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Design Challenges at a Science Center: Are Children Engineering?

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Abstract

Engineering design challenges and tinkering activities are increasingly popular in informal learning settings. Thus, these environments can benefit from foundational research on learners' engineering processes as they engage in these settings. This paper conducts an exploitive analysis of an existing design challenges program at a science center through the investigation of the design processes of 22 visitor groups across five challenges. The design processes are compared across the challenges to identify characteristics of these settings that engage learners in engineering. The premise, example designs, and materials played key roles in visitors' design processes. Findings show that (1) each challenge provided unique contexts in which to engage in iterative engineering design, (2) visitors utilized existing designs and designs in progress from other visitors for inspiration, and (3) visitors were particularly influenced by the materials and used them as a means to gather information, explore possibilities, and identify goals. Many visitors also exhibited design process progressions similar to expert engineers, suggesting that the context and materials provide opportunities for early engineering experiences.

Objectives

Increasingly more science centers are offering engineering and maker[1] programs, but these have yet to be rigorously established as educationally productive. My aim is to characterize engineering design processes of learners in these programs to inform further research on children engaging in engineering design activities.

Through the study of 22 visitor groups across five engineering design challenges at a science center, this paper aims to:

1) Identify children's engineering behaviors in these programs, particularly how their design processes compare with experts' design processes (Atman et al., 2007), and
2) Characterize design processes at five different design challenges through a comparison of challenges.

I hypothesize that through these types of engineering and making activities, children are engaging in behaviors similar to expert engineers. These may be primitive forms of engineering, but are early predecessors to expert engineering. Particularly, on the surface, children may seem to be just playing and having fun, but I anticipate that there may be deliberate choices in their actions and design processes. I hope to understand the features of these learning environments

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[1] The Maker Movement is led in part by MAKE Magazine, a magazine dedicated to Do-It-Yourself projects from electronics to crafts to cooking to art (Kuznetsov & Paulos, 2010; New York Hall of Science, 2010). The Maker Movement focuses on hobby projects where people "tweak, hack, and bend any technology" through creativity, ingenuity, and resourcefulness (MAKE, 2012).

that can successfully engage learners in engineering practices in order to determine how to take advantage of making and tinkering as accessible pathways towards engineering.

Perspectives

Informal Environments

Design challenges in classrooms and afterschool programs can be effective in promoting understanding of science and engineering (see the following section). However, design challenges in informal drop-in settings have not been well-studied. This paper intends to study design challenges in this type of environment, particularly how they engage learners in engineering design.

Informal environments are distinct from classrooms because they offer free-choice learning (Falk & Dierking, 2000). Science center visitors choose which activities to participate in and can leave any time. Furthermore, visitors tend to visit in groups with varying backgrounds (Falk & Dierking, 2000). Thus, in contrast to classrooms, science centers must attract and retain visitors to complete design challenges and accommodate intergenerational collaboration.

Making and Tinkering: Engineering Design

The renewed interest in maker projects (Kuznetsov & Paolos, 2010) has provoked questions of what is being learned in these projects (NYSci, 2010). The Maker Faire Report (NYSci, 2010) describes making as "tinkering, hacking, creating and reusing materials and technology." The constructionist perspective is to view these projects as design. Papert (1991), Resnick (2006), and Bamberger (1991) emphasize the process of constructing entities as the driver of meaningful learning. Dym et al. (2005) claim that "design is both a mechanism for learning and in itself a learning process." Beckman & Barry (2007) also liken the design process to the learning process. Lewin (1979) stresses educating engineers through design experiences, drawing out rather than forcing in concepts.

Resnick (2006) further states: "In design activities, as in play, children test the boundaries, experiment with ideas, explore what's possible. As children design and create, they also learn new concepts." Open-ended design activities give students responsibility for structuring their own processes (Edelson & Reiser, 2006) and creating personalized artifacts through highly individualized paths (Papert, 1991). Similarly, engineers design in an infinitely open solution space, then test to explore possibilities in a continued conversation with the solution space, materials, and design (Schön, 1992).

As noted above, design provides a powerful and motivating context for learning. In practice, the few studies on K-12 design practices show its effectiveness. Cunningham and Lachapelle (2011) find *Engineering is Elementary* improved interest, engagement, and performance in science and engineering in both students and teachers. Sadler et al. (2000) show that after engaging in design challenges, students' science skills increased. Kolodner (2002) finds that students in *Learning By Design* engaged in collaboration, communication, decision-making, and design of investigations more like experts. These studies focus mostly on pre- and post-assessments of science concepts and skills; further studies are needed to evaluate learners' engineering processes while they engage in design activities. However, researchers have claimed design provides opportunities for students to exercise engineering habits of mind; students can test their preconceptions (Sadler, et al., 2000), creatively develop solutions through multiple paths (Eckert, et al. 2010; Committee on K-12 Engineering Education, 2009; Papert, 1991; Resnick, 2006), engage in systems thinking (Committee on K-12 Engineering Education, 2009), iteratively refine their design and thinking (Cunningham & Lachapelle, 2011), learn from failure (Bamberger, 1991; Schön, 1992), collaborate and communicate (Eckert, et al., 2010; Kolodner, 2002; Kumar & Hsiao, 2007), manipulate and reflect with materials (Sadler, et al., 2000; Schön, 1992; Bamberger, 1991; Edelson & Reiser, 2006), and ethically and civically design for people (Tsang et al., 2001). Therefore, though empirical results are slim, we see certain design activities may engage learners in engineering. The question is: how can these learning environments optimally foster engineering practice?

Expert Engineering Design Processes

To determine the engineering design processes of visitors, this paper draws on methodology and results from Atman et al. (1999, 2007), who compare design processes of engineering students and expert engineers. Participants designed playgrounds in a lab environment and could stay for up to three hours. The authors develop design process timelines focusing on the frequency of transitions between design activities, duration of activities, and solution quality. Their overarching design stages are Problem Scoping, Developing Alternative Solutions, and Project Realization, where (1) Problem Scoping includes the design activities Identify Need, Problem Definition, Gather Information; (2) Developing Alternative Solutions includes Generate Ideas, Modeling, Feasibility Analysis, Evaluation; and (3) Project Realization includes Decision, Communication, Implementation. Atman et al. (1999, 2007) find that compared to students, experts spent more time on the problem overall, especially in Problem Scoping. Experts also gathered more information across categories and transitioned more between activities. Importantly, experts' design processes portrayed a *cascade* pattern (see Figure 1).

