Activity Design Principles that Support Family-Based Engineering Learning in Early Childhood

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Scott Pattison, TERC
Gina Svarovsky, University of Notre Dame
Smirla Ramos Montañez, TERC
Catherine Wagner, University of Notre Dame
Amy Corbett, Metropolitan Family Service (MFS)
Maria Eugenia Perdomo, MFS
Viviana López Burgos, TERC
Sabrina De Los Santos, TERC

Introducing young children to STEM is critical for cultivating early interests and understanding that ultimately contribute to broader participation in the STEM fields (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, 2020) and a growing body of literature related to early childhood science (e.g., McClure et al., 2017; Silander et al., 2018), *early childhood engineering* continues to be the focus of only a few studies (e.g., Dorie et al., 2014; Pattison, Svarovsky, et al., 2020)

This lack of research can lead to several challenges, such as the creation of early engineering experiences that are not inviting 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; Nauta & Epperson, 2003). By the time children are in elementary and middle school, their beliefs and interests related to engineering are already solidifying (Hill et al., 2010; Moote et al., 2020). Positive early learning experiences with engineering can provide young children with opportunities to participate in meaningful design-focused interactions (Dorie et al., 2014, 2015; Svarovsky et al., 2018), which can in turn lead to sustained levels of engineering interest and engagement (Pattison, Svarovsky, et al., 2020).

While early childhood engineering education programs for the classroom are gaining prominence (e.g. Cunningham, 2018), family-based learning is also a promising context for supporting engineering engagement and interest development at this age (Pattison, Svarovsky, et al., 2020; Svarovsky et al., 2018). Decades of research have documented the rich ways that families engage in STEM learning at home, in museums, outdoors, and in other informal learning contexts (Haden et al., 2014; NRC, 2009). Existing research specific to engineering suggests that engineering design opportunities arise naturally through children's everyday play and are deepened and enriched through the support of adults (Bairaktarova et al., 2011; Svarovsky et al., 2017). As parents learn more about the engineering design process, they can come to recognize the many ways it is already part of their lives, including daily problem solving and children's play (Pattison & Ramos Montañez, 2022). Given the lasting, potentially lifelong effects (both positive and negative) that early exposure to engineering can have on children, it is critical to better understand how specific components, materials, and prompts within early childhood engineering activities in these family-based contexts function in different ways and possibly lead to different impacts for young learners.

To address this need, we conducted a design-based research (DBR) study (Brown, 1992; Cobb & Gravemeijer, 2008) focused on both (b) iteratively developing and improving home-based, engineering design activities for families with preschool-age children and (b) advancing theory about strategies that support engineering design engagement for children and adult family members. The study was part of the National Science Foundation-funded Research Exploring Activity Characteristics and Heuristics for Early Childhood Engineering (REACH-ECE) project. REACH-ECE was a collaboration between STEM education researchers at the University of Notre Dame and TERC and family engagement and early childhood learning experts at Metropolitan Family Service (MFS)—a community-based organization that provides a wide range of family services across the metropolitan region of Portland, Oregon. The overarching goals of the project were to design and implement productive engineering activities for young children and their families to create broader, more accessible pathways to engineering for early learners. The primary research question guiding data collection and analysis was: How do the *elements or characteristics* of family-based engineering activities (e.g., activity materials, design/solution spaces, challenge prompts, narrative framing) influence the ways that families with preschool-age children engage with and become interested in elements of the engineering design process?

The project focused particularly on working with and supporting low-income families and families that identify as Latinx or Hispanic, which are primary audiences for MFS. Children from these families face a variety of barriers to engaging with engineering and STEM more broadly (McGraw et al., 2006; NASEM, 2018; NSB, 2018; Orr et al., 2011; ED, 2014). Nevertheless, our experience working with these communities has highlighted the incredible creativity and resilience of families and their deep commitment to their children's learning and development. The team collaborated closely with community partner staff and families throughout the planning, implementation, and analysis phases of the project and used a variety of strategies to ensure that the activities and research methods supported an equitable vision of STEM education, including collecting and analyzing data in the language of participants with a bilingual and bicultural research team, using strength-based approaches to conceptualizing and supporting family engineering engagement, and ensuring that community partners and families were meaningful collaborators in the research process (Garibay & Teasdale, 2019; Schenkel et al., 2019; Tolbert et al., 2018).

