by children emphasizes the role of child-as-protagonist by arranging the process primarily to help children develop their design competence and ability to reflect on the role of technology in their life (Iversen et al., 2017). In addition, researchers encourage children to carry out the complete design process, which consists of multiple activities - the design brief, contextual inquiry/field studies, brainstorming/ideation, prototyping/fabrication, argumentation/testing, and reflection (Druin, 1999; Iversen et al., 2017). The researcher's role was limited to scaffolding the design process to children throughout these activities.

RCCI synthesizes across RC and CI by leading children during a series of design interactions to understand children's learning behavior during the design process. While researchers may determine the overall goal – e.g., in the SDC, they determined the topic of 'The STEM Day' for episode 7 – the children decide what they do and how they do it. During the episode, children were encouraged to decide what problems they wanted to solve. Aaron and Ryan decided to make Smart Curtains as they had experienced problems manually opening curtains in their homes. Also, they decided how they wanted to improve the design of curtains – in this case, by adding a voice command feature. The researchers facilitated their learning – by introducing the idea of labeling design sketches, which helped them represent and communicate their ideas (Paper 1, *this document*).

Pillar 2: Dynamic

According to RC, the process of learning is dynamic (Cobb & Steffe, 2011). To study this process of dynamic passage from one state of knowledge to another in children, researchers create activities allowing them to observe children's interactions and make inferences about how they build up specific concepts (Glasersfeld, 2013). It does not involve teaching or curriculum in the conventional sense; activities presented to children contain problems they might have encountered in school. These activities enabled researchers to understand children's learning experiences by negotiating the initial conventions of their thinking (Cobb et al., 1992). However, TEs do not proceed along a fixed and preconceived plan, but researchers have to invent it step by step according to what the child says or does (Glasersfeld, 2013).

Although researchers establish the context, including the tools and any learning objectives, children interact with this established environment in their way. During this process of moving from one state of knowledge to another, what students do is of concern, but of more significant concern is how they do it, which is identified through dynamic indicators of learning (such as what a student's intentions were or how they used particular language in specific ways) (Cobb & Steffe, 2011; Glasersfeld, 2013). Therefore, even if the researchers come up with an overall goal (e.g., learning how to design) that guides their preparations and reactions, the overall path of the complete TE or even a single episode depends on the spontaneous actions and interactions of the children (Glasersfeld, 2013). CI emphasizes the dynamic nature of children's interactions. Planning is involved in the design episodes with children as equal partners, but the nature of these activities is exploratory rather than directive (Druin, 1999; Druin, 2002). For instance, during brainstorming, numerous ideas are explored with children, and then an area of focused interest is selected for children to pursue in more depth with prototyping. Technologically immersive environments are provided to children to observe what they can do with unique technology and time flexibility. Also, team reflections help capture design history, refocus efforts if necessary, and evaluate team processes. Although adults scaffold the design process for children by asking questions to inspire and guide them for reflection, it is ultimately on children to pursue the design process (Bekker et al., 2019). The group dynamics among the children influence their interactions and interpretations of their experiences (Mechelen et al., 2019).

Following RC and CI, RCCI emphasizes dynamic indicators of learning by focusing on how children interacted with the resources, material, tools, peers, and adults during the design process and how their learning get influenced by these interactions. Researchers plan overarching design themes (e.g., STEM) and design activities but do not control or direct children's behavior during these activities. For example, during the SDC, the researchers planned for each episode, but what happened during the episode was based on children's interests and experiences (e.g., designing a trash can).

Pillar 3: Iterative

RC claims learning is adaptive because cognitive equilibration is a kind of ideal state that is never achieved (Glasersfeld, 2014). According to RC, learning is an iterative process that involves continuous reflection. Researchers need to "continually make a conscious attempt to *see* both their own and the children's actions from the children's points of view" (Cobb & Steffe, 2011, p. 85). TEs allow researchers to test and, if necessary, revise their understanding of children's behavior in situ which is not feasible in analyses of fully collected data (Cobb & Steffe, 2011). Thus, in addition to the active role of children in shaping TEs, there is an emphasis on the active role of the researcher as a teacher in RC. Also, researchers help children to reflect on their activity from a distance as its object. Based on these reflections, iterations are made in the TE to follow children's learning.

During CI, prototyping is a critical activity for discussing design ideas. Using iterative low-tech prototyping offers a concrete way for children to discuss their design ideas (Druin, 1999). Adults encourage children to iterate different versions of their product design during low-tech prototyping (Druin, 1999). To support children engaging as protagonists, Iversen et al. (2017) proposed a circular model that illustrates design as an iterative process, as all design outcomes eventually lead to the formulation of new research problems. Moreover, it promotes iterations within and between each design activity to navigate through one's design project. It encourages children to reflect on their design process and designed products.

RCCI has researchers iterate on their episode plans as they reflect on children's learning, and children iterate between different versions of their design. After each episode with children in the SDC, researchers would reflect on what children did during the episode to prepare for the next episode. For example, episode 2 ended with children individually developing solutions as low-tech prototypes – sketches for the problem they identified. Based on this, the researcher planned episode 3 for children to reflect on the individually designed solutions – sketches - as a group and then iterate their solutions in smaller groups based on the insights of group reflections.

Pillar 4: Collaborative

According to RC, the function of cognition is adaptive and serves the organization of the experiential world (Glasersfeld, 2013). Adults can help children learn by providing an environment conducive to learning (Cobb & Steffe, 2011). However, adults' intervention does not determine children's learning; rather, children's interpretation of the adult's intervention determines their conceptual structures. Researchers learn about children's construction of knowledge based on a discussion of their interpretation of children's behavior (Cobb & Steffe, 2011; Glasersfeld, 2013). After every TE episode with children, research team members discuss their interpretation of children's behavior to understand children's conception of the activity and their knowledge. The research team reviews what happened until they can agree on an interpretation.

CI suggests collaboration among diverse ages and disciplines as design teams (Druin, 1999). Collaborations promote opportunities for children to reflect on their actions during the process (Bekker et al., 2015). Adults support children's group collaboration and scaffold their sense of ownership and legitimacy in the design process (Iversen et al., 2017). The researchers should be participant observers, talking naturally to children during the design process.

RCCI synthesizes across RC and CI by promoting collaborations at three levels: child-adult, child-child, and adult-adult. As illustrated by the planning structure of the

SDC, where children and researchers actively participated in the design episodes, researchers provided opportunities to children for peer collaboration. After each design episode, the research team collaborates to reflect on what happened and plan the design of the next episode.

Pillar 5: Representations

According to RC, a concept is a mental representation of a phenomenon that is stable enough to be represented (e.g., visualized or described) without relevant sensory-motor input (Glasersfeld, 2013). However, there is a dual use of the term 'representation': internal representations are located within the child, while external representations are in the environment (Cobb et al., 1992). External representations can include a variety of forms, including concrete materials that present known relationships among concepts but are also crucial aspects of an environment that promote the teacher and students to explicitly negotiate their differing interpretations as they engage in the activity. In particular, concrete representations include digital representations such as on Jamboard and can help students to negotiate their differing interpretations explicitly.

CI emphasizes using low-tech prototyping with children as it offers a concrete way to discuss design ideas (Druin, 1999). It also suggests selecting prototyping tools and materials based on the needs of the research area the team is exploring; the same material can be useful to explore one idea while limiting to explore of another idea (Iversen et al., 2017).

RCCI synthesizes across RC and CI and is compatible with other approaches to understanding learning that emphasize the crucial role of concrete representation –

manipulation of physical or digital tools - in the construction of knowledge (e.g., constructionism, embodied cognition, and representation fluency) (Paper & Harel, 1991; Roque & Tamashiro, 2022). In addition, there is an emphasis on capturing representational fluency to understand the embodied nature of learning (Simpson et al., 2021).

Pillar 6: Outcomes

According to RC, the primary outcome of the TE is the conceptual progress made by the children who participated in it (Cobb & Steffe, 2011). Secondarily, researchers use TEs to build models that are general enough to account for other children's conceptual progress but are also specific enough to account for a particular child's progress in a particular instructional setting. These seemingly contradictory outcomes can only be achieved by ensuring a dialectical interaction between the theoretical and empirical work, as we endeavor to do here.

According to CI, there are three outcomes of children's participation in the design process – 1) learning of team members from their engagement in the designing process, 2) improving technology design, and 3) crafting new design techniques to add to the CI approach (Druin, 1999; Druin, 2002; Walsh et al., 2013). Thus, children's learning outcomes should measure insights children gain into technology design and reflective stance towards technology in their life.

RCCI synthesizes across RC and CI by emphasizing understanding children's learning during design experiences. However, learning is embedded in the five pillars discussed above, mainly addressing "how" learning is happening rather than "what" learning. Therefore, it is crucial to understand "what" is getting learned by children, which is entails in the outcomes pillar. For example, the study of children's experiences in the SDC suggests that engaging in design provides them with multiple opportunities to learn about the affordances of sketching in design, including why to label and how to label sketches, collaboratively building on design ideas depicted in sketches (Paper 1, *this document*).

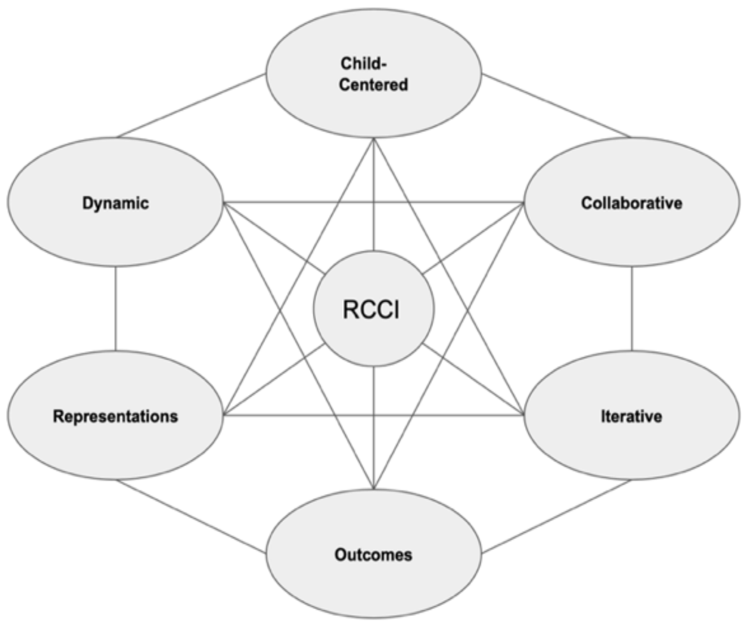


Figure 4. 4: The interplay between Six Pillars of the RCCI

To summarize, our discussion of the RCCI framework provides a pillar-by-pillar description of our synthesis of RC and CI (See Table 4.2). Our study identified six common pillars across RC and CI: namely, Child-centered, Dynamic, Iterative, Collaborative, Representations, and Outcomes. These pillars are intertwined in practice to provide a strong foundation for learning design theory (See Figure 4.4). These pillars suggest that RCCI brings the strength and history of RC to bear on understanding how children learn to design in CI contexts so that we can use RCCI to understand better, design, and implement such design learning experiences.

4.6.1 Implications

RCCI provides an update to conventional ways of making a cooperative inquiry with children where children's learning was a byproduct of their participation in the design activity versus the focus area. RCCI framework focuses on promoting children's learning through the design process, and learning is the byproduct of their participation in design. It argues for design activities to be child-centered, limiting the role of adults as facilitators of the process rather than equal partners. Hereby, a particularly powerful component of RCCI is that RC gives us the tools to examine learning in the process rather than just considering learning as summative or transfer based.

The RCCI framework provides a solid theoretical grounding for learning in the design process, as recently called for in the CCI literature (Antle & Hourcade, 2021; Eriksson et al., 2022). The six pillars of the RCCI framework provide insights into how learning can be interwoven throughout the planning, execution, and analysis process of design. We have illustrated how RCCI helps us understand the connections between learning and the designing process that holds significance to examining children learning during designing activities. A recent literature review regarding the role of learning theory in CCI has precisely highlighted the need to build novel associations between learning theories and design practices. Thus, the RCCI framework contributes by filling a recognized gap in the literature, and it holds the potential to strengthen the CCI community significantly, both in terms of research design and evaluation and thereby further developing current learning theories.

The roots of the RCCI framework are embedded in RC and CI; thus, it uniquely contributes to the field of design and education. On the one hand, RCCI provides a theoretical lens for design activities to support children's learning in the design process. On the other hand, it provides legitimacy to CI activities in educational contexts that increasingly demand learning theories and frameworks. Thus, broader adoption of design activities in educational contexts may benefit from the RCCI framework. On the other hand, the work provides a valuable foundation for future researchers and instructional designers to support children's learning through design interactions.

4.6.2 Limitations & Next Steps

RCCI is the first step towards developing a more robust perspective of learning in this field, as it identifies an established theory of learning that is commonly but only descriptively used in the CCI field. However, this work has some limitations, such as this theory is developed from a particular exploratory context, and different contexts and content could more richly nuance this theory. Also, there needs to be more exploration into the connections in Figure 4.4; filling out these connections is a ripe area for future research. For example, we consider the connection between Dynamic and Child-centered to be a quite promising area of investigation, as both RC and CI support the view that a child-centered context is naturally dynamic, as the situation adapts to the unexpected richness of children's actions and reasoning. In our future work, we will use the RCCI framework and methodologies to analyze the learning design process in detail.

4.7 Conclusion

The RCCI framework provides a solid theoretical foundation combining learning and design theories. The six pillars of RCCI - Child-centered, Dynamic, Iterative, Collaborative, Representations, and Outcomes - offer concrete components to consider while organizing future design-based learning experiences for children. Such experiences can help researchers to understand and improve interaction design for children. In addition, the children participating in such experiences will be empowered to engage with real-world design problems. The objective is to support children's learning as we develop an understanding of their design experiences to scaffold and support their development of 21st-century skills.