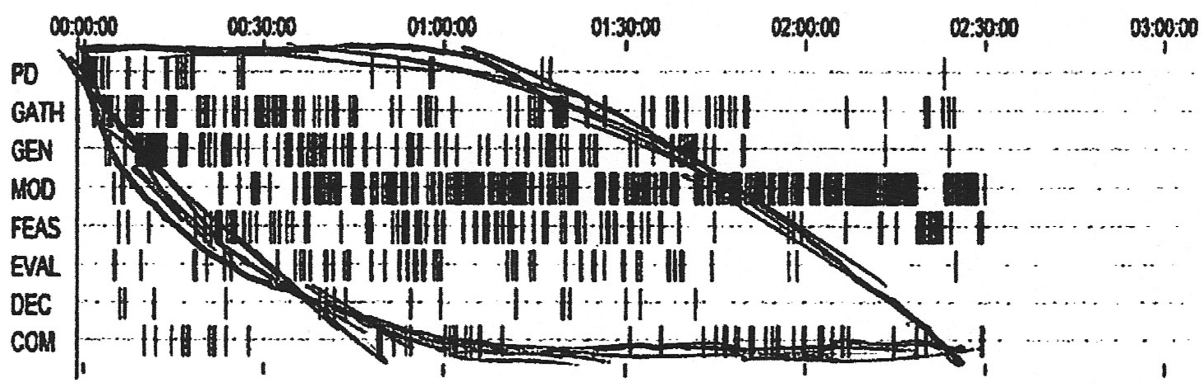


Figure 1: Example of expert *cascade* pattern (Borgford-Parnell, Deibel, & Atman, 2010). Note the progression from the upper left to the bottom right. The *cascade* pattern, or "Ideal Project Envelope," begins in Problem Scoping, transitioning between Problem Definition (PD) and Information Gathering (GATH); then progresses to Developing Alternative Solutions, transitioning between Generation of Ideas (GEN), Modeling (MOD), Feasibility of Analysis (FEAS), and Evaluation (EVAL); and throughout the process transitions to Problem Scoping and Project Realization, which includes Decision (DEC) and Communication (COM).

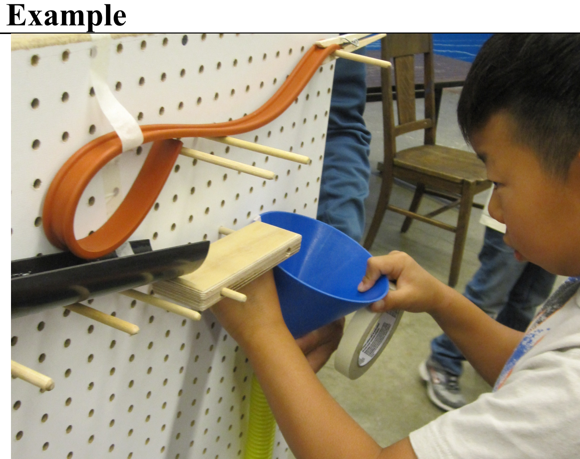
Adams (2001) further explored these participants' iterations, finding that the understanding of the problem and solutions evolves through iteration, with the more expert designers spending more time in iterations. In particular, these iterations are "coupled" such that both the problem and the solution co-evolve, similar to Schön's (1992) studies on designers' processes of "see-move-see" and how design goals emerge through exploration of the design situation.

Data

The context of this study is an engineering design program at a public science center, specifically the Ingenuity Lab at the Lawrence Hall of Science. The Ingenuity Lab was open to the drop-in public during weekends, providing open-ended design challenges to about 800 visitors a month, with ages ranging from infant to elderly. Visitors came and went as they wished; the average stay time was over 30 minutes. Each month, an engineering design challenge and theme was presented along with appropriate materials. Staff and volunteers guided visitors.

Five engineering design challenges were studied. Table 1 provides descriptions of the challenges. Visitors who came to the Ingenuity Lab in these five months during observation were asked to participate as they walked in. Most visitors (> 90%) agreed to participate. The only selection criterion was that there should be one child at least 6 years old such that the child could speak better about his/her experience for a productive interview.

Table 1: Descriptions and examples of each challenge. Descriptions modified from the science center website (Lawrence Hall of Science, 2013).

Challenge	Description	Example
Marble Machines	Using a pegboard and simple materials like rubber, PVC pipes, funnels, and tubes, design a marble rollercoaster.	
Spinning Tops	Design the longest spinning top by selecting the size of plates, number of plates, and its height. Staff help spin your top with an electronic hand mixer. See how your design compares to others on the data graph.	

Cars	Design, build, and test a robotic LEGO car by putting together the right gears and wheels and learning how to connect the microcontroller to the appropriate sensors and actuators. Time your car on the racetrack.	
Engineer the World	Design your own paper prototype for a website or mobile app, then implement it on the computer with help from staff. *This challenge was developed in collaboration with a team of engineering students and practicing engineers from a local software engineering company.*	
Sound Engineering	Create and change sound by making a loudspeaker or instrument using recycled materials, coils of wire, magnets, and rubber bands. Staff assist in testing speakers. *This challenge was developed in collaboration with a team of engineering students and practicing engineers from a local audio engineering company.*	

Video Data, Field Notes, and Interview Data

Naturalistic observations were carried out with 22 groups. The entire duration of each group's activities was video-recorded. The camera followed the active participant(s). Some groups included multiple participants who actively engaged in the activity and created designs, so the video included all participants simultaneously, if possible. Table 2 shows the breakdown of video observations. Field notes were taken by one researcher while another video-recorded. The field notes covered engagement, interaction with others, design iterations, and engineering behaviors. Interviews were conducted with the active participants before and after participation in the challenge while in the Ingenuity Lab. See Appendix A for the interview protocol.

Table 2: Participants and stay-time for each video observation. Primary active participants are bolded. Average stay-time for all visitors for the month of the challenge is included.

