Early Childhood Engineering: Supporting Engineering Design Practices with Young Children and Their Families

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In recent years, there has been an increased focus on introducing young children to STEM as a way of cultivating early interests and understanding that ultimately contribute to broader participation in the STEM fields overall (Immordino-Yang et al., 2018; McClure et al., 2017). However, while there is substantial research around early childhood mathematics (e.g., Phillipson et al., 2016; Zippert & Rittle-Johnson, 2018) and a growing body of literature around early childhood science (Oppermann et al., 2017; Silander et al., 2018), early childhood engineering continues to be the focus of only a few studies.[1]

This lack of research can lead to several challenges, such as the creation of early engineering experiences that are not optimally productive, inviting, inclusive, or engaging. Negative early experiences with engineering and design can lead to inaccurate perceptions about what engineering is and who engineers are (Knight & Cunningham, 2004) that can be extremely difficult to correct. In contrast, positive early learning experiences with engineering can provide young children with opportunities to participate in meaningful design-focused interactions (Cardella et al., 2013; Svarovsky et al., 2018), which can in turn lead to sustained and increased levels of engineering interest and engagement (Pattison et al., 2020; Pattison, Weiss, et al., 2018). Given the lasting, potentially lifelong effects (both positive and negative) that early exposure to engineering can have on children, it is critical that researchers and educators understand how to effectively engage young children with this topic.

In this paper, we summarize four recent projects that have explored how different in-school and out-of-school experiences support 3- to 8-year-old children as they engage in engineering design. Across a variety of learning contexts, including preschool classrooms, science center field trips, and family learning at home, the studies investigated how the characteristics of the activities and spaces, as well as the practices of teachers, facilitators, and parents, make space for and encourage engineering design thinking. Collectively, the studies provide a deeper understanding of the age-appropriate ways for young children and their families to engage in engineering design practices; how engineering design contributes to other important learning and development outcomes in early childhood; and the ways activity, educational design, and teaching characteristics support or hinder engineering design practices at this age. We end with a synthesis across the four studies of emergent ideas and promising directions for future research to better engage young children and their families in engineering design practices.

First Graders' Engineering Design Processes During a Field Trip Activity: Expanding Problem and Solution Spaces

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Subject/problem. Over the past two decades, the inclusion of engineering design in K-12 settings has become increasingly common (e.g. NGSS Lead States, 2013; National Research Council, 2012). This is true across school and out-of-school settings. However, while the need for engineering design experiences for younger children has been recognized (e.g., Froyd et al., 2014), there is still a need for empirical research that characterizes how young children engage in developmentally-appropriate engineering design activities, how different activities provide space for children to practice different aspects of engineering design, and how adults facilitate children's engagement in engineering design practices and processes (e.g., Miaoulis, 2014). This study examines groups of first grade children as they enage in an engineering design activity, how they make sense of the problem, and how they generate solutions to the problem.

Design/procedure. This exploratory qualitative study focuses on first grade children's and their facilitator's conversations during a fieldtrip to a small science center. Five groups of three-to-four students circulated through five stations of activities and their interactions with each station facilitator were video recorded. A total of 70 minutes of video data collected from eleven students from three groups at one of the stations were analyzed using a modified version of Powell, Francisco and Maher (2003)'s video analysis approach. In this study, the focus was on an engineering design activity that prompted children to "design something to transfer a sick animal to the animal hospital" using K'Nex construction materials. No other instruction was given to the facilitator or the children. The activity was implemented in the Animal Hospital Exhibit in which children could pretend to be an animal doctor and help sick animals. Children were free to work together or separately on their own or their group's ideas.

Finding and analysis. Analysis of the video recordings suggests that for each group of children, that the problem space and solution space expanded gradually and co-evolved as a result of children's conversation with each other and their facilitator. During this iterative design process, the formulation of the problem led to the development of ideas for the solution; refining the solution resulted in expanding the characteristics of the open-ended problem, and this process continued until each group had run out of time. The authors observed evidence of both the facilitator and children contributing to the expansion and refinement of the problem and solution spaces. However, the facilitator played a strong role in the formulation of the problem and leading children's process, whereas children were mostly involved in brainstorming ideas and expanding the solution space.

Contribution to the teaching and learning of science. NGSS has emphasized an iterative engineering design process with (a) defining engineering problems, (b) designing solutions, and (c) optimizing the solution, as three distinct core components. The findings of this study suggest that first grade children engage in a design process similar to that of adult designers, where the problem space and the solution space co-evolve (Dorst & Cross, 2001)—the formulation of a problem and ideas for a solution are developed and refined together. Therefore, teachers and curriculum designers may want to provide design opportunities for young children to engage and reflect on both spaces.