Theoretical Framework

Our approach to studying and supporting early childhood engineering engagement built on prior studies of age-appropriate engineering design practices (Cardella et al., 2013; Dorie et al., 2014), as well as research highlighting the often underestimated thinking and problem-solving skills of preschool-age children that are foundational to engineering design, such as developing questions, maintaining focus, monitoring progress, evaluating results, and understanding the goals of others (NRC, 2000, 2007; Zimmerman & Klahr, 2018). Building on this work, the current study defined engineering design for preschool children and their parents as developmentally appropriate practices related to *problem scoping* (e.g., identifying constraints, restating the goal, familiarizing with materials), *idea generation* (e.g., brainstorming, planning), and *design evaluation* (e.g., assessing success, identifying additional goals).

An additional concept used to guide data collection and analysis was *design heuristics*, or "cognitive prompts that point designers towards exploration of design variations" (Daly et al., 2012). Within the field of engineering, design heuristics are commonly used during idea generation or ideation, with the goal of helping designers further explore a design space or different variations of their early ideas. In the current project, we employed a broader conceptualization of design-focused heuristics: cognitive prompts that guide engineering engagement and learning. This definition allowed us to examine how different heuristics were more or less productive for families during different stages of the engineering design process.

Research Design and Procedures

Iterative data collection and analysis for the DBR study was organized into three phases: (1) theory development and conjecture mapping, (2) iterative testing and refinement, and (3) retrospective analysis (Cobb & Gravemeijer, 2008). During the first phase, we used prior literature to outline an initial set of interconnected hypotheses, or conjectures, as a starting place for the project. The initial conjecture map (Sandoval, 2013) identified the proposed activity embodiments (e.g., engineering activity challenge prompts) and mediating processes (e.g., family interactions) that support engineering engagement and interest development for families with young children.

During this phase, we also worked with project partners to develop initial versions of the three family-based engineering activities that embodied the primary conjectures in our conjecture map (see Figure 1). The *Protect the Nest* activity asked families to work together and use wooden blocks to keep a hen's nest and eggs out of the reach of a hungry fox (represented by a 1-foot carboard cutout). The *Tacos Para Todos* activity provided a variety of imaginative play materials for families to plan a taco party and test different processes for helping guests assemble their tacos. The *Couch for Fred and Ted* activity challenged families to use craft materials (e.g., popsicle sticks, index cards) to build a couch that would allow two friends (a small and large stuffed dog) to sit together and watch their favorite movie. All three activities included a book, which served as the inspiration for the engineering design challenge; a one-page bilingual (Spanish/English) activity guide for parents; and materials for completing the design challenges.

Figure 1. *Images of the three activities developed through the DBR study (from left to right): Protect the Nest, Tacos Para Todos, and Couch for Fred and Ted.*

In the next phase, the team recruited 16 families with preschool-age children (ages 3 to 5) from the community partner's early childhood and family engagement program to iteratively test each of the three activities over the course of approximately 5 months. Recruitment was conducted collaboratively with program staff and balanced by families' primary home language (Spanish and English). After a virtual orientation to the project, each family engaged in three rounds of activity testing. During each round, each family received a copy of the current version of one of the three activities. Using a Zoom-based video recording system, the families were asked to use their own phones to record themselves the first time they engaged with the activity. Subsequently, a bilingual member of the team conducted a virtual interview with one parent from each family to gather their input on the experience and their feedback on the activity. Both the video and interview data were analyzed using quantitative and qualitative techniques to identify improvements to the activities and inform theory development. Based on these findings, the activities were updated, and each family received the modified version of a new activity. The participants were organized into three groups, with each group receiving one of the three activities reach round. At the end of the project, 15 of the original families had completed all three rounds of data collection and provided both video and interview data for each round. One family dropped out of the study due to life challenges.