	Video 1	Video 2	Video 3	Video 4	Video 5
Marble Machines Average stay-time: 29 ± 10 minutes	**8 y.o. M** & adult M	**8 y.o. F** & adult F	**10 y.o. M**, **14 y.o. M**, & adult F	**6 y.o. F**, **9 y.o. F**, adult F, & adult F	**9 y.o. M**, 3 younger siblings, adult F, & adult M
	39 min.	16 min.	78 min.	75 min.	18 min.
Spinning Tops Average stay-time: 26 ± 10 minutes	**10 y.o. M** & adult F	6 y.o. F, **8 y.o. F**, & adult F	**6 y.o. M**, **7 y.o. F**, adult F, & adult F	**6 y.o. M**, toddler F, & adult F	
	43 min.	24 min.	33 min.	44 min.	
Cars Average stay-time: 53 ± 13 minutes	**8 y.o. M** & adult F	**9 y.o. F** & adult M	5 y.o. F, **7 y.o. M**, baby F, adult M, & adult F	**9 y.o. F**, **14 y.o. M**, adult M, & adult F	5 y.o. M, **9 y.o M**, adult M, & adult F
	61 min.	13 min.	42 min.	22 min.	65 min.
Engineer the World Average stay-time: 33 ± 13 minutes	**8 y.o. M**, **11 y.o. F**, & adult M	**7 y.o. M**, **8 y.o. F**, & adult F	**12 y.o. M**, **12 y.o. M**, & adult F		
	60 min.	41 min.	45 min.		
Sound Engineering Average stay-time: 31 ± 14 minutes	**11 y.o. M**, **13 y.o. F**, & adult F	**6 y.o. M**, **8 y.o. M**, **adult M**, & adult F	**8 y.o. F**, **13 y.o. F**, adult M, & adult F	4 y.o. M, 6 y.o. M, **7 y.o. M**, adult M, & adult F	**7 y.o. M**, **9 y.o. M**, adult M, adult M, adult F, & adult F
	57 min.	35 min.	13 min.	20 min.	33 min.

Methods

The main method was video analysis. Videos were segmented into engineering design behaviors (see Table 3). Three researchers used ELAN[2] to capture the timestamp and duration for each behavior and to annotate what happened. Researchers individually coded videos, overlapping on five (23%) videos, one from each challenge representing a typical complete interaction. The researchers met weekly to ensure consistency of codes. Discrepancies were resolved through discussion. Percentage agreement on coding the timespans of all behaviors in these videos was 91%.

The coded behaviors began as a list adapted from the Engineering is Elementary Design Process (EiE, 2013). While coding videos, the researchers refined the list weekly to identify all prominent engineering behaviors. New behaviors emerged (e.g., *Looks at/compares with other designs*) and other behaviors were combined (e.g., *Manipulates variables to achieve goal* and *Modifies design to make improvements* were combined). These behaviors were further cross-linked with design activities and stages (Atman et al., 2007), such that comparisons could be made with the expert engineers. Table 3 shows how the behaviors mostly preserve the order of Atman et al.'s general trend from the stage of (1) Problem Scoping to (2) Developing Alternative Solutions to (3) Project Realization. The last two behaviors in the table are an exception to the order and could be either Problem Scoping or Developing Alternative Solutions, depending on context. The largest difference between the context in this study and that of Atman et al. (1999, 2007) is that the participants here have materials to build and implement designs; Implementation was ultimately not included as a design activity for Atman et al.'s participants. Thus, in this study, I place Feasibility Analysis and Evaluation after Implementation, rather than after Modeling as in Atman et al. (1999, 2007).

Drawing from Atman et al. (1999, 2007), timelines highlighting behaviors were developed for each participant with behaviors listed in the order of Table 3. I sought to identify (1) the frequency and duration of behaviors, (2) the number and rate of transitions between behaviors, and (3) the overall pattern and whether it fit the *cascade* pattern of experts (Figure 1). Because the last two behaviors, *Discusses how this activity relates to the real world* and *Looks at/compares with other designs*, can occur anytime throughout the process and are not part of the preserved order of Atman et al.'s (1999, 2007) timelines, I excluded them from the cascade pattern analysis. Using the timelines for all participants across the five challenges, two researchers determined whether a cascade pattern (or multiple cascades) falling from top left to bottom right on the timeline was identifiable, independently rating the cascade as high (1), medium (0.5), or low (0) and then discussing to resolve discrepancies in order to agree on a rating. For instance, some confusion arose from timelines with multiple iterations that made the whole timeline look flat; this was resolved by identifying each iteration as a cascade. Timelines were triangulated with field notes and interviews that contained further details. Interviews were coded by question in an emergent analysis.

[2] ELAN is a tool for annotating video and audio resources (Max Planck Institute for Psycholinguistics, 2014).

Table 3: Coded engineering design behaviors and examples as related to design activities. Design activities are Identify Need, Problem Definition, Gather Information, Generate Ideas, Modeling, Feasibility Analysis, Evaluation, Decision, Communication, and Implementation (Atman et al., 1999 and 2007). Atman et al. (1999, 2007) show that expert engineers cascade from (1) Problem Scoping to (2) Developing Alternative Solutions to (3) Project Realization, with small transitions within and between each. (1) Problem Scoping includes Identify Need, Problem Definition, Gather Information; (2) Developing Alternative Solutions includes Generate Ideas, Modeling, Feasibility Analysis, Evaluation; and (3) Project Realization includes Decision, Communication, Implementation. Note that these are visitor groups, so the primary child often interacts with other children and adults in conversations; thus, quotes come from all group members.

Engineering Design Behavior	Examples	Design Activity
Describes/identifies a problem to be solved	Provided with the challenge or describes the challenge; Encounters a problem or obstacle. *"How do you connect this [the gears] so that the wheels go?"*	Identify Need (1)/ Problem Definition (1)
Expresses a design goal	States a goal or asks how to achieve a goal. *"I wanna make it* really *low."* *"How do you make them into links?"*	Identify Need (1)
Considers one or more options for achieving goal	Explanation of what can be done; Describes options for achieving goal. *"So we'll probably have to tape this, or paper clip."* *"You can talk about yourself. You can do things that you like, or where you live, sports you play."*	Gather Information (1)/ Generate Ideas (2)
Sketches design	Draws design on paper.	Modeling (2)
Explores/selects appropriate materials/tools from available options	Explores, selects, or tinkers with materials; Looks for material; Asks about materials. *"What does this do?"* *"[This] has 10 times as many. Which one do you want to use?"*	Gather Information (1)/ Modeling (2)
Makes causal inference/predictions about how design will perform	Traces out a test; Considers how design will perform. *"If it's lighter, will it go faster?"*	Modeling (2)
Builds or modifies design	Builds or constructs object with a purpose; Modifies or adjusts design.	Implementation (3)
Tests design	Tries out design with specific test.	Feasibility Analysis (2)
Analyzes what happens and what can be improved from the tests	Discusses what happens during test; Considers options for improvement. *"Oh look, it kinda slows it down, huh?"*	Evaluation (2)/ Decision (3)
Discusses how this activity relates to the real world, engineers, etc.	Makes connections to personal lives or engineering. *"Just like that guitar. Strings, they like to break."*	Gather Information (1)/ Evaluation (2)
Looks at/compares with other designs	Checks out designs that other people have made. *"See, mom, look at this one. This chain over here doesn't fall off."*	Gather Information (1)/ Generate Ideas (2)/ Evaluation (2)

Results

Marble Machines timelines (Figure 2) loosely show the cascade pattern, with a mean rating of 0.36 on the 0-1 scale for the cascade. The design processes frequently transition between *Explores/selects appropriate materials/tools*, *Builds or modifies design*, and *Tests design* throughout. The majority of time is spent in these behaviors, which, without the problem scoping behaviors, results in a flat pattern, suggesting that visitors are not necessarily planning their designs ahead of time. *Explores/selects appropriate materials/tools* and *Builds or modifies design* occur most frequently here out of all challenges. The behavior *Tests design* occurs early relative to other challenges and also occurs the most frequently out of all challenges at an average of 36 times per visitor, likely because the design was easy to test by dropping a marble. In Table 4, we see that these visitors had the greatest frequency and percentage time spent in *Describes/identifies a problem to be solved*. Four of seven participants looked at other designs, and no groups discussed the real world relation of the challenge. This is not surprising given that the content of the challenge is more abstractly related to the real world (e.g., rain gutters, roller coasters).