This paper helps expand our understanding of what engineering design can look like for young children, particularly as engineering design is considered to be not only about solving problems, but also about identifying and understanding problems. Previous studies have showed that elementary grade aged children are capable of engaging in problem scoping with and without the involvement of adults (Watkins, Spencer, & Hammer, 2014; Haluschak, 2018; Svarovsky, 2017). In this study, the facilitator's strong involvement in problem scoping may have encouraged the children to consider different aspects of the problem and prevented them from sticking to their initial ideas like beginning designers (Crismond & Adams; 2012). However, it is possible that this strong involvement may have limited the opportunity for children to engage in constructing meaningful understanding of the problem on their own and through interactions with their peers. This is aligned with the observations of Haluschak and colleagues (2018) of second graders where too much scaffolding from a teacher may have resulted in limiting the problem space or not allowing students to make connections on their own. While adults can provide important scaffolding and support for children as they engage in engineering activities (e.g. Ehsan, Rehmat, Osman, Ohland, Cardella, & Yeter, 2019; Svarovsky, 2017; Ehsan & Cardella, 2017), further research is needed to explore the ways adults can effectively support children while also making space for children to fully engage in problem scoping and other design activities.

Mapping Family Engineering Interest Development in Early Childhood

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Subject/problem. In an increasingly science- and technology-rich world, it is imperative that children from all communities develop the science, technology, engineering, and math (STEM)-related knowledge, skills, and attitudes that will allow them to succeed in school, life, and work.

Growing evidence suggests that to achieve this goal, children must develop *interests* in STEM activities, topics, and careers (Harackiewicz et al., 2016; Renninger et al., 2015). Interest is a fundamental motivator of human behavior that supports learning and engagement (Renninger & Hidi, 2011; Silvia, 2006), shapes attitudes and self-perceptions (Bathgate & Schunn, 2016; Leibham et al., 2013), guides choices about STEM engagement inside and outside of school (Azevedo, 2015; Sha et al., 2016), and ultimately influences career decisions (Tai et al., 2006; Watt & Eccles, 2008).

We now know that the foundations of these interests begin before children enter school (Ainley & Ainley, 2015), setting in motion patterns and feedback loops with long-term implications (Crowley et al., 2015). In response, an increasing number of early childhood education programs have been developed to engage preschool-age children and their families in STEM (McClure et al., 2017). However, as a field we lack knowledge of how the interests developed through these programs continue, how they influence broader family learning patterns, and what factors and resources afford or constrain these processes. This is especially true for the topic of engineering

Design/procedure. In order to advance knowledge and theory of early childhood engineering-related interest development, the team conducted retrospective home-based interviews with children and their parents one to two years after they had participated in the Head Start on Engineering preschool family engineering program embedded within the Mt. Hood Community College Head Start system in Portland, OR (Pattison, Núñez, et al., 2018; Pattison, 2019). Head Start is a national, federally funded program that promotes school readiness among children under five living in poverty through preschool programs, home-visiting services, and other family support.

Using a family systems perspective (Pattison et al., 2016, 2020; Pattison, Weiss, et al., 2018), the interviews were designed to address the following research questions: (1) What are the characteristics of engineering-related interest pathways for families one to two years after engaging in an early childhood engineering education program? and (2) What resources, contextual factors, and family characteristics appear to support or undermine ongoing family interest development as children enter kindergarten? The team worked with Head Start staff to recruit 18 English- and Spanish-speaking families and then conduct home-based interviews with children and their parents about their current interests, their memories of the program, the ways that the families had continued to use or engage with program materials and ideas, evidence of their evolving engineering-related interests, and barriers and supports to sustained interest development. Interviews were transcribed and qualitatively analyzed using NVivo software.

Findings and analysis. In-depth qualitative analysis of the interviews using inductive coding and the development and comparison of family case study descriptions (Charmaz, 2006; Patton, 2015; Yin, 2018) highlighted how the program had catalyzed and supported ongoing engineering-related interests for both parents and children. This included broadened parent perspectives on engineering, ongoing use of the program activities and materials over several years, seeking out new engineering-related resources and experiences, and using the engineering design process as inspiration for finding engineering in everyday experiences. The interviews also highlighted the diverse ways that families interpreted and built on their experiences through the program. Of the 18 families interviewed, five demonstrated strong evidence of ongoing interest and engagement specifically related to engineering design and problem-solving. Other families discussed ways the program had inspired them to focus on building activities or had supported other interests, such as spending more time together or promoting creativity. Five families indicated that they had enjoyed the Head Start on Engineering program but had since moved on to other experiences, programs, and interests. The analysis also suggested factors that shaped whether and how families extended their engineering-related interests beyond the program, including (a) existing family values, (b) parent perceptions about their roles supporting their children's interests, (c) and life barriers. Across all of these factors, the interviews demonstrated that families were resilient to life challenges and found creative ways to support ongoing interests with limited resources.