Analysis and Findings

Initial analysis of the videos in between each testing cycle was conducted using a coding document template developed by the team. For each of the videos, which ranged between 10 and 120 minutes long, a research team member reviewed the video, described the overall interaction, identified the primary engineering practices observed, and reflected on ways that the activity design, family characters, and other aspects of the interaction appeared to influence engineering engagement. Videos from Spanish-speaking families were analyzed by a bilingual member of the research team. Through an iterative series of team discussions, the summaries in each video coding template were checked and then synthesized into an overall research memo describing themes from that round. Similarly, interview data from each round were synthesized through team debriefs, descriptive statistics, and inductive coding of open-ended responses. As with the video data, these findings were synthesized into an interview research memo that informed the next iteration of the activities.

During the final phase of the study (retrospective analysis), the team worked collaboratively with MFS to document the results of the iterative testing, conduct additional analyses to further advance and test the team's conjecture map, and disseminate results to families, educators, and researchers. Following DBR guidelines (Cobb & Gravemeijer, 2008; Means & Harris, 2013) and prior work by the project team (Pattison et al., 2017), retrospective analysis included reviewing and comparing iterations of the conjecture map, checking assertions and exploring contradictory evidence, triangulating findings across the video and interview data, seeking emergent themes across the full dataset, and gathering input from community partner staff.

Retrospective analysis also included more detailed coding of the videos from the third round of the DBR study in order to further explore emergent ideas about families' engagement with engineering and the ways the activities and materials supported this process. For this round of coding, 10 family videos from the final DBR cycle were selected to provide equal representation across the three activities and among Spanish- and English-speaking families. Using a spreadsheet coding template, a research team member coded each 1-minute segment of each video for evidence of parent or child talk related to engineering design practices, including context setting, materials exploration, problem-scoping, planning, evaluation and revision, modifying the problem space, and user-centered design. For each 1-minute segment, the team member also described evidence of ways that the activity design and materials appeared to influence these practices. Finally, the coder provider a one-paragraph, wholistic description of important family dynamics evident in the video, such as the nature of adult-child collaboration. A second team member reviewed each coding spreadsheet, and the two researchers discussed any questions or discrepancies until agreement was reached.

Based on the analysis of videos and interviews, three overarching design principles for home-based engineering activities for young children and their families emerged: (1) present design challenges that leverage the ways families naturally orient to play and engagement with the materials, (2) include narrative contexts and supports that motivate engagement in engineering practices, including user-centered design, and (3) align the choices of narrative context, design materials, and design challenges to create an open, accessible, age-appropriate solution space. These principles are discussed in more detail below.

Emergent Design Principle #1: Present design challenges that leverage the ways families naturally orient to play and engagement with the materials

Across all three rounds of activity testing, observations of how families used the materials to create solutions to the design challenges, as well as the types of solutions that were developed, informed revisions for subsequent rounds. Focusing on the "first engagement" provided a useful window into how families might integrate new activities and new ideas into their established patterns of play and interaction, which can shed light on key ideas for reducing barriers to activity engagement.

For example, in the first round of the *Tacos Para Todos* activity, the initial design challenge was to create a process to make as many tacos as possible within 2 minutes. The data suggested that while families were very interested in making tacos and using the materials in the kit, they were not particularly engaged with the timed design challenge. Families also demonstrated a broad range of approaches to using the activity and making it their own. Families were observed engaging in the engineering practices of problem scoping and idea generation to develop a process (an original goal of the activity), but most of these instances were during setup and cleanup of the taco ingredients and not during their main engagement with the activity as originally theorized. To enrich the narrative context and better connect it to the ways families were already engaging, the design challenge was revised in round two. Instead of the 2-minute challenge, families were invited to make a plan for serving tacos at an upcoming party, thus positioning them fully within the design challenge and identifying clear "users" of the plans they created (friends and family who would attend the party). To further support this narrative context, multiple options for plates, platters, and bowls were added to the kit, with the hope of providing more design pathways for families to pursue as they considered their party and guests. Data from the second round suggested that families were more engaged in this design challenge and that the updated version supported a broad range of process-focused and user-centered talk.