Spinning Tops timelines (Figure 3) show behaviors are more spaced out with shorter durations; however, the cascade pattern is fairly obvious with a mean rating of 0.60, indicating that visitors here may be better monitoring their design progress to transition behaviors like experts. *Tests design* occurs less frequently and tends to occur towards the end, but a large percentage time was spent in this behavior as facilitators helped visitors test for the longest spin time. Compared to other groups, these visitors spent a greater percentage of time and more frequently exhibited *Analyzes what happens and what can be improved*, almost with the same frequency as *Tests design*, meaning that on average, they discussed the results almost after every test. This is likely explained by the help from facilitators. The ratio of *Tests design* to *Analyzes what happens and what can be improved* was the greatest of all challenges. Only one participant was observed to look at another design, and no one discussed the relationship to the real world, unsurprising as this challenge was also fairly removed from everyday concepts.

Cars timelines (Figure 4) portray a fairly flat pattern and have the lowest mean rating of 0.25 for the cascade, with almost a reverse cascade in some instances (e.g., Cars 27 and 29 in Figure 4). Visitors in Cars spent the most time of all challenges transitioning between *Explores/selects appropriate materials/tools* (38% of time) and *Builds or modifies design* (63% of time), with some exhibiting short bursts of *Tests design* throughout while others tested towards the end. These simple LEGO bricks provided a variety of ways to build, and thus may have provoked this tinkering pattern of transitioning between exploring and building. *Describes/identifies a problem*, *Expresses a design goal*, and *Considers options for achieving goal* are more prevalent in the latter half of timelines, possibly emerging from the explore and build behaviors to create reverse cascade patterns. Two participants who did not finish only exhibited *Explores/selects appropriate materials/tools* and *Builds or modifies design*. Two groups compared designs and three groups discussed the activity's relation to the real world.

All Engineer the World timelines (Figure 5) demonstrate a cascade pattern with the highest mean rating of 0.83, but with no repetition of the cascade, indicating a single iteration. The high cascade suggests that Engineer the World may have helped structure the experience in a way that visitors were able to better monitor their progress and determine which design behaviors were appropriate for their stages of progress. Because they were told to sketch before implementing, only participants at this challenge exhibited *Sketches design*, spending almost just as much time in this behavior (22%) as *Builds or modifies design* (26%); however, none return to it after implementing their website on the computer, likely due to the long time spent on implementation. As a result of the sketching requirement, these visitors were the only ones who sketched consistently, indicating that sketching out a plan may not be an intuitive step in creating designs. The lack of return to sketching also suggests that it is not intuitive. These visitors spent a relatively large percentage of time and frequency in Problem Scoping, particularly *Expresses a design goal* and *Considers one or more options for achieving goal*, mostly with facilitator guidance. The latter portion of the timeline, when visitors implemented their website, varied by facilitator during this one-on-one time. Half of participants looked at other prototype and real websites. And, with the more obvious relation to real websites, all groups discussed the activity's real world relation.

Finally, Sound Engineering timelines (Figure 6) have a mean rating of 0.59 for the cascade pattern, with four visitors exhibiting strong cascades. Specifically, those who made an instrument exhibited a flatter cascade and transitioned more frequently between *Explores/selects appropriate materials/tools*, *Builds or modifies design*, and *Tests design* throughout, with most time spent in *Builds or modifies design*. Similar to Marble Machines, these visitors could test their instrument designs easily and instantaneously. Others who designed the speaker spent most time in *Explores/selects appropriate materials/tools* then *Builds or modifies design*, with few transitions between. *Tests design* was not as frequent throughout because of the need to test with a facilitator at a specific station. The greatest time (41%) was spent in *Builds or modifies design*. These visitors exhibited *Analyzes what happens and what can be improved* consistently after tests and most frequently of all challenges, likely due to the facilitated tests. All groups looked at other designs and three groups discussed the relation to the real world.

Interviews

To further understand visitor perceptions of the activities and visitors' design processes, I analyzed interview responses. Most visitors recognized that the activity was related to engineering. Of the four who did not, one had the perception that engineering was building trains while the others mentioned not fully completing their project. In terms of relating the activity to specific real world products, an average of 61% of visitors from Marble Machines, Spinning Tops, and Cars were able to identify products while 100% of visitors from Engineer the World and Sound Engineering identified related products.

The interviews also provide some insight into the design processes of visitors. Most visitors (58%) mentioned that their goal steered their design choices. However, 42% of visitors mentioned specific materials that inspired their designs through constraints and affordances. Many visitors remarked that their idea "just came" as they explored materials; thus, their goal emerged from this process, explaining the large amount of time spent in the *Explores/selects appropriate materials/tools* behavior. Other visitor explanations for design choices include trial and error, inspiration from other people or examples, and wanting to make something unique. Over half of the visitors noted that they looked at other designs, with many mentioning gaining inspiration and ideas, some mentioning wanting to modify and build upon those designs, and others mentioning specific materials they noticed. Interestingly, during observations, visitors rarely explicitly stated their goals; however, when prompted during interviews, they could identify their goals. Importantly, a large number of visitors identified trying to achieve the "best" solution. Many pointed out the need to modify their designs for improvement, trade-offs between various designs, and specific problems that prevented them from achieving their goal. Thus, these implicit goals prompted visitors to engage in systems thinking and critical analysis, key engineering abilities. The only visitors who noted that they were not able to achieve their goals were some from Sound Engineering and all from Cars; this is interesting given that Cars was one of the most popular challenges with the greatest average attendance and stay-time (53 minutes versus 25-33 minutes for the four other challenges).