Contribution to the teaching and learning of science. These findings advance theoretical understandings of engineering-related interest development in early childhood by supporting the utility of a family systems perspective, suggesting the factors that influence how and why family interests develop, and providing more details on the role of parents (and other family members) in these processes. The study also provides insights into the ways that early childhood STEM education programs can influence family learning, engagement, and interests over multiple years—and how these programs might be improved to increase their relevance and impact for English- and Spanish-speaking families from low-income communities. For example, educators and organizational leaders can better design and connect programs to account for the unique ways that families build interest pathways and the factors that influence this process.

Novel Engineering: Characters as Engineering Design Clients

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Subject/problem. While K-12 engineering education becomes more ubiquitous in the U.S.(Achieve Inc., 2013; NRC, 2012) integrating engineering in meaningful ways into K-8 education is still a challenge as teacher wrestle with issues of time. With funding from NSF, Tufts Center for Engineering Education and Outreach (CEEO) developed an approach, entitled

Novel Engineering, that integrated engineering and literacy into combined experiences. Through this approach, students derive engineering problems from classroom texts and then move through the engineering design process as they build solutions that are influenced by the characters, settings, and plots about which they are reading. Analysis of this approach has generated new insights into how students engage in engineering.

Design/procedure. The Novel Engineering (NE) project used a design-based research approach (DBR) (e.g., Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Collins, Joseph, & Bielaczyc, 2004) grounded in work on responsive teaching (Hammer, Goldberg, & Fargason, 2012; Levin, Hammer, Elby, & Coffey, 2013; Roberston, Scherr, & Hammer, 2015) and emerging work on ambitious engineering that pushes on notions of what engineering students can do in different learning environments (Portsmore, Watkins, & McCormick, 2012; Watkins, Spencer, & Hammer, 2014). The project developed a flexible approach that focused on teacher education and allowed teachers to use their existing classroom texts as the foundation for Novel Engineering units. Significant video data of teachers and student group was collected along with student work and teacher reflections.

Finding and Analysis. One line of research for the NE project used qualitative and case-study methods, drawing on discourse (Gee, 1998) and interactional analysis (Jordan & Henderson, 1995) methods, to examine in what contexts were students engaged in sophisticated engineering practices. The line of inquiry emerged from researchers noticing that elementary student engineering practices during NE projects were often aligned with those of "informed designers" as defined by Crismond & Adams (2012). Across the multiple classrooms that were being video recorded, researchers identified moments and contexts where students were able to engage in informed designer practices. Analyzing these collected moments, the research group built memos and worked toward initial conjectures for how learning environment elements support students in engaging in more sophisticated engineering practices. For example, the authentic need for planning in order to obtain materials and the deep understanding of the book that provided character/clients' needs and physical constraints of the setting supported students doing detailed planning and sketching to support their physical prototype. Similarly, allowing students to pick their own problem, from a text that contained familiar physical settings and near-peer characters, allowed supported rich problem scoping

Contribution to the teaching and learning of science. The relative newness of K-12 engineering education means the field is still understanding and debating what activity students should be engaged in. NGSS contains some initial stances about students' engineering. However, we argue that these can be extended and enriched by recent research that show students are easily capable of much more advanced engineering practices. Moreover, this project can add to the conversation in the field about the interaction between the learning environment and the supports for teaching and learning in engineering.

Research-Based Development of a Preschool Engineering Curriculum

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Subject/problem. Early childhood educators have expressed an increased interest in engineering activities. Engineering supports the development of critical thinking, fine motor, and social-emotional skills among early learners (Davis, Cunningham, Lachapelle, 2017). However, there is a dearth of research-based, developmentally appropriate engineering curricula available.

Design/procedure. Development of the Engineering is Elementary *Wee Engineer* curriculum began in 2015 with research into child development, existing curricula, and early childhood classroom pedagogy. Through this foundational research, the team sought to understand how preschool classrooms were structured and what engineering design might look like in the early childhood setting. While the group had plenty of experience designing for the elementary grades, the team was also curious to understand which epistemic practices of engineering would be accessible and observable with this new population. These questions, among others, were answered through exhaustive literature reviews, interviews and focus groups with early childhood educators, and collaborations with experts in the field.