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Chapter 5: The Relationship between Sketching and Learning in Engineering Design

Abstract

Sketching is recognized as a crucial component of engineering design practices. However, it is unclear how we can support children in developing sketching skills in informal learning environments. To address this, we used a thematic analysis method to examine the sketching experiences of 14 children (ages 7-11 years) who participated in a MAKEngineering Project which aims to integrate Science, Technology, Engineering, and Mathematics (STEM) into the home environment. The findings show that children's sketches depict a wide variety of details about the design of their products, which guides them in building and improving their prototypes. Our findings imply that sketching engages children in learning about different design skills. Finally, we offer recommendations for educators to support children's learning about the use of sketching in STEM design. Finally, this study contributes empirically and theoretically to building knowledge about improving and sustaining design cycles by children in STEM learning contexts.

5.1 Introduction

Sketching plays a crucial role in improving the quality and novelty of ideas in the design process (Lewis & Sturdee, 2020; Sung et al., 2019) and engaging children in learning Science, Technology, Engineering, and Mathematics (STEM) (Ainsworth & Scheiter, 2021; Wu & Rau, 2019). Prior research claims that providing instructional support to children during STEM drawing activities can enhance their self-regulation processes (Wu & Rau, 2018; Zhang & Linn, 2011). The previous work on children's sketching experiences in interest-driven design activities suggests that attending to children's sketching can provide insights into children's design, collaboration, and communication skills (Paper 1, *this document*; Shokeen et al., 2023). Due to the benefits associated with the use of drawing in STEM research, there is a call for more research to focus on supporting students in developing drawing skills like STEM professionals, especially among middle-school students who are preparing to pursue STEM careers (Ainsworth & Scheiter, 2021; Schmidgall et al., 2020). We know little about how 'sketching' as a learning tool can be useful with children in STEM design environments (Paper 1, *this document*). In particular, there is still a lack of understanding supporting children's learning in STEM design (Paper 2, *this document*). Therefore, this empirical study aims to contribute to an understanding of children's learning and sketching experiences during engineering design by pursuing the research questions:

1) *How do children sketch during engineering design activities?*
2) *How do children participate in learning through sketching activities?*

Our empirical data are from the MAKEngineering Project, which aims to integrate STEM into the home environment by introducing and engaging families in the engineering design process. We performed this secondary analysis (Ruggiano &

Perry, 2019) on the video data from eleven families using an iterative and inductive thematic analysis approach (Braun & Clark, 2006; Saldaña, 2014). The details in children's sketches and their use of those sketches in the various design steps suggest that they engage in a range of learning experiences when they regularly modify, improve, and communicate their design while sketching. Through the results of this paper, we argue that learning moments can be integrated with sketching in the STEM design environment. We then offer recommendations for educators and designers interested in children's learning through sketching when they involve children in the design process. The main contribution of this study lies in offering a more detailed understanding of children's sketches and their learning while sketching for designing engineering products. Finally, it contributes to building knowledge about improving and sustaining design cycles by children in informal learning contexts.

5.2 Related Literature

5.2.1 Sketching

The terms 'sketching' and 'drawing' are found to be used interchangeably in the literature (Sung et al., 2019; Stammes et al., 2022). According to the field of STEM education, sketching is considered an important form of visual representation used to externalize information needed to comprehend and solve a problem, activating prior knowledge and increasing their attention to critical components of the problem (Ainsworth & Scheiter, 2021). In engineering design, sketching crystallizes engineers' amorphous design ideas into visible design artifacts (Sung et al., 2019). Thus, we synthesize approaches to sketching from the fields of STEM education and design, conceptualizing sketching as *a process that involves the construction of visual representations, the planning and visualization of ideas that happen before and during the construction of a visual representation, and any other forms of representations (e.g., verbal, textual) used to consider various ideas before actually making a sketch.*

In recent years, the focus on using hand-drawn visual representations of information has become prevalent in STEM education (Lane & Sorby, 2022; Wu & Rau, 2019). Research suggests that when children are asked to draw what they see, they pay closer attention to what they are viewing, which enhances the observational skills required in scientific practices (Quillin & Thomas, 2015). Likewise, there are multiple learning benefits associated with learners making visual representations. First, it helps to direct children's attention to details of scientific concepts (Schmidgall et al., 2020). Second, it encourages children to construct new knowledge by integrating prior knowledge with new information (Wu & Rau, 2019). Third, it increases students' constructive engagement with STEM contextual material (Cromley et al., 2020; Kunze & Cromley, 2021). Moreover, it increases students' coordination between modalities of visual, textual, and verbal information (Fiorella & Kuhlmann, 2020). Based on these benefits, sketching has become an area of increasing research in STEM education. The benefits of STEM sketching are unsurprising when we consider the research on drawing and learning outside of STEM. According to the cognitive model of drawing construction, when learners self-generate a drawing, they actively process the information (Van Meter & Firetto, 2013). It implies four cognitive processes involved in the construction of drawing:

1. The instruction to generate a representational drawing prompts students to engage in the cognitive activities necessary to construct a mental model.
2. The mental model is used to derive a perceptual image that can be externalized by the learner in the drawing.
3. The drawing on the paper provides feedback about the coherence and completeness of their mental models.
4. The learner's mental model can be improved by reviewing the text contents about the drawing, which helps to learn.

For this reason, a drawing task can improve a learner's mental model construction if they actively reconsider and evaluate their drawings (Van Meter and Firetto, 2013). Finally, this model provides valuable insight into the cognitive process of drawing scientific knowledge.

Fewer studies have focused on understanding the influence of differences in instructional strategies for sketching on children's learning. For example, prescribed sketching (i.e., having students copy representations without considering relations) negatively impacts children's thinking about appropriate solutions for the problem (Gagnier et al., 2017). Therefore, it is essential to understand prompts and scaffolds that afford students to leverage sketching as a productive tool for learning (Ainsworth & Scheiter, 2021).

Since this study focuses on examining children's learning through sketching in an engineering design context, next, we discuss the literature on sketching from the field of engineering design.

5.2.2 Sketching in Engineering Design

The goal of engineering education for children is to teach them how to solve problems like an engineer, so teaching sketching skills should be integrated throughout engineering education (Cunningham et al., 2018; Hill-Cunningham et al., 2018). In engineering practice, sketching serves multiple social and cognitive functions such as ideation, a short-term memory aid, communicating and documenting structural relations during the product design process, and a tool to externalize viewpoints in collaborative design work (de Vere et al., 2013; Quan & Gu, 2018). Case studies of engineers show that they first transform problems into drawings that depict concepts qualitatively or quantitatively and then iteratively evaluate and revise their drawings (Kothiyal et al., 2016). In particular, it serves two basic operations in engineering practice - externalizing the design ideas from mind to paper and internalizing the design ideas in their mind from external representation (Kelley & Sung, 2017; Sung et al., 2019).

Freehand sketching is a fundamental skill in engineering for problem solving (Lewis & Sturdee, 2020). However, sketching instructions in undergraduate engineering focus mainly on technical drawing rather than strategic sketching. Hence, engineering undergraduates often need help with sketching abilities when performing engineering design projects (Uziak & Fang, 2018). Therefore, educators should focus on developing elementary students' visualization and sketching skills to share and develop design ideas in engineering classrooms effectively (Weber & Sansone, 2016; Sung et al., 2019).

In an informal learning context, prior research on children's sketching focusing on interest-driven STEM design indicates that engaging in sketching accomplishes multiple goals, such as giving children a medium to represent their ideas, as well as giving them a tool to build on ideas and innovate (Paper 1, *this document*). Children's sketches contain information about their expectations, experiences, beliefs, and knowledge (Paper 1, *this document*). Sketch-based discussions led children to use multiple sketching properties, including sharing ideas, building ideas, and collaborative problem-solving (Shokeen et al., 2023). To the best of our knowledge, we found little to no prior literature on establishing the relationship between learning and sketching in STEM design with children. Therefore, this study focuses on addressing this gap in the research by leveraging the theoretical grounding from the field of learning and design discussed in the next section.

5.2.3 Theoretical Grounding

The theoretical grounding for this study comes from the synthesis of Radical Constructivism (RC; a theory of learning) and Cooperative Inquiry (CI; an approach to designing products with children) into a coherent framework we call RCCI (Paper 2, *this document*). This section briefly describes RC, CI, and the RCCI.

The Cooperative Inquiry (CI) research approach to design with children has its roots in the theories of participatory design, contextual inquiry, activity theory, and situated action (Druin, 1999). This view argued for involving children as equal partners in the design process (Druin, 1999, 2002). More recently, views on the technology design with children include the child as protagonist approach (Iversen et al., 2017) and the design by children approach (Gennari et al., 2022), both of which emphasize children being the lead agents when carrying out the complete design process. This shift in the design practice with children promotes learning benefits for children embedded in the design process (Gennari et al., 2022; Roumelioti et al., 2022). Often studies on children's learning in technology design research, studies "do not provide explicit theoretical grounding for aspects of learning in either the research design or result" (Eriksson et al., 2022, p. 60). This lack of a solid learning theory for understanding children's learning when designing technology has resulted in calls for future research focused on building a learning theory (Antle & Hourcade, 2021; Eriksson et al., 2022).

The theory of Radical Constructivism (RC) proposed by Glasersfeld is built upon Piagetian constructivism, promoting the idea that knowledge is the interpretation of individuals' experiences in their environment (Glasersfeld, 2013; Glasersfeld, 1995). His theory is called 'radical' to distinguish it from conventional interpretations of constructivism, and it is based on two fundamental principles (Glasersfeld, 1995, p. 18):

•knowledge is not passively received but built up by the cognizing subject; and

•the function of cognition is adaptive and serves the organization of the experiential world, not the discovery of ontological reality.

According to RC, learning happens during the process of inventing things to improve our functioning in the environment as a coherent and productive way of thinking that helps to deal with the fundamentally inexplicable world of our experience (Glasersfeld, 2013).

Considering RC recognizes that learning happens in inventing things that improve human interaction in the environment, RC aligns with the nature of the design environment, which focuses on building products to improve human experiences. A recent framework, Radical Constructivist Cooperative Inquiry (RCCI), combines the two - Design and Education - distinctive but complementary fields of knowledge (Paper 2, *this document*). This framework is built on the synthesis of literature about RC, CI, and the empirical findings from a STEM design project conducted by researchers with children. Below we provide a brief overview of the six pillars - Child-centered, Dynamics, Iterative, Collaborative, Representations, and Outcomes - of the RCCI framework (See Paper 2, *this document* for details).

1) *Child-centered* – Providing children the lead role during a series of design interactions to understand children's learning behavior during the design process. While researchers may determine the overall goal, the children decide what problems they want to solve and how they do it.

2) *Dynamics* - Dynamic learning indicators focus on how children interact with the resources, material, tools, peers, and adults during the design process and how these interactions influence their learning.

3) *Iterative* - Researchers and children iterate their learning based on their reflection on experience. Researchers iterate episode plans as they reflect on children's learning, and children iterate between different versions of their design.

4) *Collaborative* - Promote collaborations at three levels: child-adult, child-child, and adult-adult.

5) *Representations* - RCCI approaches to understanding learning emphasize the crucial role of multiple representations (physical and digital tools) in constructing knowledge.

6) *Outcomes* - learning outcomes for children should be embedded during the planning, execution, and analysis of experiences.

RCCI provides strong foundations for each pillar to support learning in design and highlights that these pillars are not mutually exclusive but interconnected (Paper 2, *this document*). However, the connections between pillars still need to be explored. Therefore, during the analysis of this study, in addition to our research questions, we also focused on understanding the connection between these pillars. Based on the RCCI views on learning, the term 'learning' in this study entails our interpretation of what knowledge about design children were acquiring through sketching experience.

5.3 Methods

5.3.1 Context of the Study

The study is a part of the MAKEngineering Project to integrate STEM into the home environment by introducing and engaging families in the engineering design process. Participating families were provided with researcher-developed engineering kits framed around an engineering problem, including all the necessary materials and tools (See Appendix – A; Simpson & Maltese (2019) for more information). In addition, the participants were encouraged to supplement the materials in the kit with items available in their homes. Participants were given a choice to select 6 kits from 12 available kits, which were delivered by Author 2 to their doorsteps, which allowed families to enact actions and behaviors of engineers in their home environments (instead of with Author 2, due to COVID restrictions at the time). The participants were asked to video record their design process using the application of Sibme (https://www.sibme.com/) or Zoom (https://zoom.us/) on their preferred device - phone/tablet/laptop. This video-recorded data was then shared by participating family caregivers with Author 2. Optional show-and-tell virtual meetings were held twice a month on a Thursday night and a Saturday morning to accommodate varying family schedules, engage families in talking about their process together and get feedback and advice from each other and the researchers.

Kits included open-ended questions for parents to pose to their child(ren) during the design process, highlighting the connections to math and science concepts, troubleshooting tips, and detailed images demonstrating how things worked. The kit manual introduced the task to the family with the kit's purpose by providing a background of the relevance of that product. A wide variety of materials were also included in the kit to make the low-fidelity prototype (e.g., popsicle sticks, aluminum foil sheets, cotton balls, a deck of playing cards, thumbtacks, yarn, scissors, masking tape, measuring tape, cardboard base). The instruction manuals in kits consist of five main steps: (1) Research, (2) Plan, (3) Create, (4) Test, and (5) Reflect & Improve. This study primarily focuses on Step 2: Plan - which prompts the child(ren) to sketch 2-3 detailed designs of the product based on their research and brainstorming (performed in Step 1) and how these sketches were useful in Steps 3, 4, and 5 of the design process.