Figure 2a: Timelines of participants at the Marble Machines challenge, continued in Figure 2b. The average cascade rating is 0.36, with individual ratings labeled. Behaviors are listed along the y-axis while the x-axis represents time in hh:mm:ss.

Figure 2b: Timelines of participants at the Marble Machines challenge, continued from Figure 2a. The average cascade rating is 0.36, with individual ratings labeled. Behaviors are listed along the y-axis while the x-axis represents time in hh:mm:ss.

Figure 3: Timelines of participants at the Spinning Tops challenge. The average cascade rating is 0.60, with individual ratings labeled. Behaviors are listed along the y-axis while the x-axis represents time in hh:mm:ss.

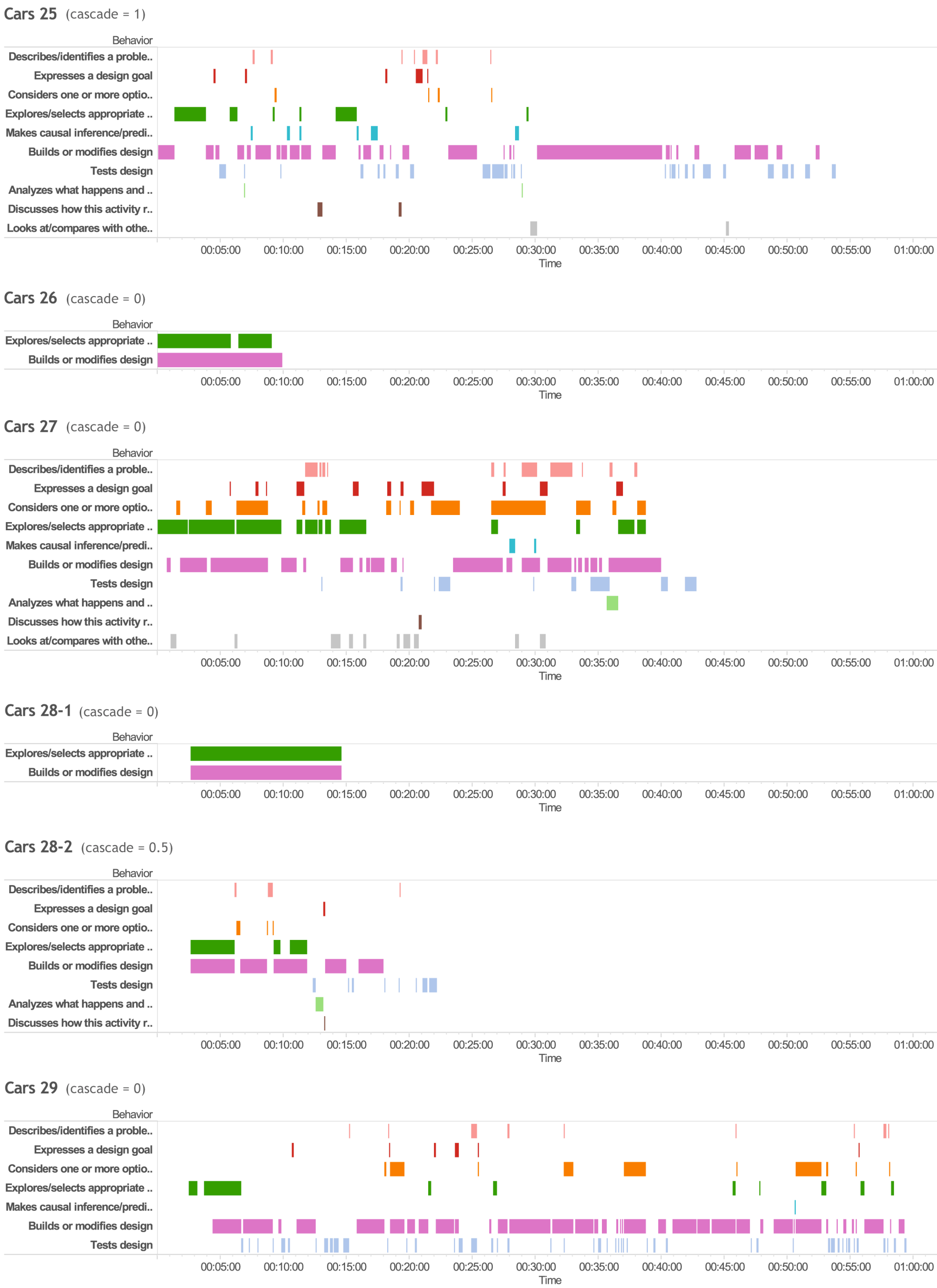


Figure 4: Timelines of participants at the Cars challenge. The average cascade rating is the lowest of all challenges at 0.25. Individual cascade ratings are labeled. Behaviors are listed along the y-axis while the x-axis represents time in hh:mm:ss.