Emergent Design Principle #2: Include narrative contexts and supports that motivate engagement in engineering practices, including user-centered design

Data from all three activities also suggested that a clear narrative context that families could relate to, connect to the design challenge, and explore imaginatively not only helped families engage in broad engineering practices such as problem scoping and idea generation, but also appeared to support a more intentional approach to user-centered design. For example, the introduction of small toy baby chicks as a narrative support for the Protect the Nest activity appeared to heighten the attention paid by families to details that would impact the experience and daily lives of the chicks in a way that was not present in earlier rounds of testing. Similarly, the narrative support of the stuffed toy dogs in the Couch for Fred and Ted activity added a layer of user-centered thinking as families discussed the dogs' comfort and needs when building with the craft materials.

The framing of the narrative context for the design challenge also appeared to be essential for engaging families in engineering practices during the activities and motivating creative exploration of the design challenges. In the first round of the Protect the Nest activity, the design challenge was for families to build a structure out of blocks that could support a nest of eggs out of reach of a paper fox. Data from this round indicated that families were excited to play with the activity and that they engaged in engineering practices such as problem scoping and idea generation. However, one of the narrative supports included in the activity kit (the paper fox) felt disconnected from the narrative context for the activity as framed by the storybook, where the fox only makes a brief appearance. In response to this data, the fox was removed and more of the focal characters from the storybook (small chicks that had just hatched) were included in the activity kit as narrative supports. The design challenge was also broadened in scope, inviting families to build a structure out of blocks that would keep the chicks and eggs safe, which led to more user-centered design by the families overall.

Emergent Design Principle #3: Align the choices of narrative context, design materials, and design challenges to create an open, accessible, age-appropriate solution space

Creating a design challenge that young children can authentically engage with requires intentional alignment between the narrative context, design challenge, and materials such that children are interested and invested in the activity, can work with and manipulate materials independently on some level, and can connect the design challenge to their own relevant experiences in order to participate in idea generation.

For example, during in the first round of activity testing, the initial design challenge for the Couch for Fred and Ted activity was to build a "couch" out of craft materials that could hold two stuffed dogs so that their eyes were at the same height. Families spent most of their time in the first round engaged in the engineering practice of problem scoping, specifically focused on trying to understand what types of structures were possible to build given the materials on hand. Many families reported that the design challenge was too difficult or too complex for their young children and that the materials were too many in number and too difficult to use. Consequently, families often built other designs for the dogs, such as simple beds and tent houses. In response to this data, several of the craft materials were removed for the second round, index cards were added as a simple and sturdy construction material, and more specific prompts for exploration were included in the activity guide in order to scaffold the activity for families. In addition, the design challenge was broadened, inviting families to build beds and houses for the doggies as a starting point. Data from the second round suggested that this version of the activity was much more successful than the original, with families engaging in more engineering practices beyond problem scoping (such as idea generation and user-centered design) and building a variety of structures for the stuffed dogs. Children seemed more able to build on their own with this combination of materials. They also seemed to connect to the design challenge more directly, which allowed them to engage in richer idea generation and problem scoping.

Contribution and Implications

This study makes several innovative contributions to the teaching and learning of engineering and STEM more broadly for young children. In particular, findings shed light on what engineering practices can look like in the home context for young children and their families, thereby refining and extending existing and often narrow perceptions of engineering (Mejia et al., 2018; Pattison et al., 2021; Vossoughi et al., 2016). The study also advances our understanding of promising engineering activity characteristics and design heuristics and how these can influence engineering engagement for families. Furthermore, the study raises key considerations for designing engineering and STEM activities for and studying learning within the context of the home, which is distinct from not only classroom-based learning but also other informal learning environments (Pattison, Callanan, et al., 2020; Vedder-Weiss, 2017).

Moving forward, we are looking to build on these findings in several ways. In addition to continuing to explore the unique context of home-based family engineering learning, we hope to test these activities in other learning settings, including the facilitated parent-child interaction groups that are a core component of MFS's early childhood program. We are also leveraging the data to explore the role of imaginative play in engineering engagement for young children with families, such as the ways that young children use imagination-based constraints and goals to motivate and evaluate the success of their designs (Pattison et al., 2022). Finally, through collaboration with our community partner and families representing low-income English- and Spanish-speaking communities, we are striving to identify new and innovative ways of supporting engineering learning and engagement for communities that have traditionally been marginalized in STEM education, and for integrating their perspectives, goals, and insights into the research process.

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