5.3.2 Participants: Selection and Participation

Participants were recruited from five local school districts. The study advertisement was sent to every family with at least one child in grades 3-6 using posts on the learning platform SeeSaw (https://web.seesaw.me/), teachers' emails, and the school district's social media posts. The call for participation in the study consisted of a short video introducing the research team, showing the engineering kits, and presenting program highlights. In addition, author 2 conducted virtual meetings with every family that expressed interest in providing more specific information about the program (e.g., dates) and the research study. In a follow-up email, consent, and assent forms from the participant. The demographic information about the families was collected using Qualtrics survey software (www.qualtrics.com/).

The overall goal of the MAKEngineering Project was to understand the child and caregiver engagement with STEM concepts in their home environment by engaging families in the engineering design process. However, this study explores the relationship between sketching and learning in STEM design activities. Author 1 (expertise in design sketching) and Author 2 determine the objective of this paper, realizing the frequent evidence of sketching within the data. Author 2 added Author 1 to the project IRB and then shared videos and demographic information about the participants using a secured Google Drive from the university account. In total, 113 videos and their transcripts were shared by Author 2 with Author 1. The authors had regular weekly meetings throughout the analysis to address the methodological guidelines for performing the secondary analysis (Heaton, 2008; Ruggiano & Perry, 2019). Additional consent from the participants was not required for this analysis as the objective of this study falls under the overarching goal of the MAKEngineering Project for which participants have consented.

5.3.3 Positionality Statement

Researchers' identities and positionality serve as a lens for viewing and interpreting their social worlds and understanding their relationships with the research context, participants, and data (Corlett & Mavin, 2018; Jacobson & Mustafa, 2019). Author 1 is an Asian female with research expertise in STEM education in informal learning environments, focusing on the design of technology products for children. This study was her third STEM program-specific research experience. Authors 2 and 3 are White females and mathematics education experts in formal and informal learning environments. All authors acknowledge that their multiple perspectives and experiences are strengths and weaknesses to the study and interpretation of the findings. Through discussions and exchange of ideas, the authors worked together to identify and mitigate implicit biases and misperceptions regarding developing sketching skills among children in engineering activities.

5.3.4 Data Analysis

Researchers used the secondary analysis (Heaton, 2008; Ruggiano & Perry, 2019) guidelines with a thematic analysis method for data analysis (Braun & Clarke, 2006; Clarke et al., 2015). The authors analyzed child and caregiver interactions in the videos using an iterative and inductive thematic analysis approach (Braun & Clarke, 2006; Clarke et al., 2015; Saldaña, 2014). Thematic analysis is helpful in experiential research, which seeks to understand what participants think, feel, and do (Clarke et al., 2015), to understand children's sketching experiences in engineering design. The multimodality (e.g., gestures, actions) of communication between the child and caregiver was considered during the coding process (Bezemer & Mavers, 2011). For the analysis process, we followed the six steps of thematic analysis (Braun & Clark, 2006).

Step 1: Become familiar with the data - Author 1 watched all the videos to get sensitized to the data. Then, she organized the data according to product kits alongside the name of the families who participated in doing that kit. The authors then discussed the various consistencies and inconsistencies in the data, such as the difference in what is video recorded by families - some captured the entire design process, including the process of planning and sketching, versus others who demonstrated their sketches only which resulted to the varying duration of video data (See Table 5). For example, some participants showed their sketches to the camera, whereas others did not. The authors also discussed details of analyzing video data, such as transcription tensions, defining the unit of analysis, and representation of context for qualitative video analysis (Ramey et al., 2016). To do the in-depth analysis, the authors decided to apply inclusion and exclusion criteria for further analysis provided below:

(i) Product Kits that had an active testing phase. For example, in the *Grabber* kit, the Grabber prototype could be tested for grabbing objects. However, in the *Trendy Tennies* kit, the prototype could not be tested as it was not feasible for the child to wear the low-fidelity prototype shoes and play tennis with them.

(ii) To look for the patterns across families in the single kit, the kits for which we had at least four families worth of data were included, and the data for kits where three or fewer were excluded considering weak data to look for patterns for a kit across families.

After applying inclusion and exclusion criteria, four kits were selected - Grabber, Paper Roller Coaster, Water Color Bot, and Package for Delivery (See Appendix for details). This selection criterion resulted in 55 videos from 11 families with 14 children (See Tables 1 & 2), resulting in 860 minutes of video data analyzed for this study. The confidentiality of data is maintained by using pseudonyms for all participants. For the next step, transcripts for videos were generated by the Otter software application (https://otter.ai) and revised manually by Author 1 regarding the video data.

Table 5. 1: Brief summary of the product kits, participants, & data.

Product & Task	Participants	Number of videos	Duration of video
1. Grabber Design a grabber that can pick up three different objects from at least two feet away without damaging or dropping them.	Beth	3	14:24 min
	Karl	2	12:21 min
	Annie	4	5:09 min
	Eliot	1	1 hour 26 min 27
	April & Dandelion	4	26:18 min
	Eve & Ashley	2	8:35 min
2. Paper Roller Coaster Design a roller coaster that is suitable for a marble to travel from the start to the finish.	Eve & Ashley	1	4:17 min
	Jim	3	43:32 min
	Aleena & Atalia	1	1 hour 19 min : 18
	Amethyst	1	2 hours 10 min :03
	Dandelion	1	7: 30 min
3. Water Color Bot	Elizabeth	5	5:05 min

Design a motorized bot that "paints."	Karl	3	4:03 min
	April & Dandelion	6	28:08 min
	Amethyst	1	2 hours 11 mins
	Jim	3	48: 32 min
4. Package for Delivery Design a way to secretly and safely share objects with your friend who lives next door (at least 6 feet away).	Beth	2	8:50 min
	Maroon	3	11: 39 min
	Eliot	1	58:46 min
	April & Dandelion	3	11:16 min
	Eve & Ashley	2	5:50 min
	Jim	3	43:33 min
		Total videos: 55	Total Duration: 860 min Range: 4 min - 131 min

Table 5. 2: Participants' Demographic Information

Serial Number	Child Pseudonym	Family Pseudonym	Gender	Race/ Ethnicity	Age	Grade
1	Amethyst	Ross	F	White	7	2nd
2	Beth	Jones	F	White	8	3rd
3	Maroon	Thomson	M	Asian	8	3rd
4	Karl	Mills	M	White	9	4th
5	Eliot	Aster	M	White	9	4th
6	Elizabeth	Clark	F	White	10	5th
7	Jim	Johnson	M	Asian	10	5th
8	Annie	Anderson	F	Biracial	11	6th
9	Dandelion	Bamford	M	Asian	8	3rd
10	April	Bamford	F	Asian	9	4th
11	Aleena	Campbell	F	White	9	4th
12	Atalia	Campbell	F	White	9	4th
13	Eve	Tuffin	F	White	10	5th
14	Ashley	Tuffin	F	White	10	5th

Step 2: Generate initial codes: Initial coding and memos were generated on the transcripts in correspondence with videos considering the six pillars - *Child-centered, Dynamic, Iterative, Collaborative, Representations,* and *Outcomes* - of the RCCI framework (Paper 2, *this document*). These pillars were not considered focused codes but the guide for inductive coding of different data dimensions. For example, the pillar of *Collaboration* guided to code of the excerpts from the transcripts regarding the nature of interactions between child-adult, child-child, and child resources; however, it did not specify which sketching patterns to look for in the data. For instance, the excerpt "Adult: *So, where do we really put your candy?* Child: *On a plate! Like a plate* [hand gestures] Adult: *What is this circle?* [pointing to a specific part of the sketch]." was coded as 'the use of sketch as a situated artifact for child-adult communication.' This same excerpt was also the 'use of multiple modalities for understanding the design depicted in the sketch,' guided by the representation pillar of the RCCI.

The coding of the entire dataset was done by Author 1. However, to ensure reliability, Author 2 checked the codes based on her familiarity with the data before moving to the next step of searching for themes. During this step, authors resolve any differences in interpretations of codes between Author 1 and Author 2. For example, it was unclear to Author 2 what Author 1 meant by the coding phase 'Iterative nature of sketching.' The discussion helped to clarify that it captures the scenarios where children changed or crossed out their sketches.

Step 3: Search for themes: After finishing coding all transcripts, discussing, and revising it with other Authors, Author 1 searched for patterns across codes and created themes in a spreadsheet with corresponding examples from all transcripts, including excerpts and memos. For example, the ‘Details in sketches versus prototypes’ theme captured the patterns in children’s sketches and prototypes built by them for the same product.

Step 4: Review themes: The themes created by Author 1 in the previous step were reviewed by Author 2 and Author 3 in this step. During the review phase, the authors considered the uniqueness of each theme and its relationship with other themes. The authors discussed ways to clarify each theme’s uniqueness and relevance and its relationship with other themes. In this phase, the authors also discussed the relationship between different pillars of the RCCI in depth. For example: If the ‘outcome’ pillar of RCCI is considered as learning about ‘sketching and sketches’ in the design, then all other pillars can be considered as a process, i.e., means to the ‘outcome.’ Further discussion on this idea led the authors to consider the ‘child-centered’ pillar as an anchor to all other pillars, the four pillars - ‘dynamic, collaborative, iterative, and representations’ - as the processes that interact and influence each other to achieve the learning pillar of outcomes.

Step 5: Define themes: This step determines the axial relationship between codes and defines themes. For example, the central theme ‘Dynamic sketches by children’ captures three sub-themes - ‘Planning before sketching’ capturing the sources of inspiration for sketches, ‘visual depiction of sketches’ capturing the details shown in sketches, followed the ‘use of the sketch’ capturing the patterns in data regarding how children’s sketches guided the builds of their prototypes.

Step 6: Write-up: During this step, the authors discussed the different ways to organize the findings. They decided to add one corresponding example for the different elements within each theme, considering the limitation of word limits and representation of the context needed to provide the illustrative examples. Given the numerous participants (14 children in 11 families, plus their caregivers), and the complexity of the 4 product kits, we followed the protocol of using the family's last name when we mentioned a child and their caregiver in the findings.

Some mitigating strategies were employed in this analysis to ensure the transferability and trustworthiness of the study: (a) the methodology contains the authors' positionality statement, and (b) Author 2 employed a thorough examination of Author 1's interpretations of the data during the initial coding process, ensuring each theme was derived rigorously from the data. Additionally, Author 3 was involved in the later stage of the analysis to reflect on the analysis process and findings critically. Thus, the authors of this study believe that the rigor of the analytical process makes the findings valid and trustworthy.

5.4 Findings

5.4.1 Children's Sketches during Design

In response to RQ1, *How do children sketch during design activities?* We found that the brainstorming content, home environment, imagination, and personal experiences inspired children's sketches. Children's sketches were dynamic with unique visuals and showed a variety of details in labeling, functionality, and perspective. Below, corresponding examples provide details on children's sketches.

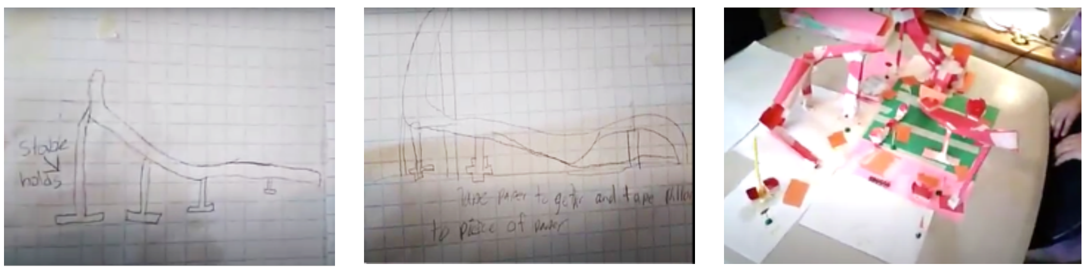
Inspiration for the Sketches

The *inspiration for the sketches* theme entails the evidence from where children found inspiration. Multiple resources inspire design ideas depicted in children's sketches, including children's surroundings in the home environment, personal experience, and brainstorming content (e.g., references listed in the kits). For example, Amethyst shared that her Paper Roller Roaster shape, *Candycane*, was inspired by the YouTube video she watched during the brainstorming. This example indicates that children drew inspiration from the internet references listed in the kits during brainstorming. Objects and resources from the home environment also inspired children's sketches. For example, while explaining the Grabber sketch, April shared that looking at the light bulb in her room ceiling inspired her to design a grabber to change the light bulb. Similarly, during the demonstration of the Grabber sketches, Beth shared that one of her sketches (See Figure 5.1-A) was inspired by the toy grabber she has in her home (See Figure 5.1-B). Similarly, the shape of the snake shape toy Karl had lying on his table inspires his Grabber sketch (See Figure 5.1-C). These examples show that children drew inspiration for their sketches from the objects from their home environments.

(A) Beth's Grabber Sketch **(B) Beth's Toy Grabber** **(C) Karl's Grabber Sketch**

Figure 5. 1: Beth and Karl's Grabber sketches with the objects of inspiration

Children’s personal experiences also inspire the design in their sketches. For example, in the Paper Roller Coaster sketches, the caretaker from the Tuffin family shared, “*So they* [Eve and Ashley] *got this idea from the Marble Runs they had when they took some kind of technology class, and they used it here with the paper*.” In this example, Eve and Ashley’s personal experience of making marble runs with technology inspired the design of their sketches and prototype for the Paper Roller Coaster (See Figure 5.2).



Sketch 1 **Sketch 2** **Prototype**

Figure 5. 2: Tuffin family’s sketches and prototype for the Paper Roller Roaster

Visual Details in Children’s Sketches

Visual details in sketches entail a wide variety of the details found to be depicted in children’s sketches, such as labeling different parts, naming the designs, differences in functionality, and materials useful for prototyping. In addition, caretakers were found to prompt children to consider the perspective within their sketches. Below we discuss the details we found in children’s sketches with examples.