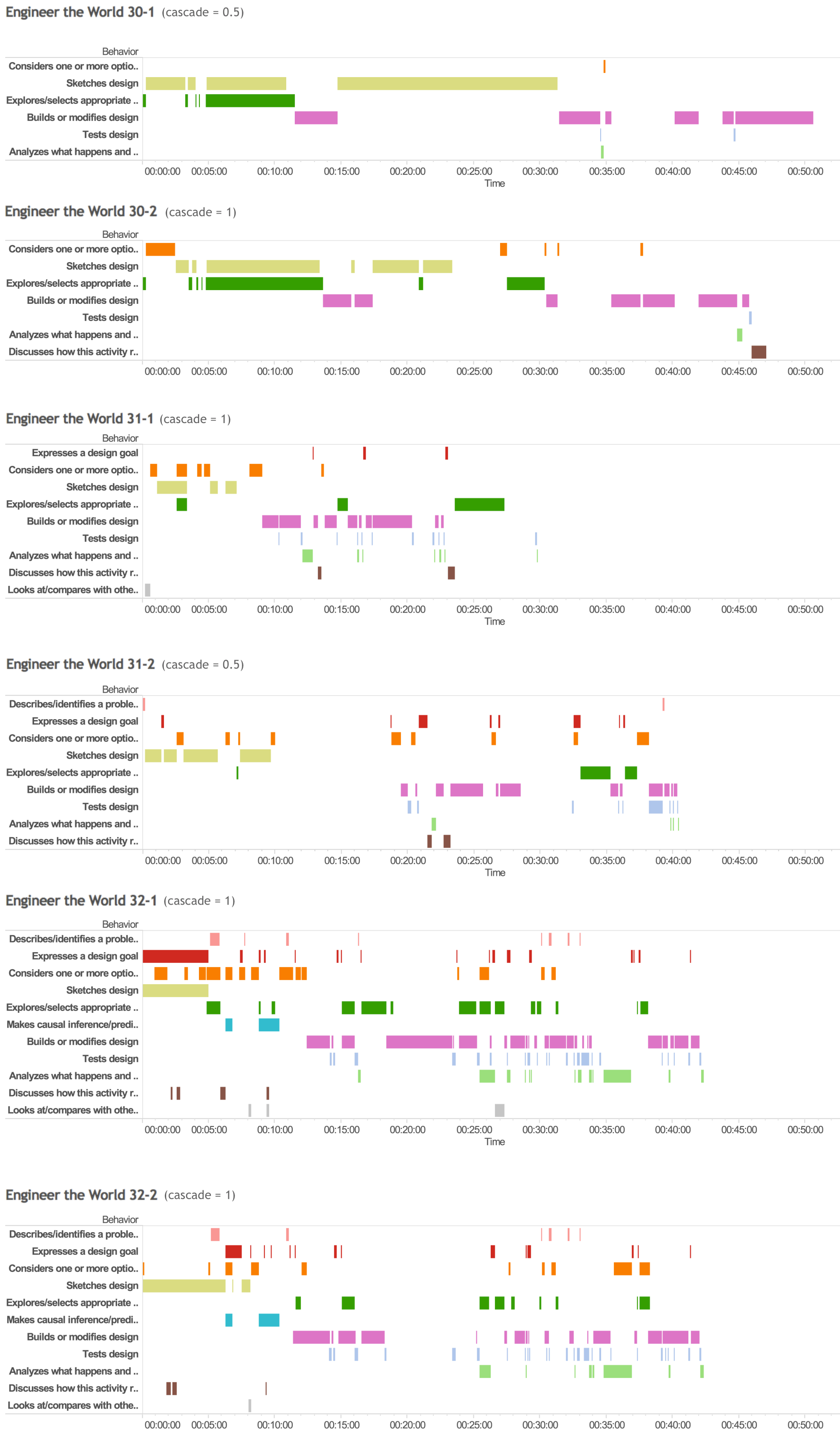


Figure 5: Timelines of participants at the Engineer the World challenge. The average cascade rating is the highest of all challenges at 0.83. Individual cascade ratings are labeled. Behaviors are listed along the y-axis while the x-axis represents time in hh:mm:ss.

Figure 6a: Timelines of participants at the Sound Engineering challenge, continued in Figure 6b. Numbers 39, 42, 40-3, and 40-1 beginning at 12 minutes and 40-2 beginning at 22 minutes engaged in the instrument design while Numbers 41, 43, and the beginning parts of 40-1 and 40-2 engaged in the speaker design. The average cascade rating is 0.59, with individual ratings labeled. Behaviors are listed along the y-axis while the x-axis represents time in hh:mm:ss.

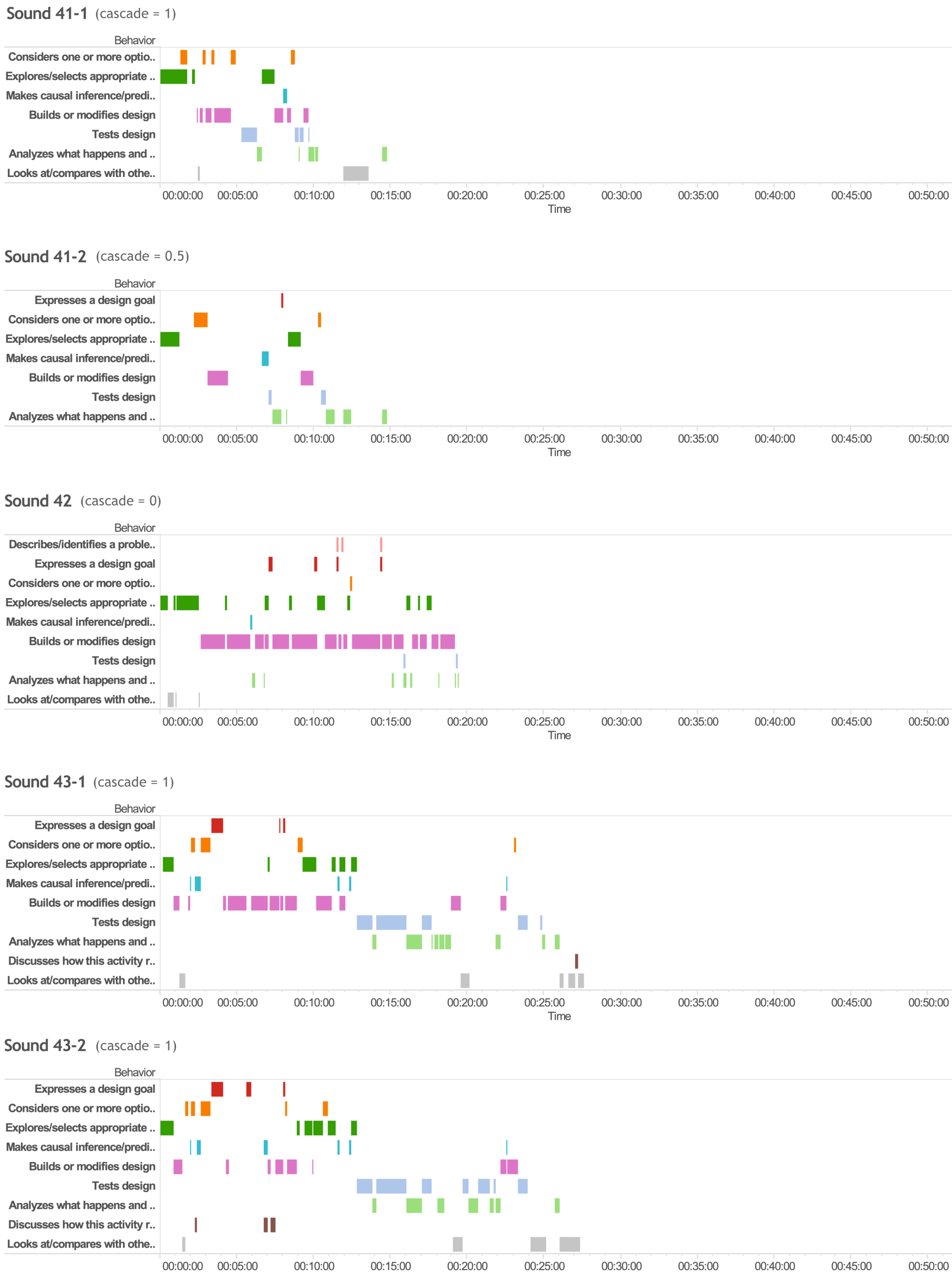


Figure 6b: Timelines of participants at the Sound Engineering challenge, continued from Figure 6a. Numbers 39, 42, 40-3, and 40-1 beginning at 12 minutes and 40-2 beginning at 22 minutes engaged in the instrument design while Numbers 41, 43, and the beginning parts of 40-1 and 40-2 engaged in the speaker design. The average cascade rating is 0.59, with individual ratings labeled. Behaviors are listed along the y-axis while the x-axis represents time in hh:mm:ss.