After a year of foundational research, the team began conceptualizing and drafting activities. Following the Engineering is Elementary (EiE) project's curriculum design process, activities were drafted, piloted locally, improved, piloted nationally, improved again, and finalized for release. In accordance with EiE's goals of inclusivity and accessibility, all pilot sites were carefully chosen through a rigorous application process, which allowed the team to select sites which would be representative of the national preschool audience while attending specifically to under-represented populations.

Data collection instruments were all drafted in-house and included observation and interview protocols, online educator feedback forms, and focus group discussion guides. In addition to focusing on the functionality of drafted activities, these tools provided insight into the epistemic practices of early childhood engineering and the design considerations necessary to accommodate these early learners.

Findings and analysis. Through development and evaluation of the Wee Engineer curriculum, the team found that children as young as three can engage in the process of engineering. While differences exist between the engineering practices of preschoolers and their older peers, there are many core components of engineering that are nonetheless accessible and observable. For example, preschoolers are capable of engaging in goal-directed activity when it is introduced and scaffolded appropriately. The Wee Engineer curriculum uses an engineering puppet to situate the engineering challenges within a meaningful and engaging context. The team found this approach was more developmentally appropriate than storybooks, which have been used to introduce the topic for older children. Additionally, preschoolers are capable of following an engineering design process (EDP), though this too looks a bit different. The ubiquitous five-step EDP was consolidated down to three steps and is introduced using the mnemonic device of a simple song to the tune of Farmer in the Dell. Finally, preschoolers are capable of using data to make decisions and to improve upon their designs, a critical practice of engineering. This is accomplished by first creating challenges with clear, developmentally appropriate goals (i.e., a soft pillow, a loud noise maker) and then allowing children to explore materials and test them with the goal of the challenge clearly in mind.

Contribution to the teaching and learning of science. As the field of early childhood engineering curriculum development continues to emerge, there is a need to share current practices so that others may learn from and build upon prior work. The development of Wee Engineer represents a body of work that includes 145 educators, 478 children, and 600 hours of development time. Many lessons were learned during this endeavor which can serve as fodder for future research and development in the field.

Synthesis of Session Papers

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The four studies presented in this paper provide a collection of insights into the types of engineering design practices that young children are capable of engaging in. Across the four studies, we see that children are able to not only develop solutions to engineering design challenges but also engage in problem scoping behaviors to understand the challenge; identify goals and specific problems to solve; consider the needs of specific clients, users, and other stakeholders impacted by the design; and think about design criteria and constraints. Strategies for facilitating problem scoping included the use of storybooks and puppets to introduce characters as design clients, the presentation of design challenges embedded in the context of a science center exhibit, equipping parents to identify engineering design opportunities in everyday settings, and allowing children to pick their own problems to solve. Within the individual studies, we see additional engineering design practices that young children engage in. In the first study, we saw evidence of children engaging in iterative design. In the third study, children engaged in planning and sketching to support their physical prototypes. In the fourth study, we also saw evidence of children engaging in evidence-based decision making in which they used data to make decisions and improve their designs.

The third study identifies design-based research (DBR) as their approach to research and development. This is fitting—that engineering design education researchers would use a design approach to understand how children engage in design. While the other three studies did not articulate a DBR approach, there is clear evidence that each project was informed by the same core design practices that we saw evidence of amongst our 3- to 8-year-old engineers. Just as we want children to learn problem scoping skills and the idea of designing for someone, we are conscientious that we are designing our activities and research plans for specific people. As we design activities, materials, programs, and curricula, we need to have a deep understanding of the needs and strengths of the populations we are designing for, whether it considering their developmental needs, cultural contexts, or language preferences. Study two in particular demonstrated this commitment, advancing our understanding of early engineering by reminding us of the need to consider not just the children as learners but children as part of a Family System. Likewise, across the four projects, the activities and curricula were developed using iterative processes informed by the research data we collected.

As we contemplate directions for future work, we must continue to enact the design practices that we hope to make space for children to engage with: rich problem scoping and human-centered, iterative, and evidence-based design. We must continue to conduct research that allows us to better understand children, families, and educational systems and the unique needs and strengths of different populations and different contexts. Finally, we must continue to consider not only the engineering design knowledge and skills that children can learn, but also the approaches and systems that promote interest in engineering—and make space for children to connect their own interests to engineering.

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[1] This paper was written to summarize a symposium that was planned for the NARST 2020 Annual International Conference. The conference was cancelled due to the COVID-19 pandemic. When the conference program was released, we learned that nine other groups planned to present work focused on early engineering learning: Andrews & Wendell; Batrouny ; Lottero-Perdue & Tomayko; McGrail; Shea & Sweetman; Shechter& Spektor-Levy; Schellinger, Jaber, & Southerland; Yang, Hong, & Lin; and Yesilyurt.