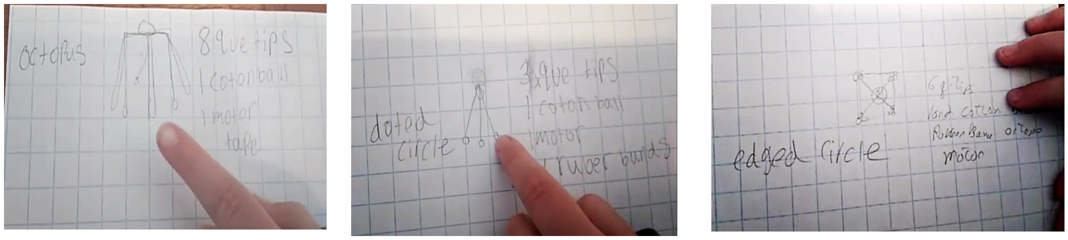
1. <u>Labeling:</u>

There was a variety of labeling found in children’s sketches, such as - labeling different parts of the sketch, labeling the material that will be useful for sketching, specific measurements for the prototype, and naming the sketch itself. For instance, Karl made three sketches for the Grabber (See Figure 5.3). He used labels for his Sketch 1 and Sketch 3 as a communicative resource while explaining the details of those sketches. When explaining Sketch 2, Karl realized that the sketch was not labeled, "*For some reason, I didn't label this one. I don't know why*" (See Figure 5.3-B). In Sketches 1 & 3, he labeled the parts (e.g., mouth, handle, base) and materials (e.g., tape, pulley, string) to be helpful during prototyping; however, in Sketch 2, he only mentioned 'pull to open' and 'pull to close' which was not as communicative as the labels in his other sketches. This example indicates the variety found in the labeling of sketches.

(A) Sketch 1 **(B) Sketch 2** **(C) Sketch 3**

Figure 5. 3: Karl's three sketches for the Grabber

Children found naming their different sketches. For example, Elizabeth labeled her three Water Color Bot sketches with names - *Octopus, Dotted Circle,* and *Edged Circle* - and listed the material required next to her sketches (See Figure 5.4). The variety of labels in sketches shows the dynamic nature of children's sketches during the designing process.



(A) Sketch 1 **(B) Sketch 2** **(C) Sketch 3**

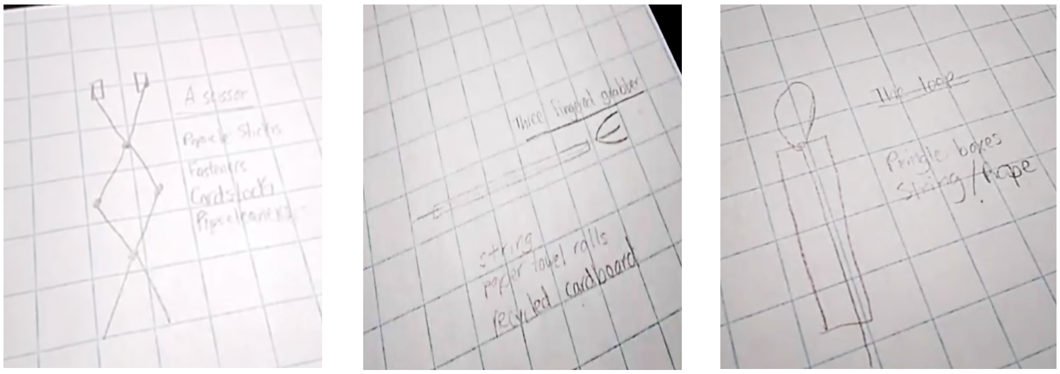
Figure 5. 4: Elizabeth's three sketches for Water Color Bot

2. <u>Variety in functionality:</u>

Children's sketches differ in the utility and outcomes of different designs. Children were considering various design considerations for different product kits, including the strength, sturdiness, utility, and functionality of the material used to build the prototype. For example, in the Grabber kit, children considered the differences in grabbing ability based on the difference in the shape of the mouth of the grabber. For instance, while presenting her sketches, Annie shared the differences in the shape of the grabber month (See Figure 5.5),

> "*... one that's like a scissor* (See Figure 5.5-A). *So, when you would close the side, it would move that side so you could grab something. And then we have this one* (See Figure 5.5-B) *where you pull a string which opens when you let go of the string. It would close them so it could grab something. And then this one* (See Figure 5.5-C) *you would look around something and then pull the string and it would tighten it and then you could pull it back and forth*."

In this example, Annie designed different sketches for grabbers that worked differently, and her demonstration of the sketches included the action required by the user and the task performed by the grabber. This example indicates that children's multiple sketches about the same product differed in functionality.



(A) Sketch 1 **(B) Sketch 2** **(C) Sketch 3**

Figure 5. 5: Annie's three sketches for the Grabber

3. Perspective: Point of view

The perspective of the sketch is about the representation of three-dimensional products in two dimensions (e.g., drawing on paper). For example, during the Paper Roller Coaster sketching, the Ross family was found to be discussing sketch perspective - 'point of view.' It began when the caretaker asked Amethyst about her sketch (See Figure 5.6),

Figure 5. 6: Amethyst's sketch of Paper Roller Coaster

Caretaker: "*Is this from a bird's eye point of view?*"

Amethyst: "*I have no clue what that means?*"

Caretaker: "*So, a bird flies in the air, right?"*

Amethyst (nodding): "Yes.

Caretaker: *"So, when it looks down and everything looks flat* [gesturing by expanding her both hands over the table to indicate flat]. *If you look down and you see the table. Is it flat?*"

Amethyst: "*This* [table] *is not flat*".

[Then, the caretaker then asked Amethyst to stand on the chair and look at a piece of tape lying on the table from the top]

Caretaker*:* "*If you stand right above it* [Tape] *and look directly above it* [Tape]. *It just looks like a circle… If you hold it* [Tape] *right in front of your eye level, it looks like a thick block.*"

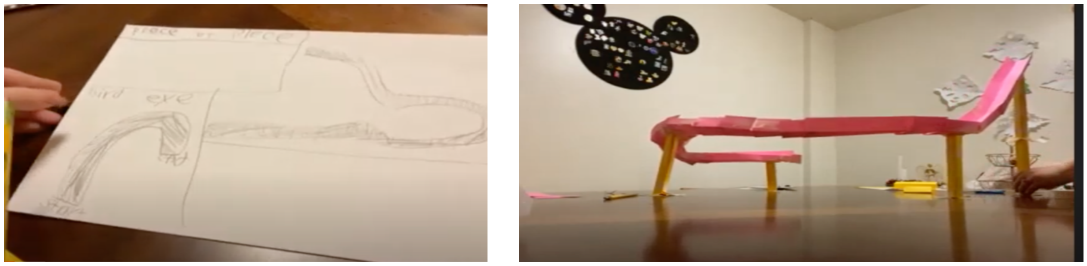
In this example, the caretaker explained to Amethyst the difference between looking at a 3-dimensional object from different points of view. To begin, she explained verbally, using hand gestures. However, Amethyst was not able to understand the difference. Then, she asked Amethyst to stand on the chair and look at an object [Tape] lying on the table from the top and then from the front [at eye level] to experience the difference between looking at the same object from different directions. This exchange helped Amethyst to understand the difference between looking at something from a different point of view. In this example, the caretaker explicitly asked the child about the viewpoint of her sketch. However, there were some occurrences where caretakers and children struggled to communicate the point of view of their sketches.

Use of sketches in the Prototyping

Children followed the designs depicted in their sketches closely during the prototyping phase. The details in children's sketches guided them to make design considerations for building prototypes, such as which material to use to build which parts. Before beginning the prototype, children evaluated their different sketches and selected which sketch to pursue building the prototype. For instance, considering the stability of the Water Color Bot, Karl eliminated two of his sketches by putting a cross next to them in his sketches and pursued Sketch 3 for building the prototype (See Figure 5.7).

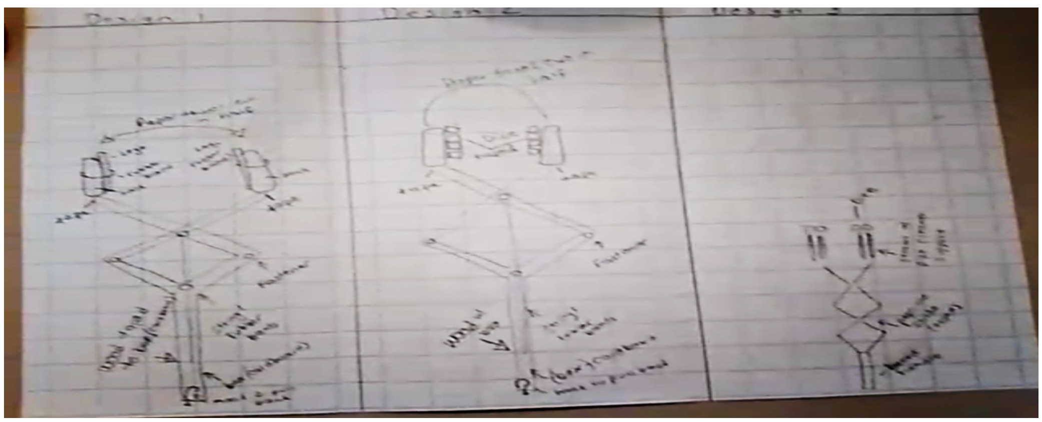
Figure 5. 7: Karl's three Water Color Bot sketches

While building the prototype, sketches act as a situated artifact to help participants adhere to the initial design. In particular, it is challenging for caregivers to encourage children to keep their initial design the same when completing it. For example, in the Ross family, the caretaker encouraged Amethyst to adhere to the 'candy cane' shape she drew in her sketch while building the prototype, "... *It's not a candy cane. If you're going to change the design, then change it. But don't say you're going to do one thing and then do another just because it's more convenient*." Their final prototype of the Paper Roller Coaster matched the shape drawn by Amethyst in her sketch (See Figure 5.8).

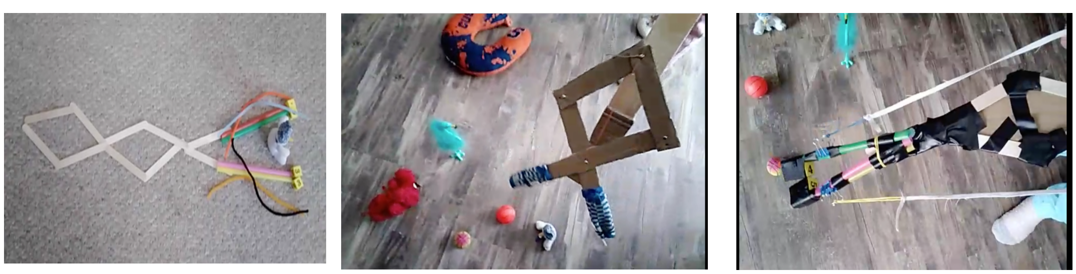


Sketch Prototype

Figure 5. 8: Amethyst's sketch and prototype for the Paper Roller Coaster



(A) Three sketches



(B) Prototype 1 **(C) Prototype 2** **(D) Prototype 3**

Figure 5. 9: Tuffin family's three prototypes for the Grabber

There were occurrences when children pursued design from their sketches and figured out that the design, they sketched was not sturdy enough while building the prototype or testing phase. For example, Tuffin's Prototypes 1 and 2 failed the test to grab objects (See Figure 5.9-A & B). During the Prototype 2 testing phase, Eve said, "*All right, so it* [Grabber] *fell apart. We got an injured one. So, we're going to put this one aside* (See Figure 5.9-B)." They returned to their sketches and pursued a different design sketch (See Figure 5.9-A) for building Prototype 3. They made specific updates in the choice of materials listed in the sketch to build their Prototype 3, "... *we use the popsicle sticks. We didn't use the other rubber band device thing because it was an epic fail with the previous one. So, we used a lot of tape on this one…And then we also added these binder clips in there and rubber bands...*" (See Figure 5.9-C). While they pursued the different sketches for the prototype, their learning about the properties of certain materials from the failure of Prototype 1 and 2 helped them build Prototype 3, which passed the grabbing test. This example indicates that children returned to their sketches to pursue a different design when their initial prototype failed.

5.4.2. Dynamic Learning in Sketching

In response to RQ2, *How do children participate in learning through sketching activities?* Children's learning about sketching was found to be composed of three interrelated facets: *dynamic collaboration, dynamic representations* (which manifested in collaborative representations and multiple representations), and *dynamic iterations* which captured the dynamic nature of learning about sketching in design. Each of these facets of dynamic learning indicates different learning dimensions that occurred during sketching, such as children regularly modifying, improving, and learning how to better communicate and collaborate during sketching about their design ideas. Below we discuss each of these facets of dynamic learning about sketching in design with corresponding examples.

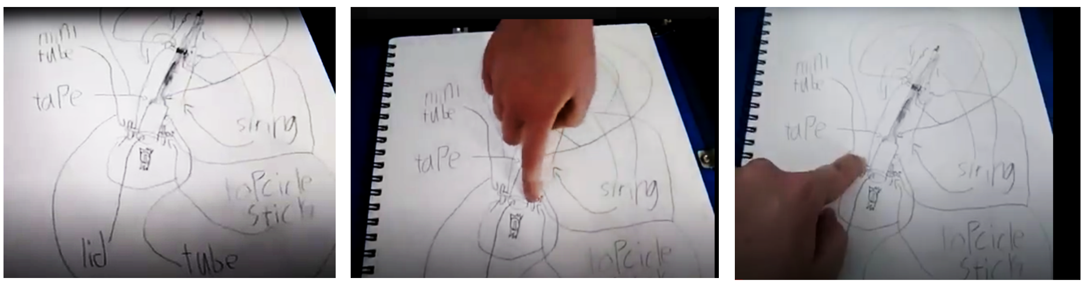
Dynamic Collaboration in Sketching

Dynamic Collaboration in Sketching entails differences in the collaboration during sketching between child-child, child-adult, and child resources in different families. As shared in the previous section's findings, children's sketches have various details. Although sketches were primarily developed by children, during sketching, there was a child-centered collaboration between child and caregiver, where adults scaffolded the design and sketching process. The dynamic nature of collaboration in sketching entails the variety of ways in which child-child and child-adult collaborate. The collaboration dynamics in different families influenced the differences in children's sketches. For example, some family caregivers encouraged children to draw three sketches as suggested in the kit. However, other family caregivers did not follow up if the child drew one or two sketches. These dynamic differences during sketching influence the learning about sketching in design for children in different families.