Summary

Table 4: Similarities and differences across challenges, by behavior. Average frequency (f) and percentage of time spent (p) by challenge is noted with grey shading, with darker shades indicating greater frequency and percentage (see Appendix B for shading code). MM = Marble Machines, ST = Spinning Tops, C = Cars, EW = Engineer the World, and SE = Sound Engineering.

Engineering Design Behavior	Observations	MM (f, p)	ST (f, p)	C (f, p)	EW (f, p)	SE (f, p)
Describes/identifies a problem to be solved	Not very common across all challenges; low frequency and short durations for all except Marble Machines and Cars.	6.43, 1.76%	0.93, 0.65%	4.27, 1.51%	1.58, 0.63%	0.60, 0.34%
Expresses a design goal	Uncommon across all challenges; low frequency and short durations except Marble Machines and Engineer the World.	6.14, 2.91%	2.53, 1.68%	3.66, 1.38%	5.16, 3.19%	1.80, 1.67%
Considers one or more options for achieving goal	Not very common across challenges, except Engineer the World. Also occurs more in collaborations.	3.90, 2.48%	2.66, 2.17%	4.77, 4.80%	9.50, 7.26%	2.40, 3.08%
Sketches design	Only Engineer the World engaged visitors in sketching regularly, but no visitor returned to this behavior after implementation.	0, 0%	0, 0%	0, 0%	4.08, 22.41 %	0.10, 0.10%
Explores/selects appropriate materials/tools from available options	Marble Machines, Cars, Engineer the World, and Sound Engineering engaged visitors heavily in this behavior using unfamiliar materials or familiar materials in unfamiliar ways.	14.95, 10.10 %	2.53, 7.31%	6.00, 37.94 %	6.25, 14.16 %	6.05, 13.56 %
Makes causal inference/predictions about how design will perform	Very uncommon across all challenges.	3.24, 0.97%	1.80, 0.73%	1.27, 0.51%	0.33, 0.83%	2.00, 1.39%
Builds or modifies design	Most common behavior across all challenges.	34.52, 44.77 %	7.60, 14.01 %	24.05, 63.39 %	12.00, 25.91 %	13.20, 40.86 %
Tests design	Occurred in all timelines with complete participation. Especially common in Marble Machines and Sound Engineering's instrument challenge, which let visitors test their designs in-situ; visitors transitioned frequently between *Builds or modifies design* and *Tests design*.	36.14, 8.64%	4.60, 10.79 %	16.67, 6.25%	10.08, 2.95%	9.65, 12.79 %
Analyzes what happens and what can be improved from the tests	Most frequent in Spinning Tops, Engineer the World, and Sound Engineering, which had facilitators assist in testing; Tops also had visitors graph and compare results.	2.38, 0.58%	3.93, 4.49%	0.55, 0.63%	4.33, 2.91%	5.35, 5.90%
Discusses how this activity relates to the real world, engineers, etc.	Cars, Engineer the World, and Sound Engineering visitors discussed more real world relevance of the challenges.	0, 0%	0, 0%	0.55, 0.33%	1.42, 1.50%	1.25, 0.55%
Looks at/compares with other designs	Sound Engineering, with a table of examples, was the only challenge where all groups looked at example designs. All other challenges only had 2-3 groups look at other designs.	1.10, 0.42%	0.80, 0.48%	1.22, 0.97%	0.50, 0.51%	2.35, 3.80%

Like the experts in Atman et al. (2007), many visitors exhibited a cascade pattern. The cascade indicates that visitors are acting like expert engineers and are able to successfully monitor their design progress to transition behaviors appropriately, rather than just randomly playing. We do see many variations within challenges, and note that some visitor timelines had no indication of a cascade pattern while others exhibited very strong cascade patterns. For some, we even see repeating cascades, indicating multiple iterations of refinement that are characteristic of expert engineering design. The multiple iterations suggest the persistence of the learner in achieving a working solution and his/her ability to integrate information from previous iterations. In general, the easier it was to test the design, the more iterations we saw, since the ease of testing gave quick and frequent feedback about the success or failure of the design. The variation of timelines is not surprising given the diversity in visitor backgrounds and the strong influence of facilitators on the visitors' design processes. However, one-way ANOVA of the means of the cascades shows that Spinning Tops, Engineer the World, and Sound Engineering engaged the observed visitors in stronger cascade patterns while Cars visitors exhibited much weaker cascades ($F(4, 29) = 2.99$, $p = 0.035$). Thus, the nature of the design task and the materials at each challenge may have led to particular patterns in visitor behavior.

Unlike the experts, visitors spent less time problem scoping. The problem was not necessarily defined; some challenges had more specific goals (e.g., achieve longest spin time in Tops), while others were broader (e.g., make a website in Engineer the World). Visitors instead spent most time modeling and implementing: exploring and selecting materials, building, and testing, which are the top three behaviors by time spent for all except Engineer the World. Because of its unique requirement to sketch before implementation, Engineer the World participants spent relatively more time in the problem scoping behaviors. Interviews reveal that for problem scoping across the challenges, children identified problems and obtained information while tinkering with materials, gaining inspiration from this process; they also utilized information from existing designs in the space and examples from the real world, often engaging in conversation with others and asking about the materials, designs, and examples. These processes suggest primitive forms of information gathering that similarly inspires experts (Ennis & Gyeszly, 1991); the visitors gathered information mostly on the design context, while experts further consider users, clients, environmental and social impact, etc. Thus, engagement with the tangible can serve as a stepping-stone towards expert engineering actions.

In terms of variations across challenges, the timeline patterns vary because of the complex context of each challenge. Different behaviors were observed in different design situations (Table 4), as found by Jin & Chusilp (2006). For instance, Marble Machines visitors engaged in frequent testing throughout most of the process because the design could be tested by dropping a marble at any time. Most Spinning Tops visitors regularly analyzed their design after each test possibly due to the facilitation of all tests by staff or volunteers. Cars visitors were observed most greatly by time to explore materials and build since the building process was much more complex than other challenges. Engineer the World visitors were the only ones who sketched, as sketching was part of the challenge. Finally, Sound Engineering consistently looked at other designs because of the presence of a table of examples.