During sketching, children and adults discuss the pros and cons of particular design ideas, design considerations for specific functionality, and material properties useful for prototyping. For instance, the Mills were considering the functionality of the design in their Grabber sketches (See Figure 5.10),

> Karl [pointing]: "*We have popsicle sticks going through it, and we could pull those to open and close.*"
>
> Caregiver [pointing]: "*And it looks like for this design, you have a string on either side of both popsicle sticks so you can pull in one direction or the other to open and close. Right*?"
>
> Karl [nodded]: "Yes".

In this example, *first*, Karl explained the design idea to his caretaker in reference, and *second,* the caretaker revoiced her understanding of Karl's design ideas. Karl and the caretaker were pointing at the specific element of the sketch to specify what they were talking about in the sketch. This example indicates the moment of learning about the communication about design ideas, as collaborating on the design activity required a shared understanding of the design ideas.



(A) Karl's Sketch 1 **(B) Karl pointing** **(C) Caregiver pointing**

Figure 5. 10: Karl with his caregiver communicating about the Grabber sketch

The dynamics of collaboration were different in families with two children with one caregiver participating in the same project. In the Bamford and the Campbell families' children have made separate sketches, whereas, in the Tuffin family, children worked on the same sketches and prototypes. These dynamic differences in collaboration influenced the interaction and learning opportunities for children. For example, in the Bamford family, when April and Dandelion participated in the Grabber kit, they asked each other design questions during the sketch demonstration. For instance, Dandelion asked about April's Grabber sketch (See Figure 5.11-A),

Dandelion to April: "*How can you grab it and twist, if you twist it will just slide?*"

[No response from April]

Caretaker: "*Pretend this* [a blue egg-shaped object] *is a light bulb and, April's idea is to put like a couple of paddles to hold the light bulb and then use a string from the bottom, it would tighten there and grab the light bulb tight.* (See Figure 5.11-B & C)*"*

In this example, April's silence in response to Dandelion's question indicates that she did not know how to explain her design idea to Dandelion better. Then, the caretaker took over their communication and explained Dandelion's design with the help of concrete material. The focused attention of children on the caregiver's response indicates it was a learning moment for them. Here, they learned two things - First, they learned how to explain their design ideas in response to questions. Second, they learn about using concrete representations to visualize a design idea better as the caregiver shifts the visualization of the design idea from 2-dimensional sketches to 3-dimensional objects. Overall, this example suggests that during sketching, children learn how to communicate better their design ideas depicted in their sketches.

(A) Sketch **(B) Concrete Material** **(C) Hand- Rotations**

Figure 5. 11: Bamford family communicating about April's Grabber sketch

Dynamic Representations in Sketching:

The theme of *dynamic representations* in sketching captures the use of a wide variety of modalities (written, verbal, pictures, gestures, actions) by families for communicating their design ideas during sketching. Although children made sketches mainly on their design ideas, sometimes, the design depicted in those sketches were design ideas that emerged from the communication between children and caregivers. These communications between child and caregiver involved using different forms of representations, including verbal, visual, hand gestures, and actions of manipulating concrete objects. For example, in the Johnson family during Water Color Bot, the caretaker struggled to understand Jim's design from the sketch.

Caretaker: "*What shape will it make on the paper?*"

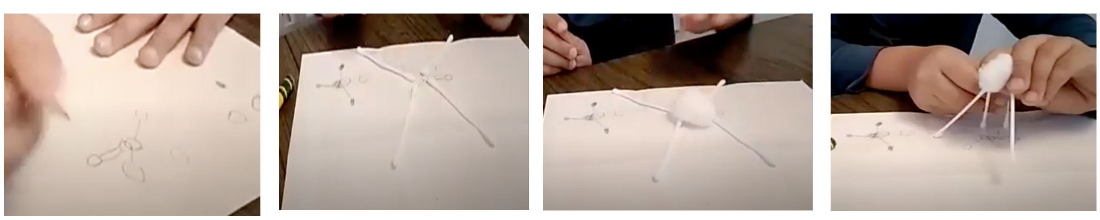
Jim [tracing pencil over his sketch]: "*On the paper, this is like an X shape*"

Caretaker: "*So you design X shape or it is going to draw X?*"

[No response from Jim, he looked confused]

Caretaker: "*Can you show this with cotton sticks? I don't really see how it will draw X*".

Then, Jim manipulated the Q-tips and cotton to make the caretaker understand his design (See Figure 5.12).



(A) (B) (C) (D)

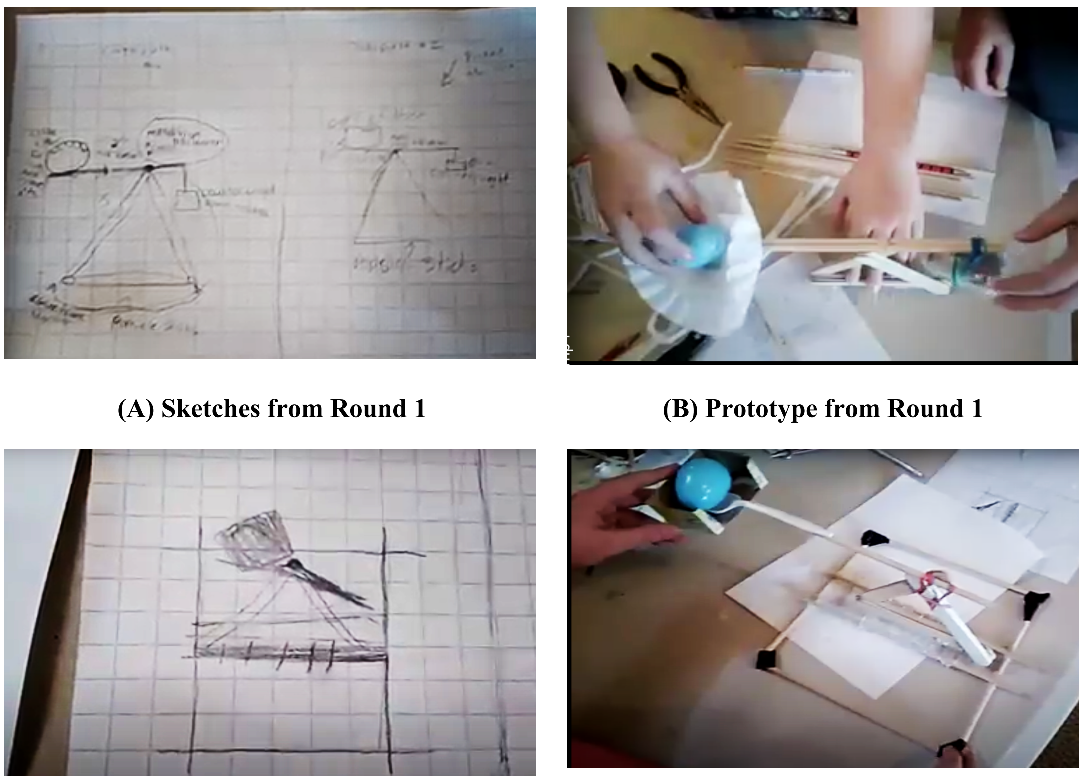
Figure 5. 12: Jim's use of different representations during sketching

Looking at the manipulation of the concrete material, the caretaker realized Jim was referring to 'X' as the shape of the water bot itself rather than the shape that will be drawn by the bot (See Figure 5.12). In this example, Jim and his caretaker struggled to communicate about the design depicted in his sketch. Jim's manipulation of 3D objects helped him communicate this design better. The use of concrete material was new knowledge for Jim, as he was instinctive about using hand gestures; however, it was not instinctive for him to use concrete materials to explain his design idea better. He used the concrete material when his caretaker asked him to do so. Thus, at this moment, Jim learned that using concrete materials can help explain the design ideas depicted in 2D sketches during the design process. Here, the manipulation of concrete material allowed the child and caregiver to communicate better about the design depicted in the sketch. This example indicates that during sketching, children learn about using multiple representations to aid verbal communication of design ideas depicted in the visuals of sketches. The use of multiple representations is a vital learning element for design communication.

Dynamic Iterations in Sketching

Dynamic iterations in sketching entail a variety of iterations that occurred when children participated in sketching for design. The iteration made by different families during the participation in the same product kits differs, which indicates the dynamic nature of iteration that occurs during sketching in the design process. Children learned that their sketches acted as situated artifacts for them to reflect on, use to communicate, and build on design ideas. By participating in different design steps- Create, Test, Reflect & Revise - listed in the kits, children learned the benefits of reflecting and revisiting the design ideas depicted in sketches while building the prototype and testing steps of the design. Children were iterating their initial sketch design based on the issues found while building and testing their prototypes. For example, during the Friendly Delivery Package in the Tuffin family, Eve and Ashley’s Prototype 1, built on their initial sketch, failed, then made another sketch and built Prototype 2. While demonstrating Sketch 2 and the prototype, Ashley shared,

> "*Our last one* [design] *didn't work very well* (See Figure 5.13-A & B). *It couldn't even go near six feet. So, we decided to put on rubber bands for the pivot and we took a dowel and attached a spoon to it. Now, when we tried flinging it with the spoon, it didn't work. So, we tried using a box around the spoon. So, the egg would stay in it* (See Figure 5.13-D)."



(A) Sketches from Round 1 **(B) Prototype from Round 1**

(C) Sketch from Round 2 **(D) Prototype from Round 2**

Figure 5. 13: Tuffin's Friendly Delivery Package sketches and prototypes

This example shows three iterations in the design, *first*, the re-doing of the sketch itself (See Figure 5.13-C); *second*, adding rubber band, spoon, and other updates; and *third*, the adding of a new part to the prototype - adding a box around the spoon in the design to stabilize the egg in the prototype (See Figure 5.13-D). In these moments of engaging in three rounds of iterations, Eve and Ashley learned about the iterative nature of sketching in the design process. In overall data, this was the first time Eve and Ashley did the sketching again after testing their prototype. They learned that sketches play an essential part in the design process of brainstorming and organizing design ideas. However, it is only possible to consider some design elements in sketches, and one needs to iterate the design based on the insights from the prototype-testing phase. Overall, this example indicates that children engaged in multiple rounds of sketching with design can learn that sketches give them the flexibility to explore and evaluate different ideas.

5.4.3 An updated version of the RCCI Framework

As discussed above, we leveraged the RCCI framework while analyzing children's learning and sketching in STEM design. However, the context of this study differs significantly from the empirical study referred to in framing the RCCI framework. Based on this analysis, we have adapted the RCCI framework to this study. These adaptations include expanding the constructs of pillars and establishing the relationship between pillars, as presented below (See Figure 5.14).

First, during the coding phase, we found that every interaction can be coded as *child-centered* as children made all the sketches. Therefore, we considered the child-centered pillar a guiding anchor implicit in the design experience. It is the topmost pillar during the planning of design experiences that guides other pillars.

Second, during analysis, we found that the *dynamics* of an experience directly influenced the 'collaboration,' 'iterations,' and 'representations' that occurred during the experience. Therefore, we placed dynamics directly below 'child-centered,' connecting to the pillars - collaborative, iterative, and representations.

Third, as presented in the findings above, we found connections between *collaborative*, *iterative*, and *representations*. Therefore, we used double-sided arrows to show the fluidity between these pillars.

Fourth, we found that *outcomes* are the knowledge children acquire through experience. These outcomes are the results and consequences of participating in an experience. For instance, in this study, 'outcomes' were insights into learning and sketching. Therefore, we considered 'outcomes' at the end where an experience ends.

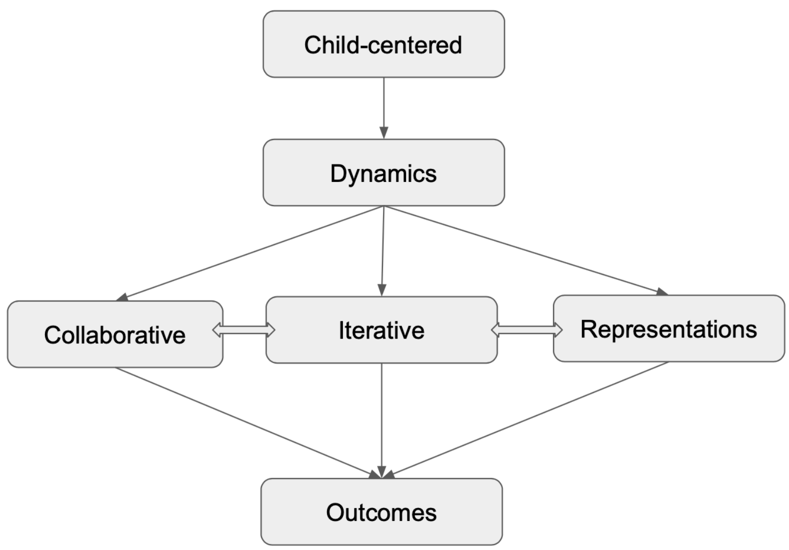


Figure 5. 14: An adaptive version of the RCCI framework

<u>*5.5 Discussion*</u>

Responding to our research question 1, *How do children sketch during engineering design activities?* We found that different resources, including the brainstorming content, home environment, imagination, and personal experiences, inspired the design ideas depicted in children's sketches. The findings indicate that children add a wide variety of design details in their sketches, which guide them to make considerations for building and improving their prototypes. In response to our research question 2, *How do children participate in learning through sketching activities?* We found that children were engaged in different learning outcomes due to the differences in the dynamics of their interactions. Children learn to communicate and explain their design ideas by discussing their sketches with their caretakers. They learn to use multiple representations - text, gestures, concrete objects - to visualize and explain their design ideas while sketching. Children also learned that sketching could help them to refine their design ideas for building and improving prototypes. Finally, some children referred to their sketches to build a different prototype when their prototype failed the testing. Based on our findings, we argue that children's learning intertwines with sketching in the STEM design environment.

As presented in the findings, this study expanded the theoretical underpinnings of the RCCI framework by establishing connections between different pillars. Future researchers can use this updated version of the RCCI framework as a theoretical lens for framing children's learning experiences in similar design environments. However, future research is needed to determine how the RCCI framework can be consistently adapted across different contexts - that is, different environments may require re-arranging the pillars in different ways. Investigating this, and establishing a reliable methodological step for such re-arrangement, is up to future researchers.

There are similarities between the findings of this study with children's sketching experiences in formal learning contexts. For example, our research found that using sketches is a supportive communication tool for children when verbally explaining their design ideas to others. This finding is like Fiorella and Kuhlmann's (2020) research with college students, where they found that creating drawings on paper by students when they explained the learning material to others led to better final learning outcomes than students who only orally explained. Like adults, children sketching facilitate explaining. In our study, we found children using their sketches as a tool to evaluate the different design ideas based on their perceived strength and utility before beginning the process of building the prototype. They used sketches to record their design ideas and referred to them while building the prototype. These findings are similar to Quan and Gu's (2018) study on visualization forms in collaborative design activities with graduate students. They found that freehand drawing was the prevalent visualization form serving various social and cognitive affordances. Similar findings were reported in the study on professional engineers highlighting the importance of external representation on iterative model-based reasoning processes for engineering estimation (Kothiyal et al., 2016). These similarities indicate that design sketches play a critical role throughout the design process, from brainstorming to testing amorphous design ideas for professional engineers, graduate students, and children.

Additionally, we found that children's learning was related to the communication caregiver had with them during sketching. This finding is similar to Sung and colleagues (2019) quasi-experimental study with elementary graders, which found that "students who received advanced sketching instructions such as the strategic use of sketching and 2D layout models were better able to generate and communicate designs to their teammates" (Sung et al., 2019, p. 199). Thus, further research in a similar context can evaluate the impact of standardized instructions from caregivers on children's learning. Our findings indicate that, like professional engineers and engineering college students, children can use sketching to solve engineering problems. Therefore, we argue that sketching during design activities with children supports their learning about design. Based on our findings, we provide recommendations for examining and supporting children's sketching in engineering design.

5.5.1 Recommendations

Based on the findings of this study, we recommend that educators encourage children to engage in sketching and attend to different solutions depicted in their sketches to support them in learning STEM design. To examine and support these moments, educators should focus on what is happening, who is doing what, and how - once we understand this, we can support children to learn and develop design skills required by STEM practitioners. In hindsight, sketching is a problem-solving tool that holds the potential to be used as a learning tool as it encourages children to: think of potential solutions; evaluate those solutions; communicate solutions with others; build a prototype based on the most efficient solution; and iterate the solution based on the insights from testing. Our findings provide seven practical implications for educators to support children's learning through sketching in design.

1. Encourage children to draw multiple sketches

First and foremost, we want to re-emphasize the importance of sketching in STEM design. It is essential to make children understand the relevance of sketching as a tool for envisioning different solutions to engineering problems. Children should be encouraged to consider sketching as a tool for thinking and visualizing different ideas. The findings indicate that having three sketches, in the beginning, helped children to evaluate the pros and cons of various design ideas. Children sometimes refer to their sketches to pursue different ideas when their prototypes fail the testing. This study's findings suggest that having multiple sketches help children to learn to evaluate and filter different design ideas. Therefore, we recommend encouraging children to draw multiple sketches depicting different design ideas, which can be evaluated and compared.

2. Encourage children to brainstorm

Children should be supported with a wide variety of brainstorming content to initiate their process of sketching for design, as we found evidence that children begin sketches inspired by the brainstorming content. For example, it could be easier for children to design a sketch with inspirational examples. The initial step of brainstorming sets the stage for children to consider other resources in their home environment or imagine new ideas based on their experiences. Therefore, educators should encourage children to brainstorm their funds of knowledge by providing them with the space and inspirational objects they might need to help them begin to sketch.

3. Encourage children to include details in sketches

Children should be encouraged to include details about their sketches, such as labeling the parts, measurement, and materials. Adding all these details will make children consider more dimensions about the visualizations of their design idea during sketching, which can help explain the sketch to others and build the prototype.

4. Encourage children to make sketches from different points of view

Considering the different points of view - such as front view, top view, and side view of the product drawn - while sketching can be helpful for better understanding and visualization of the design ideas. Our findings indicate that sometimes caretakers struggled to understand the point of view of sketches, which turned out to be a learning moment for children if the caretaker took the initiative to explain different points of view to the children. Therefore, we recommend encouraging children to consider sketching from different points of view for better visualization and communication of the design ideas depicted in sketches.

5. Encourage children to explain their sketches

When adults asked children to explain their sketches, it allowed them to learn how to communicate the design ideas. Our findings indicate some cases in which children initially struggled to explain design ideas depicted in their sketches; however, when encouraged, they could do so. Thus, we recommend encouraging children to explain their sketches to help them learn how to communicate the design ideas.

6. Encourage children to use their sketches for building prototypes

Our findings suggest that sketches were helpful for children to think about different design ideas, communicate their ideas, and build prototypes. The prototypes built by some children closely resemble their sketches. This study's findings suggest that reference to sketches can guide the prototype-building process for children. In some cases, sketches were an instrument for the caretaker to encourage children to follow the plan and not change the plan out of convenience. Thus, we recommend encouraging children to refer to their sketches to guide their building and to reflect on how their designs have evolved from the sketches to the prototype.

7. Encourage children to use multiple representations

Different modalities – visual, verbal, pictorial, concrete - supports children to visualize better and communicate their design ideas. Our findings indicate that it can be difficult for children to visualize and depict design ideas in visual representations only. Hence, manipulating concrete materials, verbal explanations, and hand gestures supported the communication of design ideas. Therefore, we recommend encouraging children to use different forms of representations to support the visualization and communication of their design ideas.

5.5.2 Limitations & Next Steps

First, this study is an exploratory step to understand children's learning in sketching while participating in engineering design activities in their home environment with their parents to support their learning about the role of sketching in engineering. We call for future research to expand on ways to support children's learning and development of sketching with different modalities in formal and informal design environments.

Second, the findings are limited based on the parents scaffolding the sketching process for children with the support from facilitation guides in kits. Providing demo design sessions to caretakers was beyond the scope of this study. However, further research can examine the influence of the researcher team scaffolding the design process by conducting demo sessions with caretakers on children learning.

Third, this study approaches data analysis with a particular focus on children's learning in design sketching during their participation in at-home engineering design activities. These findings are limited in multiple ways, such as irregularities in video data; some recorded the entire design process, and others only recorded the demonstration of their sketches and prototypes. For example, two children's sketches were not visible in the video data. Therefore, we did not focus on analyzing the frequency of patterns in children's sketching; instead, we focused on examining various emerging patterns of children's learning design sketching activities. Future researchers can build on this study to investigate the similarities and differences in scaffolds for supporting children's learning in larger groups versus smaller groups.

5.6 Conclusion

This study provides meaningful insights into the details of sketches drawn by children, and those sketches get used by them during the overall design process. It also provides insight into learning while children sketch for designing engineering products in their home environment. Based on these findings, we conclude that children learn essential design skills when sketching for engineering products. Therefore, we argue that sketching can be a powerful tool for engaging children in learning environments. This study contributes to the field of technology design with children in two ways - first, it provides an understanding of children's sketches, sketching, and learning experiences in the STEM design; and second, it provides an updated version of RCCI establishing the relationship between various pillars of learning in the design process. Finally, this study offers practical recommendations for future design educators on supporting children in developing sketching skills during STEM design practices.

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Chapter 6: Synthesis & Conclusion

Learning and design fields aim to improve human experiences by solving problems. Design activities provide a rich context for learning through planning, defining, making, building, or programming. Traditionally, design theorists have focused primarily on the product, while learning theorists have focused on the process. Recently, learning and design theories have begun to move toward one another. Now, designers focus on understanding objective constraints and subjective meanings during the design process. At the same time, learning theorists have begun to pay more attention to the role of products and artifacts. In this way, design overlaps with learning as both focus on constructing meaning (See Figure 6.1).

Design scholars argue that we need to understand children's learning experiences in design better, and learning scholars claim that design approaches can help children learn (DiSalvo et al., 2017; Eriksson et al., 2022; Giannakos et al., 2022). However, a need exists to understand how to support children in developing their design abilities and learning as they participate in design (Antle & Hourcade, 2021; Bulger et al., 2021; Ito et al., 2020). Therefore, the intersection of design and learning is among the most active research areas in child-computer interaction (CCI) literature (See Figure 6.1). Design-based learning environments combine the arts and the sciences, school and play, and work and life (Dindler et al., 2020; Scheltenaar et al., 2015). This dissertation aims to contribute to the intersection of design and learning, exploring the nature of learning in design and learning by design, its cultural contexts, activities, and tools (See Figure 6.1).

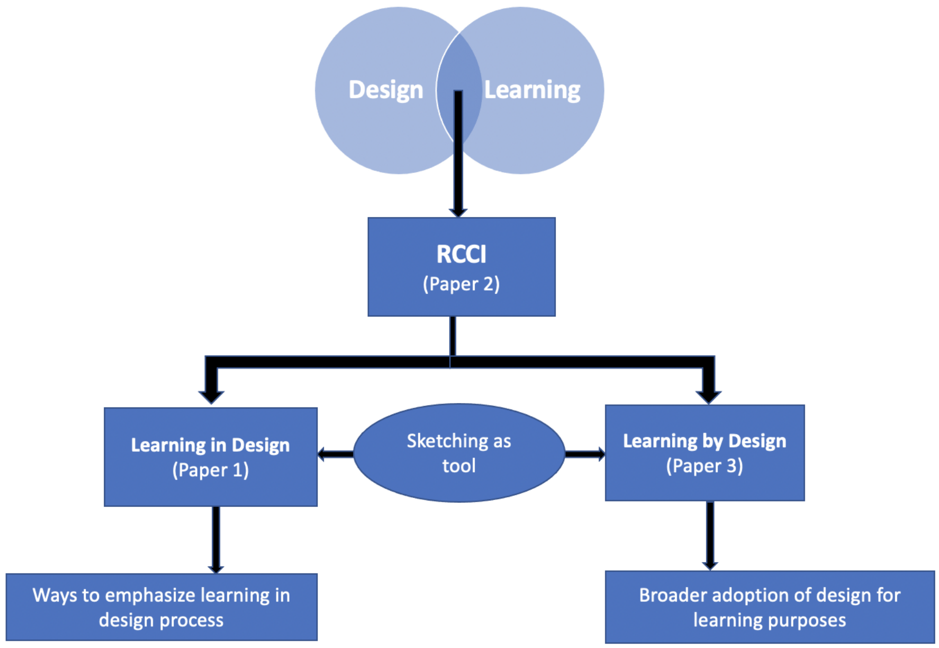

Figure 6. 1: Synthesized overview of the dissertation

"To meet the demands of the increasingly complex globalized labor market, all our children must develop their creativity, flexibility, and problem-solving" (Gallagher-Mackay, & Steinhauer, 2017, p. 7). Due to the increasing innovation and advancement in technology in every segment of the human experience, we need to prepare our children to tackle the future challenges associated with the use of technology (Díaz & Ioannou, 2019). It is difficult to determine what forms future problems might take. Therefore, it is essential to help children develop a critical stance toward the role of technology in human experiences (Chen & Chiu, 2016; Iversen et al., 2017). One way to do this is to let children identify problems in their daily experiences and encourage them to solve them. Design becomes a helpful approach for developing children’s problem-solving skills as it breaks down the problem-solving process into distinct steps.

Paper 1 of this dissertation explores the learning opportunities that occur when children are encouraged to lead the design process while working on solving problems based on their interests. The findings from Paper 1 suggest that design activities can serve as a learning tool for children to develop their communication, collaboration, and problem-solving skills. However, it is difficult to identify what, when, and where learning happens in design activities as the field of CCI lacks clarity and consistency in the theoretical understanding of learning (Christensen & West, 2018; DiSalvo et al., 2017; Eriksson et al., 2022).

In a recent literature review on the Theoretical Framing of Learning in Design, Eriksson et al. (2022, p. 60) highlighted, "The role of learning theory in CCI is mainly application, meaning that the theory is used ‘as is’ (Lyle et al., 2020). Moving towards a more generative perspective, using learning theory as analysis or synthesis could be a way forward." This dissertation work, particularly the development of the RCCI framework, is a response to this call. Paper 2 provides the called-for generative perspective through synthesis with a learning theory to understand ‘learning in design’ (See Figure 6.1). Paper 2 suggests ways to emphasize learning in the design process. The data from Paper 1 is used in Paper 2 to demonstrate using RCCI as a guiding analytic tool for examining children’s learning in design. Paper 3 further builds upon Paper 2 and forefronts the generative nature of RCCI. Despite the differences in the design context and approach of Paper 1 and Paper 3, using the RCCI framework (Paper 2) helps to identify ‘learning by design’ (See Figure 6.1). Here ‘learning by design’ entails the study focusing on children's learning by engaging in the design process (See Figure 6.1). Finally, Paper 3 suggests that the RCCI framework can be productive and generative within and for various design environments.