Interestingly, Cars timelines demonstrate an anomaly of a reverse cascade and have the lowest mean cascade score. None of these participants reported that they achieved their goals even though the average stay-time was longest of all challenges. The unfamiliar materials and context – microcontrollers and gearing – prompted many visitors to begin transitioning between *Explores/selects appropriate materials/tools* and *Builds or modifies design*, then *Describes/Identifies problem* emerged through this process, thus producing a reverse-looking cascade. Furthermore, the persistence in exploration and aiming to get the car to "run" is intriguing in face of the failure to achieve their goals. Visitors indicated in surveys that they understood failure as a method of learning rather than as a result of their inability. We also note that this challenge included the only visitors who stopped before completing at least one iteration. Thus, the context of the challenge may have fostered extreme forms of participation: long and persistent participation or short and incomplete participation. With regards to the persistence, the multiple iterations and testing may have provided small steps of success that further encouraged visitors. The presence of other similar visitors with working designs may also have made them feel that success was possible. Deeper exploration of these visitors' processes can provide insight into these visitors' tremendous persistence.

Thus, in contrast to expert engineers in Atman et al. (2007), these visitors engaged heavily in tangible activities as a form of problem scoping. Without the foresight of expert engineers familiar with the domain and materials, the visitors spent a lot of time exploring materials, but in a way to gather information and identify problems that influenced their designs. Through co-evolutionary design (Maher & Tang, 2003; Dorst & Cross, 2001), their understanding of the problem and solution evolved (Adams, 2001) as they explored materials in a reflective conversation between the materials, design situation, and design outcome (Schön, 1992). Thus, they iterated frequently between exploring materials, building, and testing, where the physical materials helped scaffold them to transition opportunistically between information gathering and concept generation like experts (Ennis & Gyeszly, 1991; Atman et al., 2007). However, the experts in Atman et al. (2007) did not implement their designs and consequently did not engage in any building, only modeling. These findings are similar to early analyses from ongoing work on parent-child dyads in informal engineering learning environments (Cardella et al., 2013).

Further, these visitors were strongly influenced by other designs, a behavior unreported by Atman et al. (2007). This behavior emerged through the video coding process. Contrary to experts in the isolated lab, these visitors worked in a non-isolated context and were able to see others' evolving and final designs. Consequently, visitors copied and improved upon others' designs, or made a design unique to others.

Constant across all challenge contexts was the open-endedness. All challenges allowed for open access to the materials and self-paced progressions through designs. The environment also allowed for visitors in various design stages to work next to each other, and guidance was available through facilitation. Observations show that with the variance in materials, the constancy of the open-endedness, the ability to observe others, and the guidance of facilitators, these contexts may be fostering a range of engineering design behaviors similar to experts.

Limitations

Videos could not always capture all participants simultaneously; thus, some gaps in observation are noted. Furthermore, as a naturalistic observation, no probing was implemented and behaviors were observed while non-spoken thoughts could not be observed. And, the small sample size and the variety in backgrounds and context, including the individual facilitator influence, mean that the cases are not necessarily representative of the larger population. Therefore, these cases need to be considered with all the background and context details.

This study also did not include any expert engineers; thus, these findings should be considered in light of the differences between this study context and Atman et al.'s (2007) study context. The greatest difference is the presence of physical materials to build with in the public and live science center program while Atman et al. (2007) only considered experts' paper-and-pencil planned designs in an isolated lab setting. However, this study provides a better understanding of the ways in which these expert patterns might be created by the various design contexts, contributing as a step towards optimally designing contexts for engineering learning.

Significance

Open-ended design challenges in informal settings are common (e.g., Maker Faire, science centers); thus, research on children's engineering processes can benefit these education venues. This study provides fundamental analysis on what children do when they play in these settings.

Three key points from the results are: (1) each challenge provided opportunities to engage in engineering design in different forms, (2) the presence of other designs in the context was important for inspiration, and (3) physical materials provided a critical means for visitors to identify problems.

These timelines provide a powerful representation to compare design processes person by person and challenge by challenge to increase our understanding of engineering expertise. They show how budding engineers engage in engineering and are a means to characterize challenges. Further cross-comparison studies should explore how people of varying engineering expertise may engage in this type of live environment with physical materials to determine if they also exhibit more exploration of materials and building as a means of problem scoping. Perhaps, then, exploring materials may be a pathway towards expert engineering processes. It would be interesting to see if other informal environments show a similar pattern in their engineering-related learning contexts, confirming that if given the right environment and materials, children naturally engage in engineering design and problem-solving.

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Appendices

Appendix A: Visitor Pre- and Post- Interviews. Personal Meaning Mapping is a method used by Falk, Moussouri, & Coulson (1998) in museum setting interviews.

Visitor Pre-Interview

Script: *Hi, my name is ______. I'm talking to people and observing what they do here at the Ingenuity Lab to find out what they thought about these activities. Is it OK if I ask you some questions and if I observe and videotape what you do at the Ingenuity Lab? The questions will take about five minutes before and ten minutes after. While you're in the Ingenuity Lab, you should totally ignore us and enjoy yourself. You can stop at any time.*

1. **Personal Meaning Mapping**: Please write and draw anything that you think of when you see the word below.

Engineering

2. What do you think engineers do?

3. Do you feel like you're an engineer? [Have you engineered things before?]

Visitor Post-Interview

1. Could you show me your design(s)? How did you choose what to make? Did you look at other designs/projects? [Have you built things like these before?]

2. What were you trying to do with it [design goal]? Did it do what you wanted it to do?

3. (If worked with others) How did other people help you? Did you help anyone else?

4. How is what you did here related to the real world or anything you've seen before?

5. Have you done something like this before? How is it similar?

6. Do you think you'll continue doing activities like this? What would you want to do? / Do you feel like you can engineer other things?

7. **PMM**: *Now we're going to go back to what we did before you started your project here. We're going to look again at what you said about "engineering."*

8. What do engineers do? Did you feel like what you did was engineering? Why/why not?

Appendix B: Formula for coding shaded representation of average frequency (f) and average percentage time spent (p) on each behavior. Shading ranges from 0 to 70, with 0 as white and 70 as the darkest grey.

$$shade(f,p) = \begin{cases} 0 & s = 0 \\ 10 & 0 < s \leq 2.5 \\ 20 & 2.5 < s \leq 5 \\ 30 & 5 < s \leq 10 \\ 40 & 10 < s \leq 20 \\ 50 & 20 < s \leq 40 \\ 60 & 40 < s \leq 80 \\ 70 & s > 80 \end{cases}$$

$$s = f + 100p$$