This dissertation work is a first step in establishing the shared connection between the theories of design and learning, empirically and theoretically demonstrating that learning can be part and parcel of design activities with children. Paper 1 and Paper 3 explicitly focus on one design activity - 'sketching' - as it is predominantly used in learning and design (See Figure 6.1). However, we need to understand better how to scaffold sketching to children in design (Merzdorf et al., 2021; Stammes et al., 2023; Sung et al., 2019). Collectively, the findings of this dissertation suggest that designers can benefit from integrating learning into design activities, and educators can benefit from the broader adoption of design activities for learning purposes (See Figure 6.1 for connections). This dissertation research reveals new ways to plan, execute, and examine design environments to support children's learning.

6. 1 RCCI Framework

The RCCI framework provided in Paper 2 emerged from the synthesis of the 'design with children' approach of Cooperative Inquiry (Druin, 1999; Iversen et al., 2017) and the Radical Constructivist theory of learning (Cobb & Steffe, 2011; Glasersfeld, 1995). As the pillars of the RCCI framework emerged from the interaction of design with children's literature, it is natural and intuitive that these pillars occur already in the design practices with children. However, the RCCI pillars expand on design practices with an established learning theory to provide unique ways of improving children's experiences in design practices. It provides six pillars that can provide the foundation for learning in design activities. These six pillars are - Child-centered, Collaborative, Dynamics, Iterative, Representation, and Outcomes. These six pillars break down the learning into identifiable components, which can be helpful as a guiding tool for future design activities. Consequently, future CCI researchers can use the six RCCI pillars to see new learning aspects through this lens. Below is the discussion of new ways RCCI pillars propose to identify and support children's learning in design practices.

First, the Child-centered pillar: The conventional view of CI argued for involving children as 'equal' design partners in the design process (Druin, 1999); more recently, scholars in the field of CCI argued that making children the lead agent in the design process promoting the 'design by children' approach (Gennari et al., 2022; Roumelioti et al., 2022). However, the previous research is unclear on who should identify the problems that get solved by children during the design process. Thus, the RCCI Child-centered pillar updates the previous role of children in design by adding the component that children should decide what problems they want to solve based on their interests or choices. The Child-centered pillar also posits that examining children's untutored design approach is essential to understand their thinking and learning about design.

Second, the Dynamics pillar: Prior literature on the interaction design with children explored the 'dynamics' of the design process and the role of relationships between the child and adults, emphasizing the differences in scaffolding and facilitation conducted by different adults in the design process (Yip et al., 2016; Yip et al., 2017). However, the previous design research on the 'dynamics' in design lacks clarity on how differences in design activities' dynamics influence children's learning. Thus, the RCCI Dynamics pillar provides a new dimension of dynamics that emphasizes the change in children's learning based on the change in the design environment. RCCI details what 'dynamics' looks like in design activities to support children's learning.

Third, the Iterative pillar: Prior research in design explains the 'iterative' nature of design activities. However, there is a need for clarity on the 'iterative' nature of learning that happens during design activities. The Iterative pillar suggests that adults need to iteratively design sessions based on children's responses between and within each design episode to support learning. Adults must iterate their facilitation based on children's engagement in design activities.

Fourth, the Representation pillar: The term 'representations' is commonly used in the design process; however, its use is limited to low-fidelity and high-fidelity prototypes. In design with children, low-fidelity prototyping is usually a 'bag of stuff' consisting of concrete materials. More recently, scholars have started examining what design with children looks like in virtual environments (Constantin et al., 2021; Fails et al., 2022). However, what representations might be helpful during the virtual design process with children needs more clarity to support learning in design and learning by design. Therefore, the RCCI Representation pillar suggests researchers take a broader view of different modalities used to represent information: textual, visual, gestures, actions, concrete material, and verbal. This pillar suggests that using multiple representations in design activities can help adults identify and support children's learning moments in design activities.

Fifth, the Collaboration pillar: Prior work in design with children emphasizes the collaboration between adults and children in the design process (Yip et al., 2016; Yip et al., 2017). Often the adults lead the design process as an expert in design. However, we need more understanding of facilitating collaborative interactions for children's learning in design. The construct of the Collaborative pillar in the RCCI framework entails the collaboration in child-child, child-adult, and child-child-adult interactions; here, adults are not necessarily designers and researchers but could be caretakers. Collaboration in design and learning can occur at multiple levels, which may or may not include adults who may or may not work with multiple children during the design process. If two individuals, child-child or child-adult, work together on a design, it can provide learning opportunities for children.

Sixth, the Outcomes pillar: During the design activities, 'outcomes' are often measured regarding product or team development; however, in design with children, one of the critical outcomes to be measured is what children learn during the design process. Learning outcomes often need to be noticed when focusing on technology development. Sometimes, learning outcomes are evaluated cumulatively through post-design sessions, questionnaires, and interviews. These evaluations are beneficial but less helpful in understanding what learning occurred and how – understanding which can be useful for supporting individual development. In RCCI, the Outcomes pillar addresses a wide range of learning outcomes possible with children's engagement in design activities.

6. 2 Recommendations

Below, I provide pedagogical recommendations based on the two empirical contexts, Paper 1: SDC and Paper 3: MAKEngineering Project, that can benefit designers and educators interested in supporting children's learning in design and learning by design. There are five categories of recommendations – Child-centered, Dynamic Representations, Collaboration, Brainstorming, and Sketching.

6.2.1 Child-centered

Design activities should be customized based on children's interests to support their learning. For instance, the SDC sessions were iteratively designed based on children's responses and engagement in the previous section. The nature of child-centered activities was different in the MAKEngineering project; children selected the kits that interested them out of the predetermined list of product kits; however, they decided the design of the product based on their interests. Thus, child-centeredness in design activities can be composed in multiple ways. Below are some ways how we can design child-centered design activities.

First, allow children to choose the problem they want to solve via the design process. For example, in the SDC, children decided on the design problems and solutions based on their interests. Encourage children to identify and solve their problems and limit the adult's role to scaffolding the design process to children. In such scenarios, children may or may not develop novel solutions, which is less important than children's learning during and about the design process.

Second, adults should encourage children to create and test their prototypes during design. For example, in MAKEngineering, adults encourage children to create and test the prototypes of design ideas, and findings indicate that children learn a lot about their designs by testing their prototypes. Therefore, I recommend providing children the opportunity to test the design of the prototype created by them.

Third, adults should encourage children to reflect on what they learn during the design process about conceptual knowledge and skills. In the SDC and MAKEngineering projects, there was no summative assessment of children's learning; however, within the design process, children were encouraged to reflectively think about how they approached the design process.

6.2.2 Collaboration

The dissertation research indicates that differences in collaboration opportunities in design activities lead to differences in learning opportunities for children. For example, in the SDC, more child-child collaborations led to learning opportunities for brainstorming and building on ideas collectively. However, in the MAKEngineering project, there was more collaboration between adults and children due to the low ratio between adults and children, which led children to learn how to use concrete representations to elaborate on the design ideas depicted in visual representations. These examples suggest that children should be engaged in different collaborative activities. Finally, there are multiple ways in which we can provide children opportunities to collaborate in design activities, as discussed below:

First, adults should encourage children to collaborate among themselves without the direct supervision of adults during design activities. As noted in the SDC, engaging in a collaborative activity as a pair allowed children to learn how to negotiate the differences of opinions and develop a shared solution.

Second, children should be allowed to engage one-on-one with adults during design activities. As found in the MAKEngineering project, children's collaboration with their caretakers during the design process allowed them to learn new knowledge in movement and better communication of design ideas.

Third, provide children with opportunities to collaborate with different individuals. For instance, in the SDC, the children were in pairs, and the adults in the group were rotating so that children had a wide range of opportunities to learn from each other.

6.2.3 Use of Dynamic Representations

The findings from Paper 1 and Paper 3 demonstrate that using multiple representations supports children's learning in different ways. For example, in the SDC's virtual environment, children's verbal explanations in design activities explain the contextual information behind their visual representations. Additionally, while engaged in collaborative sketching, children were found using hand gestures with their verbal explanations to communicate their design ideas. Similarly, in the MAKEngineering project, children were observed using visual and concrete representations to discuss their design ideas with adults. These examples suggest that children can benefit from using additional representations, such as gestures and verbal explanations, in order to articulate their design ideas depicted in sketches. This dissertation's findings recommend that scholars address the fluency in different forms of representations used by children in design activities as it can reveal necessary information about children's learning during the design process. Practitioners should allow children to use various representations in design activities to communicate and collaborate on their ideas. In addition, there are multiple ways to facilitate the use of multimodal representations in design activities with children, as discussed below:

First, adults should demonstrate using hand gestures and manipulating concrete objects when communicating design ideas with children. As noted in Paper 3, using gestures and manipulatives by adults during verbal explanations helps children learn better communicate ideas during collaboration. Therefore, scholars should demonstrate the use of different representations in communication and collaboration to support children in learning to leverage different forms of representations while communicating design ideas.

Second, adults need to explicitly state to children that they can leverage different modalities (e.g., manipulations of concrete objects present in the surrounding) to demonstrate their static visual representation. For example, in the MAKEngineering project, adults encouraging children to use concrete objects to explain their sketches found to help children and adults to develop a shared understanding of ideas depicted in static visual representations. Similarly, when children struggle to develop a shared understanding of visual representations in the SDC, pictorial representations (images) help them reach a consensus on how to depict a design into a visual representation.

Third, adults should attend to children's gestures and visual representations when they verbally explain their ideas, as it can reveal additional information, which needs to be followed by adults re-voicing children's explanations to confirm whether their interpretation of children's ideas matches what the children intended to communicate.

6.2.4 Brainstorming

Brainstorming helps designers to collect ideas around a problem. In CI, children usually brainstorm using sticky notes and 'bags of stuff.' This dissertation suggests that sketches can be a great brainstorming tool for and with children. In Paper 1, examining children's visual and verbal representations in the SDC reveals much information about their personal experiences, expectations, and beliefs. In Paper 3, examining children's sketching experiences indicates that sketches are an excellent tool for children and adults to brainstorm ideas. During brainstorming in the SDC, children mostly sketched digitally and discussed using digital sticky notes in a virtual environment, whereas, in the MAKEngineering project, children drew sketches on paper in the physical environment of their homes. Despite the differences in the modality of sketches in the SDC and MAKEngineering, both contexts indicate that sketching proves to be a valuable brainstorming tool. Therefore, future researchers and educators should encourage children to use sketching for brainstorming. There are multiple ways of incorporating sketching into the brainstorming activity:

First, in the design environment, adults should allow children to brainstorm ideas about pictorial representation using sticky notes. As noted, in the virtual design context of the SDC, children were found discussing ideas related to sketches and images. It allows them to learn how to build on ideas during the design process. In similar contexts, static visual representations can act as situated artifacts for children to brainstorm ideas.

Second, adults should encourage the child to draw multiple freehand sketches to brainstorm ideas in the design planning phase. Adults should ensure that children are free to draw whatever they think can be the potential solutions to the problem they are trying to solve, as these ideas can be used or evaluated later for their pros and cons. For example, in the MAKEngineering project, multiple sketches drawn by children were helpful in the later stages of the design process. In some cases, the design ideas pursued by children for building prototypes were a mix of the ideas depicted in their different sketches.

6.2.5 Sketching

Sketching is a problem-solving tool prevalent in design and learning fields. However, in both fields, there is a need to understand how to best support children in developing sketching skills (Stammes et al., 2023; Sung et al., 2019). This dissertation research suggests that children can develop sketching skills in design activities if supported with in-moment feedback on different sketching components. In Paper 1 and Paper 3, sketching was a critical component of the design process, and in both contexts, solely children did the sketching. However, there were differences in what children learn about sketching in both contexts. For instance, in the SDC, children learn about collaborative sketching and the affordances of digital sketching for virtual collaborations during the design process. In the MAKEngineering project, children learn about the relevance of different points of view in design (e.g., top-view, side-view, and how to represent a three-dimensional product in two dimensions). Therefore, as educators, we should encourage children to sketch whenever they are involved in the design. Adults can support children in developing their sketching skills during design activities in multiple ways. Below are some recommendations to support children's development of sketching skills in design.

First, adults should scaffold the different components of sketching gradually to children. For instance, in the SDC, children were gradually introduced to different sketching components. In session 1 of the SDC, children drew their favorite technology product to focus on sketching rather than brainstorming a design idea. Later, during their sketch demonstration, they were introduced to the importance of labeling their sketches. In later sessions, children learned to use sticky notes to build on design ideas depicted in sketches. Finally, they were encouraged to engage in collaborative sketching once comfortable with individual sketching. This session-by-session progression in sketching skills helps children learn and adapt to different sketching components. Thus, I recommend that adults break down the sketching process into simplified steps for children to adapt to their sketching.

Second, it is essential to explicitly state to children that they can draw information from their experiences and surroundings during the design process. As found in Paper 1 and Paper 3, brainstorming, research, and children's personal experiences inspired the designs in their sketches. Thus, scholars should gauge children's different funds of knowledge during research and brainstorming steps to give them a wide variety of inspiration.

Third, adults should encourage children to explain their sketches to someone. As noted in the context of the SDC and MAKEngineering project, children's verbal explanations of their sketches helped them better understand the design and ideas depicted in them. In response, the questions asked by the children and adults helped them think about the different pros and cons of their design and reflect on the ways to improve the design. Therefore, I recommend that children be allowed to explain their sketches to others who ask them questions about their sketches.

Fourth, adults should encourage children to use textual representations in their sketches. For instance, in the SDC and MAKEngineering project, children were encouraged to use textual labels in their sketches, increasing their visual representations' communicative value. Therefore, I recommend that adults explicitly explain to children how textual information can help improve the communicative value of sketches.

Fifth, adults should provide children with options for choosing the modality for sketching. For instance, in the SDC, children could choose whether to sketch their ideas digitally or use paper and pencils. These choices allowed children to express themselves in a virtual environment fully. Therefore, I recommend providing children with choices for modalities in which they prefer to sketch, whether it is a virtual or in-person design environment.

<u>6.3 Broader Implications</u>

This dissertation explored children's learning within design activities and suggests that design activities hold the potential to help children learn abilities useful in STEM fields. This dissertation demonstrates that design activities can help plant the seeds of how to approach real-life problems collaboratively. Design activities hold the potential for developing lifelong career-relevant skills such as problem-solving, collaboration, and communication. Therefore, the field of learning can benefit from the broader adoption of design activities with children. Design activities give children tools to approach a problem holistically and develop their problem-solving ability at the intersection of STEM. With the design approach, we can support children in developing their competence to solve complex problems.

The potential of using design activities to improve children's learning experiences is vast, and this dissertation is the first step in this direction that explores children's learning experiences in informal STEM environments. This dissertation suggests that further research needs to explore the potential of design in other areas of learning to fully leverage the benefits of design approaches in children's education.

Children's learning in design activities is not only beneficial for children, but it holds value for designers as well. For instance, if children learn to sketch their ideas, they can contribute more information in design sessions, especially about their expectations, experiences, beliefs, and knowledge. Researchers can collect information about the broader context of children's lives if they learn how to better communicate and collaborate during design. The findings from this research imply that researchers interested in developing learning technologies can benefit from children's learning how to perform design activities as it will help designers identify children's needs and areas of interest. Therefore, designers should support children's learning in design activities.

6.3 Limitations & Scope of Future Research

This dissertation demonstrates that we need to understand better the process of learning during design to provide appropriate support for children to develop STEM skill sets. This dissertation has offered some suggestions, but further research is needed to investigate how we can best support children learning to sketch to solve problems in STEM design. There was consistency in the scaffolding provided to children in the SDC context, as the same researcher led all the sessions with the same group of children. However, there were some limitations to working with families and caregivers as widely varying facilitators of the design process. The caregivers were not trained with any facilitation workshop to support children in making design process other than the content and prompts in the kit. The inconsistency in facilitating the design process by adults leads to a wide variety of scaffolding they provide to their children. For example, some children labeled different parts of their sketches, but others did not. These differences in scaffolding imply that future research in similar contexts - e.g., future kit design - can benefit from using the recommendation discussed in this work and provide some training for caregivers to support children in developing their sketching skills.

This dissertation demonstrates a wide variety of learning in the two design contexts - SDC and MAKEngineering context. However, despite differences, the RCCI framework helps to examine learning moments in both contexts. The findings of Paper 3 imply the flexibility and adaptability of the RCCI pillars, and future researchers can use the RCCI pillars for planning, conducting, and evaluating learning in design activities for children.

This research shows promising learning benefits of using sketching in STEM design. However, due to the novelty of the research questions examined in this dissertation, there are still many open questions about educators' role in scaffolding sketching and learning during design activities for children. In terms of understanding the moments of learning in sketching during STEM design, we need future research to address the questions such as - Does it make any learning difference if children engage in sketching on paper versus digital sketching for STEM design? Are there any learning differences if children are sketching with their caretaker versus researchers and designers? Is it possible to facilitate learning about sketching in an asynchronous virtual environment? All these are open questions about children sketching and learning that will help us better understand the actual use of sketching for learning in STEM design.

This research provides recommendations for supporting children learning in sketching activities, which designers can utilize to develop future technologies-software applications to support children learning and sketching. In particular, the latest virtual reality and augmented reality application that promises to enhance the perception and understanding of complementary affordances of 3D (immersive, unconstrained, life-sized) and 2D (precise, constrained, ergonomic) interaction for in situ 3D conceptual design (Arora et al., 2020; Drey et al., 2020). However, they are currently facing the challenges of providing appropriate scaffolding or constraints for these interactions (Kent et al., 2021; Drey et al., 2020). Therefore, future work in design can benefit from investigating the affordances of different platforms that claim to support sketching in design and finding ways to improve those applications designed for children learning about sketching based on the insights from this work.

The insights of this dissertation are also limited to theoretical synthesis and study of two informal STEM design environments - public libraries and children's homes with a wide range of influential factors in the data. These findings are limited to small-group STEM design interactions. However, providing insights on how to support the learning and design with larger groups of children was beyond the scope of this dissertation. Further research can examine children's sketching and learning experiences in large groups or formal STEM design contexts.

Due to the exploratory nature of this research, there are some limitations regarding the context of the studies included in this dissertation. For example, Paper 1 and Paper 3 of this dissertation focus on children's learning about a particular STEM design skill, 'sketching.' Future research can examine learning other design skills, such as problem-solving and collaboration. The sketching was implicitly included in the activities' design of SDC and MAKEngineering projects, making these contexts appropriate for this dissertation work. Future research can leverage this work's empirical and theoretical findings to design and conduct research with an explicit focus on the learning of sketching in STEM design with children.

This dissertation mainly focuses on middle-school-age children's STEM education via design activities. However, further research can explore the potential of design activities in making children learn about literature, history, and other topics. For instance, we can encourage children to create stories together using design activities such as brainstorming, sketching, and layered elaboration.

Conclusion

The fields of learning and design are evolving rapidly, and there is complementary information between these two distinct communities of knowledge. The scholars in these communities can benefit from each other's theoretical foundations of learning to facilitate better learning experiences for children. This interdisciplinary dissertation explores the complexities of children's learning experiences with design, which needs to be understood by both the learning and design fields. Learning is implicit in the design of experiences; however, we need to empirically and theoretically unpack the affordances of design activities in children's learning experiences. We need to understand *how to support children in developing STEM skill sets*.

This dissertation is the exploratory step towards establishing an understanding of children's learning and sketching experiences in informal STEM design environments. This work provides theoretical and empirical foundations for attending and supporting children's sketching and learning in STEM design activities. The contribution of this study is a better understanding of children's sketching to strengthen future design processes with children and prepare researchers to support children's sketches better. Moreover, it establishes that understanding children's sketching by providing insights into what children do while sketching, the way they do it, and how we can examine and support children's moments of learning in design practices.

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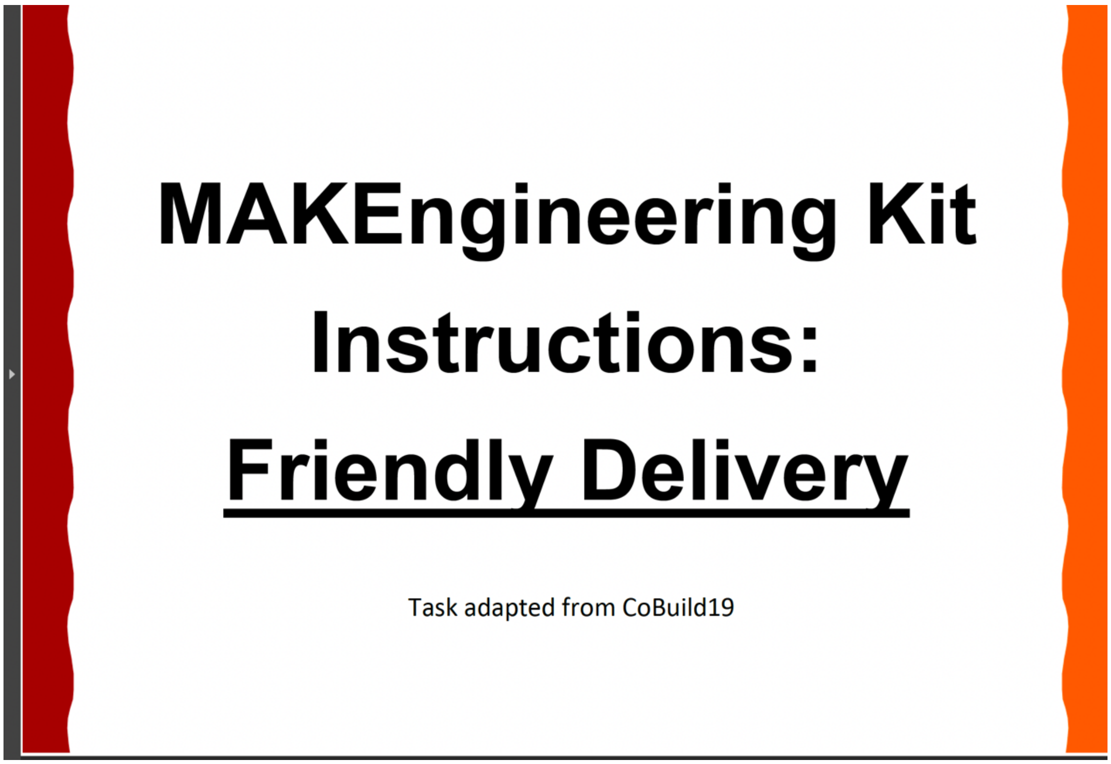
Appendices

Appendix A



ENGINEERING TASK

You want a way to secretly and safely share objects with your friend who lives next door. You choose to design a prototype that will deliver an object at least 6 feet.

1

DID YOU KNOW…?

In August 2020, Amazon got a "yes" to deliver packages by a drone. A drone is a flying object with no human pilot, but controlled remotely by a user or computer program.

2

MATERIALS IN KIT

- Ziploc bag of pasta
- 10 pipe cleaners
- 10 Paper clips
- 10 rubber bands
- 10 wooden dowels
- 10 large popsicle sticks
- 10 straws
- ~3 feet of yarn
- 6 fabric softener sheets
- 6 sandwich bags
- Fishing wire
- Scissors
- Electrical tape
- Hot glue gun & 2 sticks

3

STEP 1—RESEARCH

Let's consider some of the different types of delivery options and how they work.

A zipline? A wind-powered car? A catapult? An airplane? A bird? Superman?

On the next page is a link to information to get you started in your research. What do you notice that might be helpful in designing a solution for your task? Remember to take notes and feel free to explore other delivery options.

4

STEP 1—RESEARCH

How do ziplines work?

https://adventure.howstuffworks.com/zip-line.htm

How does a car run by wind power?

https://youtu.be/3sxileCaBIc

What things should be considered when designing an airplane?

https://www.foldableflight.com/post/how-to-design-your-own-paper-airplane

How does a trebuchet, a special kind of catapult, work?

https://youtu.be/W5RFoowvGkw

5

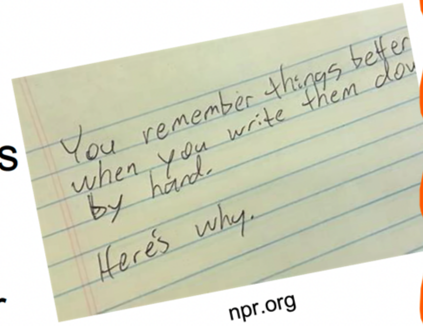
MATERIALS IN HOME—BINGO STYLE

Now that you have two designs, let's find materials around your home to make it happen. As a family, work together to find items to complete the bingo card on the next page. As you search for objects, think what kind of parts do ____ (e.g., cars) have?

7

STEP 2—PLAN

What will you deliver?
How will you deliver it?



npr.org

Draw two detailed designs or sketches for your delivery system. How did your research inform your designs? Keep in mind the size, weight, and shape of your object to deliver.

6

MATERIALS IN HOME—BINGO STYLE

Now that you have two designs, let's find materials around your home to make it happen. As a family, work together to find items to complete the bingo card on the next page. As you search for objects, think what kind of parts do ____ (e.g., cars) have?

7

Paper-based item	Something that is round or a cylinder but as many of this item as you want.	Something that is flat and sturdy
Random items from a “junk” drawer or recycle bin	FREE SPACE (anything that will help you innovate)	Food container of any kind
Something that will help keep things together	Something that clips	Something that adds personality

8

STEP 3—CREATE

Pick one of your designs from Step 2 and build a prototype.

What are the wheels on this car?

What could that paper airplane deliver?

9

STEP 4—TEST

Now that you have built your prototype, it's time to test.

(Psst. Some wise person, William Whewell said, "Every failure is a step to success.")

Document or write down your failures…

and celebrate your successes.

10

STEP 5—IMPROVE

"Changes call for innovation, and innovation leads to progress." ~Li Keqiang

As a family of engineers, discuss the following:

What are three ways you can improve upon your prototype? How are these based on the results from your testing step?

11

DID YOU KNOW...?

Bubble wrap was crated in 1960 in an attempt to create a trendy new textured wallpaper. Oops! IBM was the first to use bubble wrap to package and transport a computer.

Some adults use Legos as a prototyping resource. You know, those toys that kids play with?

It took 36 prototypes to create Wheaties, a popular breakfast cereal. Yes, development of a new food item is prototyped just like your prototype of a friendly delivery system.

12

EXTENSION

"Don't limit your challenges. Challenge your limits" (Anonymous). Are you up for a challenge?

- Deliver an object further than 6 feet. 10 feet? 12 feet? 20 feet?
- Complete a delivery with an obstacle in the way (e.g., chair)
- Deliver additional objects. How much weight can your prototype hold?
- Build a different container. What shape of the container can hold the most weight?
- Complete a delivery in a time faster than your first prototype.

13

DID YOU KNOW...?

Mechanical engineers research, design, develop, build, and test mechanical devices, including tools, engines, and machines. Jobs for mechanical engineers are projected to grow 4% from 2019 to 2029 and considered to be one of the most popular engineering fields. But in the year 2018, only about 15% of Bachelor degrees in mechanical engineering were awarded to women.

14

WHAT TYPE OF ENGINEER ARE YOU?

Add a sticker to your Engineering Passport that identifies the type of engineer you were most like in the design of a friendly delivery system. Don't forget to write why you chose the type of engineer.

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